How to Secure Reliable Power Supply to Mega Cities

Final Report

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WORLD ENERGY COUNCIL
CONSEIL MONDIAL DE L'ÉNERGIE

CONTENTS

1. Executive Summary

1.1 Background

The 2010 WEC Report "Energy and Urban Innovation" noted that retrofit of infrastructure and new solutions must be implemented to avoid disruptive blackouts.
For a mega city as the center of politics and economics, maintaining adequacy and security of the electricity supply and preventing blackouts are crucial supply side issues.
At the Daegu Congress 2013:

- Became aware of the risks from the energy-water nexus, extreme weather events, and cyber-attacks exposing our energy infrastructure to potential disasters.
- Need to urgently adapt, re-think, and redefine **"resilience"** for energy infrastructure.

1.2 Objective

1. Identify the following points
    - ► Common causes of past large-scale blackouts in large metropolitan cities.
    - ► Possible future risks that could cause major blackouts in large cities.
    - ► Best practices for the prevention of blackouts in terms of:
        - Power system planning
        - Power system operation
        - Facility design
2. Make a recommendations on how to secure a reliable and "resilient" electric power supply for the Mega cities

1.3 Measures

In order to achieve the objective, the study team conducted a subsequent survey to gather information on the following:

1. **Past major blackouts** in large cities
2. Possible **future risks** that could cause major blackouts in large cities
3. **Best practices** both in power system planning/operation and facility design
4. **Future technologies** under Research & Development

1.4 Results of survey

1.4.1 Past major blackouts in large cities

As shown in Table 1-1, 6 cases of 10 large scale outages are cascading events due to the malfunction of islanding control or frequency instability.

In 20 century, most of large blackouts were caused by accidental destruction by third parties and operational inaccuracy.

After greeting the 21 century, cascading blackouts due to abnormal weather occurred frequently. Besides these cases, there are many blackouts in Asian countries due to abnormal weather missing in this table; tsunami in Indonesia, typhoon in Philippines etc.

Table 1-1 Experiences of Large Scale Outages in Member Countries

Date	*Area*	*MW Lost / Duration*	*Cascading / Non-cascading*	*Causes*	*Critical Phenomenon*
Mar. 1984	*Kowloon and New Territories, Hong Kong*	*Unknown /4 hours*	*Cascading*	*Operational inaccuracy*	*Frequency instability*
Aug. 1987	*Tokyo*	*8000MW /4 hours*	*Cascading*	*Operational inaccuracy*	*Voltage instability*
Nov. 1999	*Tokyo*	*1600MW /3 hr 19m*	*Non-Cascading*	*Accidental destruction*	*Frequency instability*
Jul.	*Chongmin,*	*165MW*	*Cascading*	*Operational inaccuracy*	*Overloaded lines*

2005	*Shanghai*	*/2 hours*			*Frequency instability*
Apr. 2006	*Jeju*	*348MW /2 hr 34 m*	*Cascading*	*Accidental destruction*	*Frequency instability*
Aug. 2006	*Tokyo*	*2160MW /59 min.*	*Non-cascading*	*Accidental destruction*	*Frequency instability*
Jun. 2008	*Sheung Wan District, Hong Kong Island, Hong Kong*	*Minimal /12 hours*	*Non-Cascading*	*Abnormal weather*	*Flooding*
Mar. 2011	*Wide area including Tokyo*	*Unknown*	*Cascading*	*Natural disaster*	*Frequency instability*
Apr. 2012	*Shenzhen*	*759MW /1hr 37m*	*Non-Cascading*	*Trouble at facilities*	
May 2013	*14 southern pro vinces of Thaila nd*	*4.13GWh /4 hours*	*Cascading*	*Abnormal weather*	*Frequency instability*

1.4.2 Possible future risks that could cause major blackouts in large cities

Each member company selects the disturbances from the following categories and items, and considers a worst-case scenario which results in a severe outage.

Table 1-2 Categories and Items of Disturbance

Categories	Items
Abnormal weather	Typhoon/Rain storm, Lightning strike, Flooding, Tornado, Blizzard/Ice-storm, Drought/Heat wave, Others
Natural disaster	Earthquake, Tsunami/Tidal wave, Volcanic eruption, Landslide/Avalanche, Forest fire, Wildlife/Tree contact, Geomagnetic storm, Others
Trouble at facilities	Aging, Defects, Explosion/Fire, Accidental destruction, Intentional destruction (Conflict, Terrorism, Cyber-attack), Others
Operational inaccuracy	Demand-forecasting, Deficiency of power source, Supply-demand control (Deficiency of reserves), Voltage-reactive power control, Mis-operation/Malfunction of facilities/control systems/relays, Others
Others	Pandemic, Others

The risk of each disturbance realizing the worst scenario is assessed using the following Probability/Impact chart method.
As shown in Figure 1-1, countermeasures for each disturbance are prioritized into 3 degrees – “High”, “Moderate” and “Low/Ignorable” according to the 3-color-classification of the Probability/Impact chart.
In particular, the “Low probability high impact” zone (enclosed in thick red line) should be closely watched to enhance the “resilience” of the power system.
For a detailed description of the methodology, refer to section 4.3.2.

The results of the survey are as per the figures in 1-2.

In terms of the results of the survey with the Probability/Impact Chart assessment, the following disturbances are identified as the threats to the “resilience”:

- **Abnormal weather**: Blizzard/Ice storm, Drought/Heat wave
- **Natural disaster**: Tsunami/Tidal wave, Volcanic eruption, Geomagnetic storm
- **Trouble at facilities**: Intentional destruction, Explosion/Fire
- **Operational inaccuracy or other**: Deficiency of power supply, Pandemic

Most of them are difficult to predict, and they may cause significant damage to the power supply facilities once they occur.
Therefore, the survey this time has reached a reasonable conclusion.

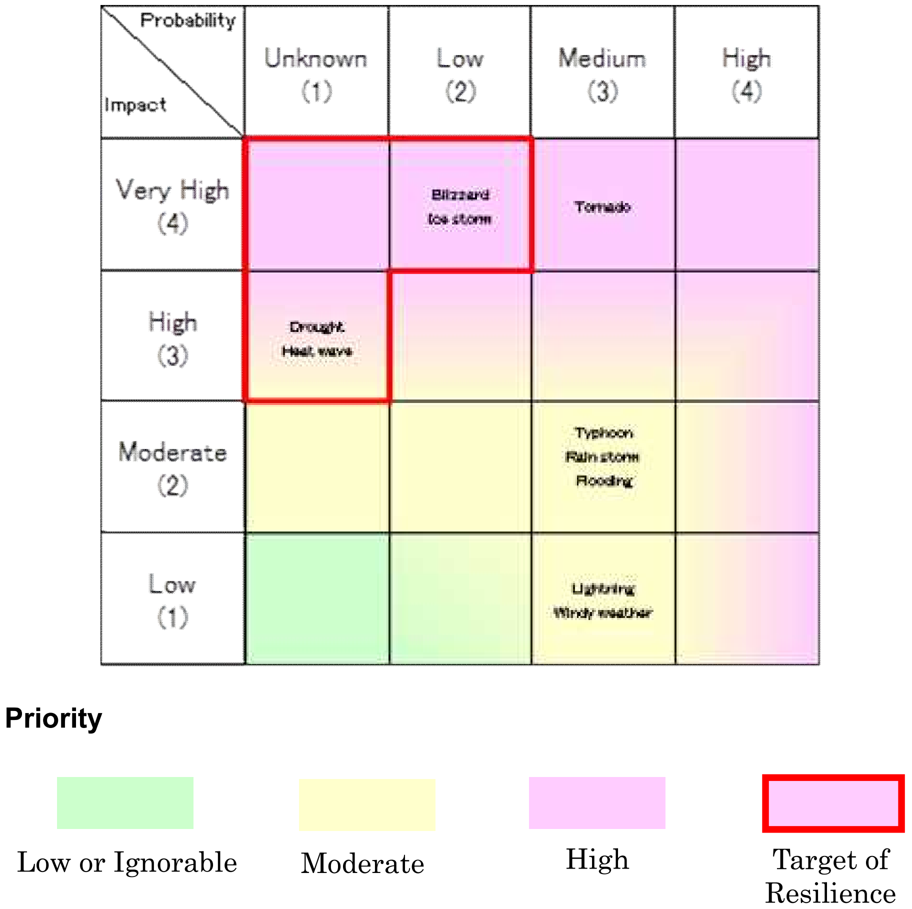
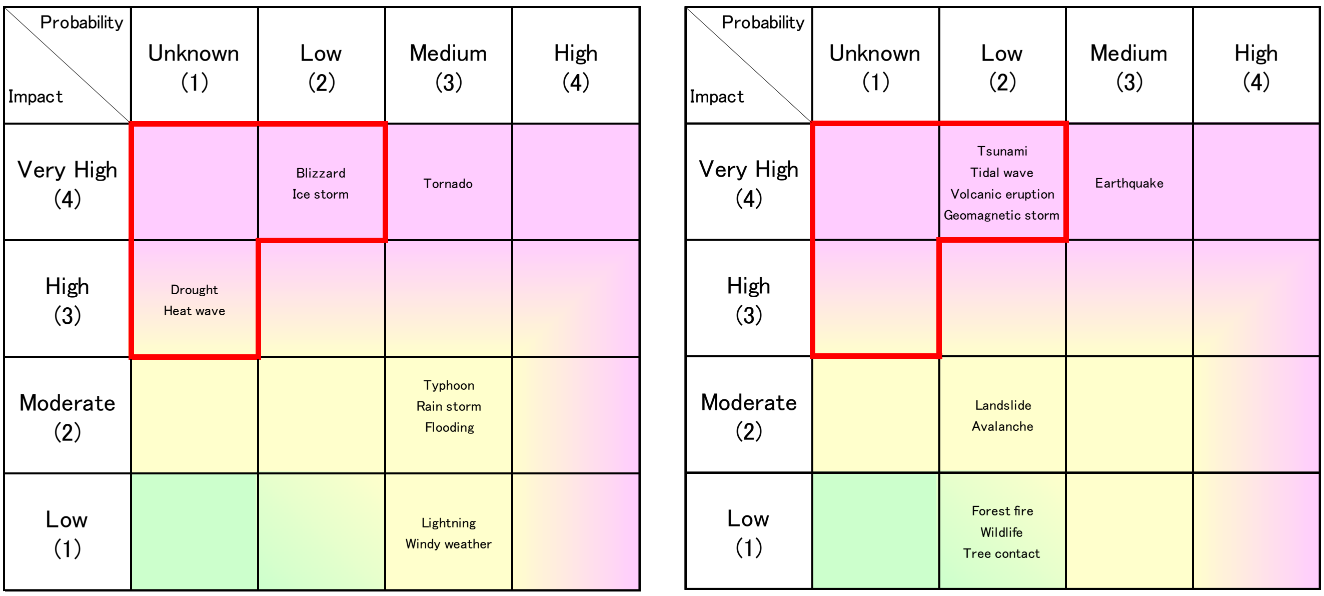


Figure 1-1 Conceptual Priority Assessment Method with Probability/Impact Chart



(a) Abnormal weather (b) Natural disaster

Impact \ Probability	Unknown (1)	Low (2)	Medium (3)	High (4)
Very High (4)	Intentional destruction	Explosion Fire		
High (3)				
Moderate (2)		Aging Defects		
Low (1)		Accidental destruction		

(c) Trouble at facilities

Impact \ Probability	Unknown (1)	Low (2)	Medium (3)	High (4)
Very High (4)		Deficiency of gen.		
High (3)	Pandemic	Voltage control		
Moderate (2)		Demand forecast Balancing Miss operation		
Low (1)				

(d) Operational Inaccuracy or other

Figure 1-2 Survey Results of the Probability/Impact Chart Assessment

1.4.3 Definitions of measures

Mitigation measures or hardening measures may refer to topology and structural changes to make the network less vulnerable to severe events. In this survey, the “mitigation measure” is mainly targeting the primary equipment.

Adaptation measures (in a broad sense) refer to a broad set of operational measures that can be taken to improve the observability, controllability, and operational flexibility of a power system, particularly in response to an extreme event.
In this survey, we divide them into the “hybrid” and the narrow set of “adaptation measures”.

Hybrid measures are targeting the installation of auxiliary equipment or PACS (protection and control system).

Adaptation measures (in a narrow sense) are targeting pure preventive or restorative operational actions
Hereinafter, the term “Adaptation measures” means this narrow set of adaptation measures.

1.4.4 Measures (Best practices or future technologies) for boosting resilience

As a result of survey, Mitigation measures can be categorize into three (3) activities.

<Hardening facilities>

- Reinforce a power system, structures and foundations
- Duplication or taking special measures for abnormal weather or natural disaster
- Relocation to underground, indoor elevated ground, or other less disturbance-prone area
- Strategic replacement of the same model/type equipment, a part of which found to have defect.

<Strategic power system planning>

- Grouping/sectionalize the downstream network

<Quality enhancement activities>

- Periodic network security review and reinforcement planning of network
- Standardization

For more details, refer to section 4.6.1.

In order to boost the “resilience” of the power supply system, “Low probability, High impact” incidents should be targeted. Therefore, the measures should be carefully assessed from the viewpoint of “cost-effectiveness”.
According to this fundamental concept, “Hybrid measures” and “Adaptation measures” must play important roles in the enhancement of resilience.

In this survey, the study team tried to evaluate the current status of resilience by classifying hybrid and adaptation measures into these points.

(1) The ability of **<u>anticipating</u>** the extraordinary incidents

(2) The ability of **<u>rapidly recovering</u>** from the disruptive situation

(3) The ability of **<u>absorbing lessons</u>** from past experience for future events

As the results of surveys, the hybrid measures and adaptation measures can be classified as per the following tables:

Ability	Hybrid	Adaptation
Anticipating	**Predictability Observability/Visibility** ● Condition monitoring system ● Alarm system ● Lightning strike tracking and locating system ● Monitoring/Surveillance system ● Authentication system ● Remote inspection tool ● WAMAC, Dual RTU ● New aging marker	**Predictability Observability/Visibility** ● Manage inspection ➢ Perform special inspection, ➢ Shorten inspection period ● Condition Monitoring Test ➢ Insulation or grounding resistance test ➢ Infrared Ray (IR) inspection
Rapidly recovering	**Automatic recovery system** ● Emergency restoration system (ESR) ● Intelligent switch ● Auto-reclosing scheme ● Automatic self-testing/monitoring scheme	
	Backup/Alternatives ● Use of mobile generators ● Preparation of spare parts, Universal parts	**Backup/Alternatives** ● Securing adequate reserve ● Arrange temporary supply from adjacent supply sources
	PACS for localization of the disturbance ● CBF protection scheme ● Load shedding scheme with under-frequency relay ● PSS, PSVR, VQC, AVC, VMS ● UPSS, ISAS	**Operation for localization of the disturbance** ● Change of power system configuration ● Implement radiation configuration ● Proactively switch out ● High voltage profile operation
		Preparation of emergency plan ● Preparation of Black-start procedure, Rolling outage procedure

		Emergency support ● Request for emergency support, manpower
Absorbing lessons	**Quality enhancement** ● Calculator for assessment ● Real-time simulator for shift operators' drill (PGS)	**Quality enhancement** ● Establishment and periodic review of: ➢ Comprehensive network reliability and operation plan ➢ Comprehensive crisis management plan ● Periodic drill

As shown in the table above, countermeasures are properly and thoroughly taken.
In the best practice, many of the remarkable measures can be categorized into hybrid measures. Therefore, the hybrid measures may occupy an influential position and will keep it for the future.

1.4.5 Future Works

In the near future, exponential connection of renewable energy, especially photovoltaic or wind power, will have a greater influence on stable supply-demand and frequency control. Therefore, development for:

- Accurate demand forecasting technology
- Output prediction technology for PV and wind power

are eagerly desired.

2. Overview

2.1 Background

Activities of World Energy Council (WEC) for "resilience" of power systems

2010 WEC Report "Energy and Urban Innovation" noted:

- To avoid disruptive blackouts and shortages, infrastructure must be retrofitted and new solutions implemented. The reliability and efficiency of the electricity network is a crucial point for many developing-country cities.

Since mega-cities (metropolitan cities) are the center of government and economics, maintaining adequacy and security of the electricity supply and preventing large scale outages in these areas are crucial supply side issues.

At the Daegu Congress 2013, we became aware of the Risks from the energy-water nexus, extreme weather events, and cyber-attacks exposing our energy infrastructure to potential disasters. We need to urgently adapt, re-think, and redefine "resilience" for energy infrastructure.

Each country in the Asian region has developed and implemented its own measures to maintain supply reliability and prevent large-scale blackouts in their mega-cities.

Thus, it would be meaningful for Asian MCs to share their experiences and best practices so that this regional deep-dive study can contribute to a more sophisticated understanding of the existing and emerging risks facing energy infrastructure, and hence deliver a "resilient" energy infrastructure.

2.2 Objective

The objective of this project is to study the following and make recommendations on how to secure a reliable and "resilient" electric power supply for the Mega cities:

1. Common causes of past large-scale blackouts in large metropolitan cities.
2. Possible future risks that could cause major blackouts in large cities.
3. Best practices for the prevention of blackouts in terms of:
   - Power system planning
   - Power system operation
   - Facility design

2.3 Measures

In order to achieve the objective, a study team, consisting of Asian countries, was organized. The study team selected the Mega cities in the Asian region to be surveyed, and conducted a subsequent survey to gather information on the following:

1. Past major blackouts in large cities
   - Sequence of events
   - Root causes
   - Countermeasures taken

2. Possible future risks that could cause major blackouts in large cities

3. Best practices both in power system planning/operation and facility design
   - Category-A (Mitigation or Resistance): To limit blackout areas and frequency
   - Category-B (Adaptation or Resilience): To speed up restoration

4. Future technologies under Research & Development

In addition, in order to exchange useful information and promote friendship with each other, the study team members were brought together in Tokyo (Japan) on August 27th and 28th, 2015.

A timeline of the activities the study team has conducted is shown in Figure 2-1.

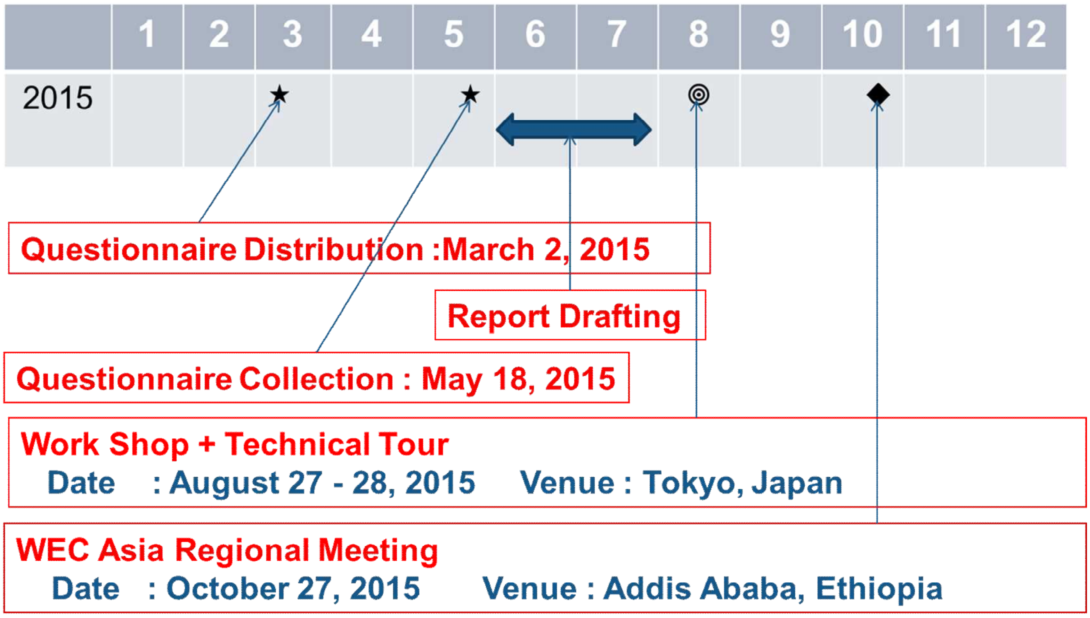


Figure 2-1 Timeline of the Task

2.4 Study Team Members

NAME	COMPANY	COUNTRY
Mr. Shinichi IMAI (Leader)	TEPCO	JAPAN
Mr. Shinichi SUGANUMA (Sub-Leader)	TEPCO	JAPAN
Mr. Masafumi SHINOZAKI	TEPCO	JAPAN
Mr. Kenji HIBI	TEPCO	JAPAN
Mr. Zentoku TAKAMOTO	TEPCO	JAPAN
Ms. Shizuka SUGIURA	TEPCO	JAPAN
Dr. Hideaki TANAKA	WEC Japanese MC	JAPAN
Mr. Chi Pui NG	CLP Power	Hong Kong, CHINA
Mr. Warren Yuk-cheong WU	HK Electric	Hong Kong, CHINA
Dr. Fei XIAO	SMEPC, SGCC	CHINA
Mr. Minjie JIN	SMEPC, SGCC	CHINA
Mr. Zhang Zheng	SMEPC, SGCC	CHINA
Mr. Zhiliang Yin	SMEPC, SGCC	CHINA
Mr. Zhixin Suo	GPSB, CSGC	CHINA
Mr. Wenjian Gao	Guangxi PGC	CHINA
Ms. Fengjian Luo	Guangxi PGC	CHINA
Mr. Fachi Chen	Shenzhen PSC	CHINA
Dr. Young-Jin WON	KEPCO	KOREA
Mr. Chulhyu Lee	KEPCO	KOREA
Mr. Kuseop Yun	KEPCO	KOREA
Mr. Tawatchai SUMRANWANICH	EGAT	THAILAND
Mr. Kittidet SAMAKNGAN	MEA	THAILAND

2.5 *Acronyms*

Names of member companies

CLP	CLP Power Hong Kong
EGAT or EG	Electricity Generating Authority of Thailand
GPSB, CSGC	Gangzhou Power Supply Bureau of China Southern Grid Corp.
Guangxi PGC	Guangxi Power Grid Corp.
HK Electric or HEC	The Hongkong Electric Company, Limited.
KEPCO or KE	Korea Electric Power Corporation
MEA	Metropolitan Electricity Authority
SMEPC,SGCC or SG	Shanghai Municipal Electrical Power Company, State Grid Corporation of China
Shenzhen PSC	Shenzhen Power Supply Co., LTD
TEPCO or TE	Tokyo Electric Power Company

Technical Terms

AVC	Automatic Voltage Controller (SMEPC)
AVR	Automatic Voltage Regulator
CBF	Circuit Breaker Failure (Relay/Scheme)
DMS	Distribution Management System
EMS	Energy Management System
GIS	Gas Insulated Switchgear
ISAS	Islanded System Automatic Synchronizer (TEPCO)
OH (OHL)	Over Head (Line)
PACS	Protection and Automatic Control System
PGS	Power Grid Simulator (TEPCO)
PMU	Phasor Measurement Unit
PSS	Power System Stabilizer
PSVR	Power System Voltage Regulator (TEPCO)
RTU	Remote Terminal Unit
PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition
SPS	Special Protection Scheme
UFR	Under Frequency Relay
UG (UGC)	Under Ground (Cable)
UPSS	Urban Power System Stabilizer (TEPCO)
VMS	Voltage Management System (KEPCO)
VQC	Voltage Q (Var) Controller (TEPCO)
WAMAC	Wide-Area Monitoring And Control (KEPCO)

3. Definition of Resilience

3.1 What is a "resilience" of a power system?

In recent years, increasing the "resilience" of power infrastructures to high-impact, low-probability events, such as extreme weather phenomena driven by climate change, is of key importance for keeping the light on.
"Resilience" comes from the Latin word "resilio", which literally refers to the ability of an object to rebound or return to its original shape or position after being stressed. [1]
In 1973, C.S. Holling first defined "resilience" on an ecological systems viewpoint as follows:
"Resilience" determines the persistence of relationships within a system and is a measure of the ability of those systems to absorb changes of state variables, driving variables, and parameters, and still persist. [2]
Since this foundational definition, the concept of "resilience" has evolved remarkably in several fields, such as psychology, education (pedagogy), safety, or disaster prevention management, organizational, and socio-ecological ones.
In the context of power system, it refers to the ability of a power system to recover quickly following a disaster or, more generally, to the ability of anticipating extraordinary and high-impact, low-probability events, rapidly recovering from these disruptive events, and absorbing lessons for adapting its operation and structure for preventing or mitigating the impact of similar events in the future, according to [1].

In other words, we need to distinguish blackouts from disaster. A blackout occurs when a large portion of a power grid is disabled by a combination of unplanned contingencies, resulting in a temporary power interruption. A reliable and well-designed power system should be capable of minimizing the amount of power disruption and of recovering very quickly from a blackout. On the other hand, a disaster, which usually includes blackouts, refers to severe and rapidly changing circumstances possibly never before experienced. A disaster can cause the incapacitation of several and often large parts of a power grid, which may last for a long period, depending on the extent of the disaster. Hence, a power infrastructure that can maintain high levels of performance under any conditions should be reliable in the most "common" blackouts, but also resilient to much less frequent disasters.

3.2 Difference between Resilience and Reliability

3.2.1 Features of the "resilience"

Figure 3-1 illustrates the conceptual resilience curve. The resilience level should be expressed as a function of time with respect to a disturbance event. This figure demonstrates the key resilience features that a power system must possess for coping effectively with the evolving conditions associated to an event, for instance, a heavy storm moving across the system.

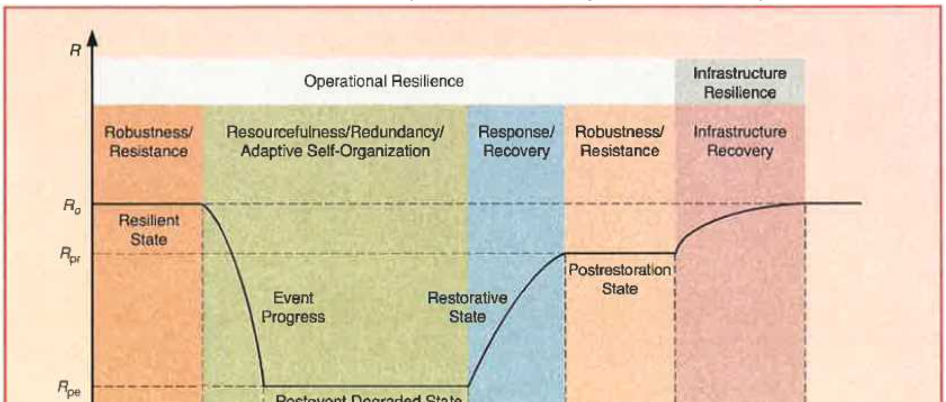


Figure 3-1 A conceptual resilience curve associated with an event

As also indicated in Table 3-1, this “time dimension” is an important feature that distinguishes resilience from reliability.

Reliability	Resilience
High probability, low impact	Low probability, high impact
Static	Adaptive, ongoing, short and long
Evaluates the power system states	Evaluates the power system states and transition times between states
Concerned with customer interruption time	Concerned with customer interruption time and the infrastructure recovery time

Table 3-1 Reliability versus resilience

3.2.2 Long-term Resilience Framework

Figure 3-2 shows the framework for conceptualizing a cyclic procedure of evaluating and improving power systems resilience, which is depicted by the resilience enhancement cycle.

The adaptation capacity, which enables the long-term resilience planning, is thus a critical resilience feature as it provides the capacity to deal with unforeseeable and continuously changing conditions.

As can be seen in Figure 3-2, **the first step** toward this goal is to perform vulnerability and adaptation studies using the input from past experiences and/or simulations.This would help detect the vulnerabilities of a power system at the different stages associated to an event, i.e., before, during, and after, and develop the adaptation strategies necessary for improving the key resilience features and enhancing the response of the power system to the evolving conditions during a similar event that were to occur in the future.

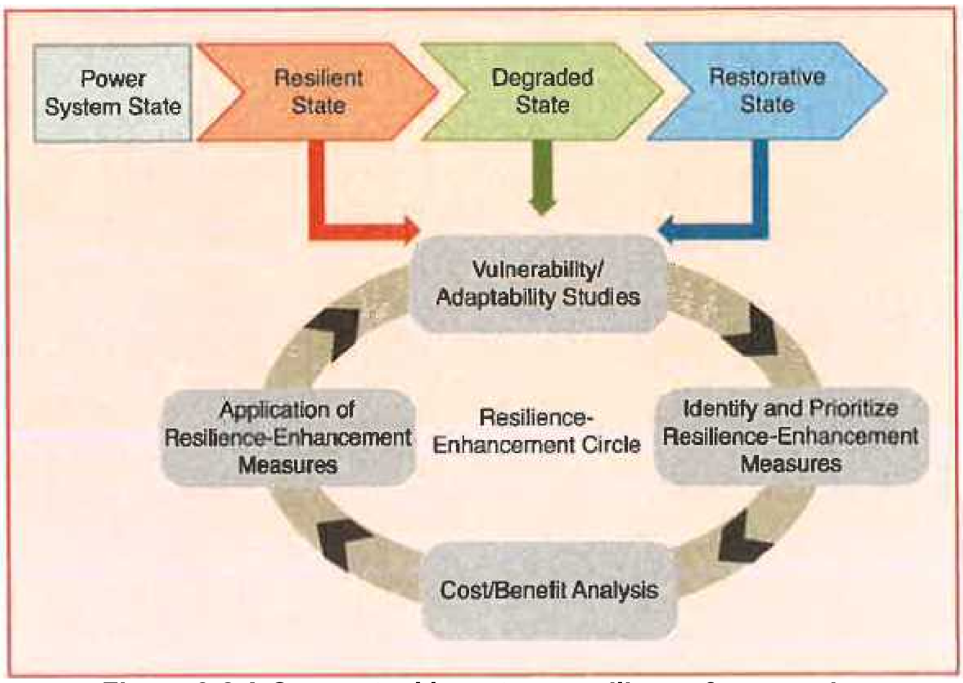


Figure 3-2 A Conceptual long-term resilience framework

Based on the analysis described above, **the second step** is to identify and prioritize the resilience enhancement measures depending on the criticality and contribution of each measure for improving resilience.
These measures are classified into two categories as shown in Figure 3-3:

- Mitigation measures - Hardening/Reinforcement measures
- Adaptation measures - Smart/Operational measures

In general, hardening measures have relatively high effectiveness for resilience and less affordable cost performance. On the other hand, operational measures have relatively low effectiveness and more affordable one.

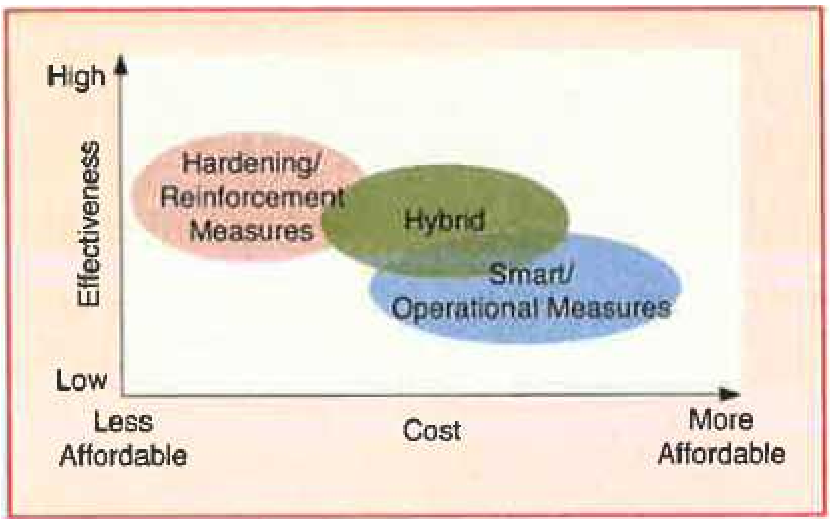


Figure 3-3 A conceptual comparison of cost versus the effectiveness of resilience engineering approaches

Therefore, as **the third step**, cost/benefit analysis would help gain insights on the benefits of implementing each measure over the cost of realizing the measure.
Following this analysis, the resilience actions can be ranked and implemented based on both their resilience- and cost-efficiency indices, which would help build a power infrastructure that satisfies both resilience and cost efficiency requirements.

Based on this fundamental considerations, it is clear how adaptive management, as a learning procedure that is function of time, is therefore another concept that distinguishes resilience from reliability and is necessary for understanding and building resilience.

3.3 Boosting the Resilience of Future Power System

3.3.1 Mitigation measures

Mitigation measures or hardening measures may refer to topology and structural changes to make the network less vulnerable to severe events. In this survey, the "mitigation measure" is mainly targeting the primary equipment

- Moving distribution and transmission lines underground
- Upgrading poles and structures with stronger, more robust materials
- Elevating substations
- Relocating facilities to areas less prone to extreme weather
- Rerouting transmission lines to areas less affected by weather
- Redundant transmission route

3.3.2 Adaptation measures

Adaptation measures in a broad sense may refer to a broad set of operational measures that can be taken to improve the observability, controllability, and operational flexibility of a power system, particularly in response to an extreme event.

- Distributed energy systems and decentralized control
- Microgrid
- Adaptive wide-area protection and control schemes

－Advanced visualization and situation awareness systems
－Disaster response and risk management

3.3.3 Hybrid Measures

In general, the mitigation measures may come at a significantly higher cost than the adaptation measures. Therefore, a hybrid of both measures might be the solution for boosting the resilience of future power systems in an economically feasible way.

In this survey, we set a new category - the “hybrid measure”, which is targeting the installation of auxiliary equipment or PACS (protection and control system) because it may be more affordable than the hardening measures, and more effective than the operational measures. Thus, the hybrid measure includes followings for example:

- Distributed (decentralized) equipment
- Adaptive wide-area protection and control schemes
- Advanced visualization/situation awareness systems

These measures are generally categorized into adaptation measures in a broad sense, defined in section 3.3.2.
However, in this survey, we divide them into the “hybrid measures” and the narrow set of “adaptation measures”, as shown in the Figure 3-4 because the hybrid measures are playing important roles of boosting “resilience” at present and will become the mainstream countermeasures in the future, instead of mitigation measures.
The narrow set of adaptation measures are mainly preventive or restorative operational actions. Hereinafter, “adaptation measures” mean those in a narrow sense.

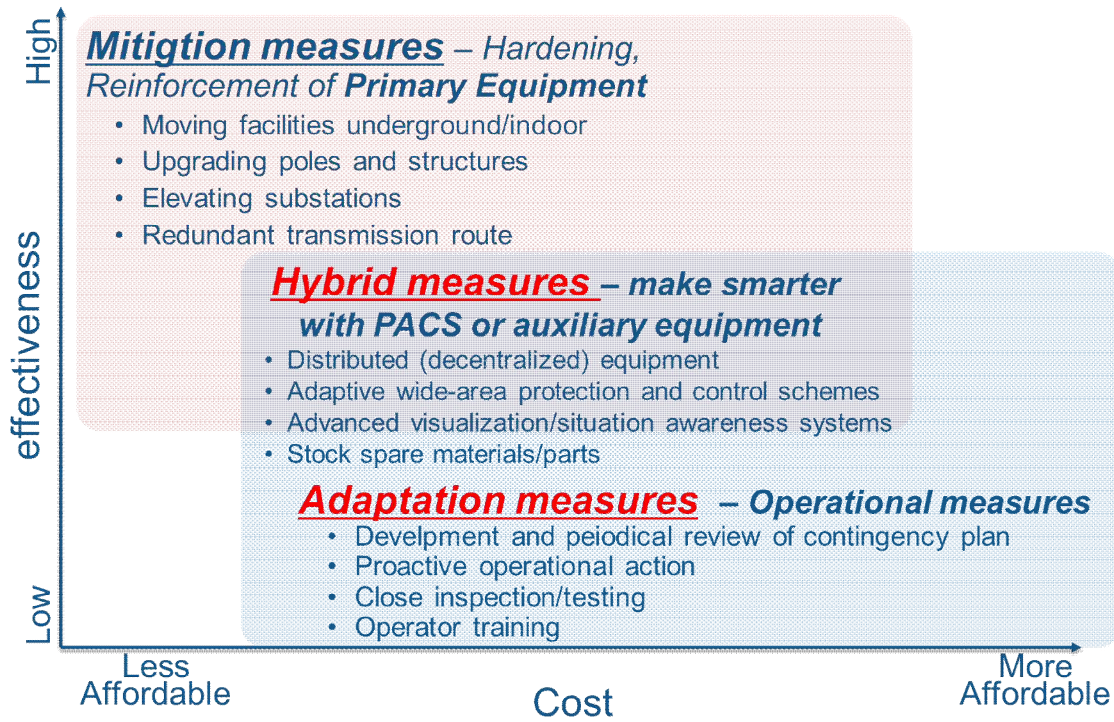


Figure 3-4 Conceptual Diagram regarding the Definition of the Mitigation, Adaptation, and Hybrid measures and Relationship among them

3.3.4 How to evaluate current status of resilience in our power system?

In this project, the study team set the following three (3) points need to be checked regarding the achievement for resilience of our power system.

In order to boost the "resilience" of the power supply system, "Low probability, High impact" incidents should be targeted. Therefore, the measures should be carefully assessed from the viewpoint of "the cost-effectiveness".

According to this fundamental concept, the "Hybrid measures" and "Adaptation measures" must play important roles in enhancement of resilience.

In this survey, study team tried to evaluate a current status of resilience by classifying hybrid and adaptation measures into these points.

(1) The ability of **anticipating** the extraordinary incidents

(2) The ability of **rapidly recovering** from the disruptive situation

(3) The ability of **absorbing lessons** from past experience for future events

4. Survey Results

4.1 Profiles of the Member Companies

4.1.1 Service Area, Number of Customers, and Peak Demand

4.1.1.1 CLP Power, HK Electric – Hong Kong, China

		CLP Power (The end of FY2014)	HK Electric (31 Dec. 2014)
Service Area		Kowloon, the New Territories and most of the outlying islands	Hong Kong Island and Lamma Island
	Mega cities	Hong Kong	Hong Kong
	Size (km^2)	972	94 (Oct. 2014)
	Population (million)	5.8	1.3
Electricity customer accounts (million)		2.46	0.57
Peak Demand (MW)	2010	6,766 8/Sep	2,510 Jun
	2011	6,702 30/Aug	2,498 Aug
	2012	6,769 28/Aug	2,494 Aug
	2013	6,699 20/Jun	2,453 Jun
	2014	**7,030** 23/Jul	2,460 Aug
	Past Record	**7,030** 23/Jul/'14	**2,597** Jul/'06

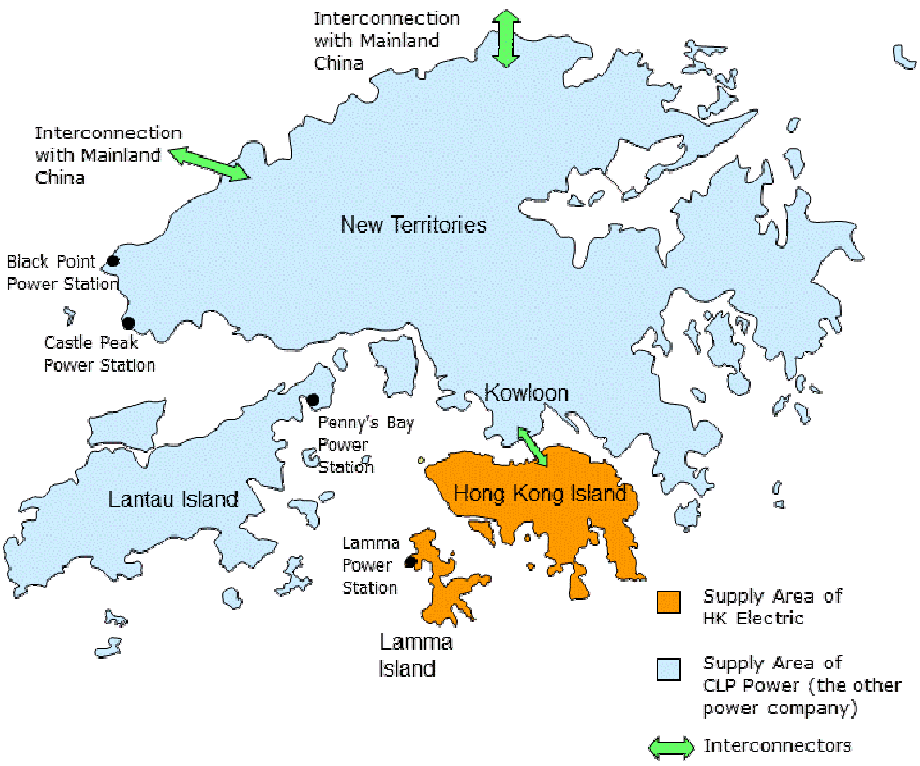


Figure 4-1 Electricity Service Area of CLP Power and Hongkong Electric

4.1.1.2 SMEPC - China

		SMEPC (The end of FY2014)
Service Area		Shanghai Metropolitan area and its environs
	Mega cities	Shanghai
	Size (km²)	6,300
	Population (million)	23.6
Electricity customer accounts (million)		9.63
Peak Demand (MW)	2010	26,210 12/Aug
	2011	25,490 26/Jul
	2012	25,910 15/Aug
	2013	**29,400** 7/Aug
	2014	26,800 6/Aug
	Past Record	**29,400** 7/Aug/'13

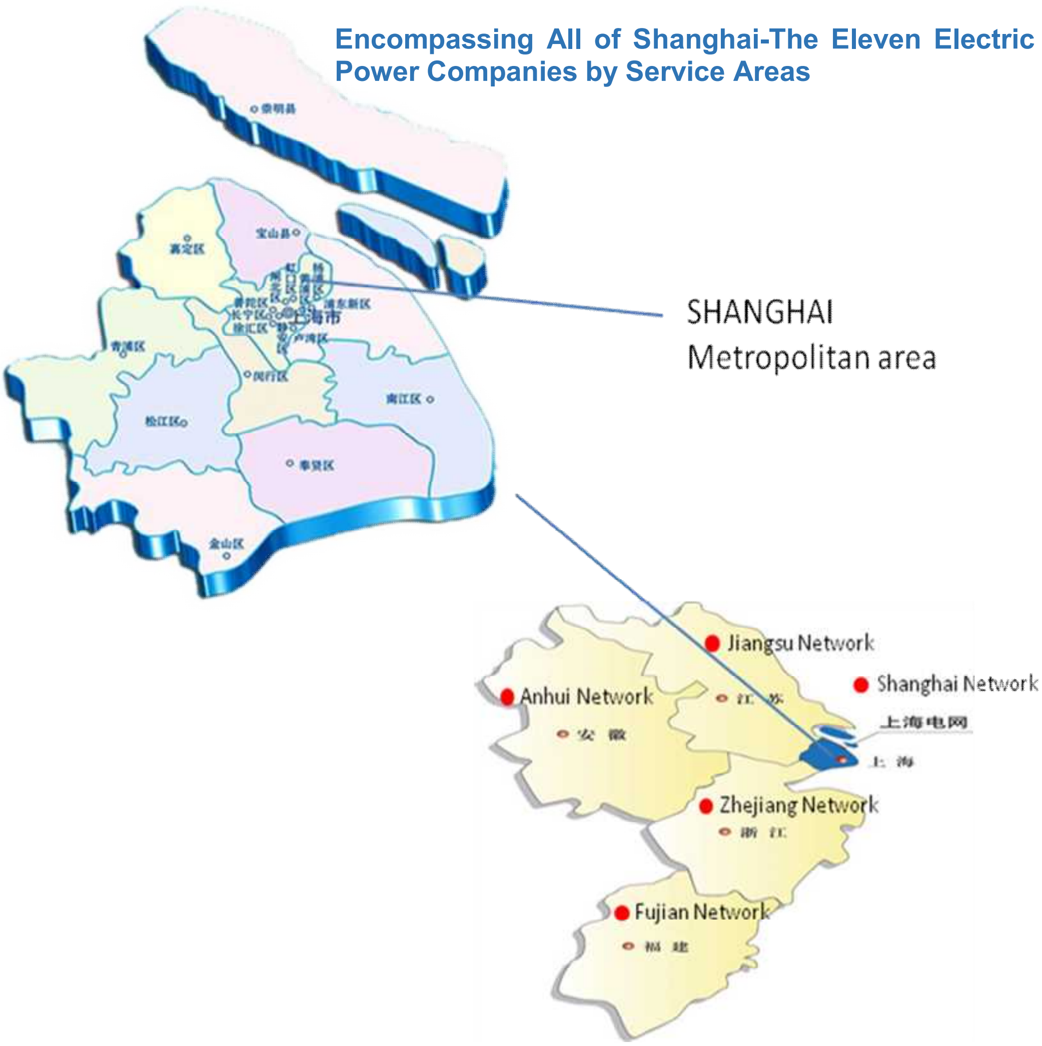


Figure 4-2 Electricity Service Area of SMEPC

4.1.1.3 KEPCO - Korea

		KEPCO (The end of FY2014)
Service Area		All of South KOREA
	Mega cities	Seoul
	Size (km^2)	99,720
	Population (million)	51.3
Electricity customer accounts (million)		21.5
Peak Demand (MW)	2010	69,890 20/Aug
	2011	72,190 31/Aug
	2012	74,290 6/Aug
	2013	76,520 3/Jan
	2014	**80,150** 17/Dec
	Past Record	**80,150** 17/Dec/14

KEPCO supplies electric power all of South Korea

Figure 4-3 Electricity Service Area of KEPCO

4.1.1.4 EGAT - Thailand

		EGAT (28 May 2015)
Service Area		*All regions of Thailand*
	Mega cities	*Bangkok*
	Size (km^2)	
	Population (million)	
Electricity customer accounts (million)		*(*)*
Peak Demand (MW)	*2010*	*24,009.9* *10/May*
	2011	*23,900.2* *24/May*
	2012	*26,121.1* *26/Apr*
	2013	*26,598.1* *16/May*
	2014	*26,942.1* *23/Apr*
	2015	***27,345.8*** *11/Jun*
	Past Record	***27,345.8*** *11/Jun/'15*

(*): There are three main customers:

1. *Provincial Electricity Authority (PEA),*
2. *Metropolitan Electricity Authority (MEA)*
3. *EGAT's Direct Customers*

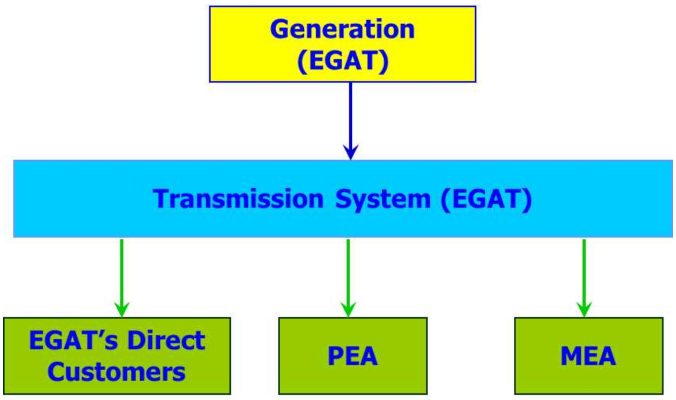


Figure 4-4 Organizational Structure in Electricity Industries

4.1.1.5 Shenzhen PSC-CHINA

		Shenzhen PSC *(The end of FY2014)*
Service Area		most parts of Shenzhen
	Mega cities	Shenzhen
	Size (km^2)	*2,000*
	Population (million)	*15*
Electricity customer accounts (million)		*2.75*
Peak Demand (MW)	2010	*1,3867* *11/Aug*
	2011	*1,3156* *26/Jul*
	2012	*1,3675* *9/Aug*
	2013	*1,3867* *12/Aug*
	2014	***1,5044*** *27/May*
	Past Record	***1,5044*** *27/May*

Shenzhen, the important economic centre of China and high-tech manufacturing base, is located in the southern coast of China, adjacent to Hong Kong.

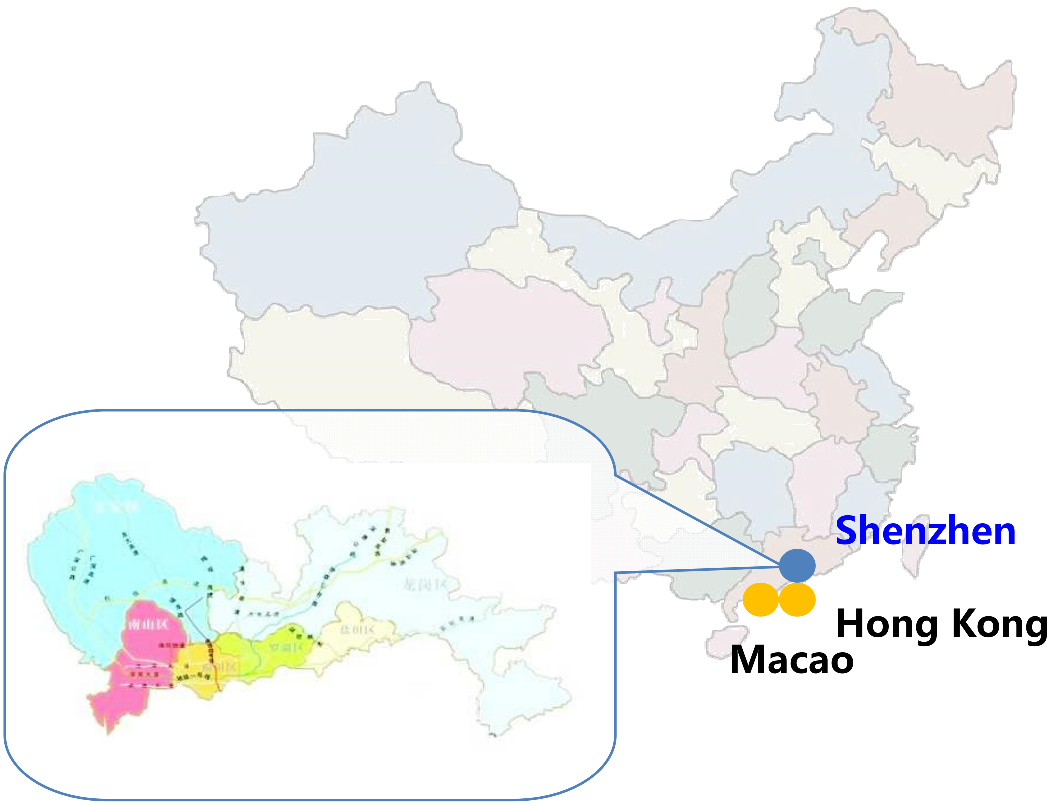


Figure 4-5 Electricity Service Area of Shenzhen PSC

4.1.1.6 TEPCO - Japan

		TEPCO (the end of FY 2014)
Service Area		Tokyo Metropolitan area and its environs
	Mega cities	Tokyo
	Size (km^2)	39,576
	Population (million)	44.8
Electricity customer accounts (million)		29.2
Peak Demand (MW)	2010	59,990 23/Jul
	2011	49,660 20/Jan
	2012	50,780 30/Aug
	2013	50,930 9/Aug
	2014	49,800 5/Aug
	Past Record	**64,300** 24/Jul/'01

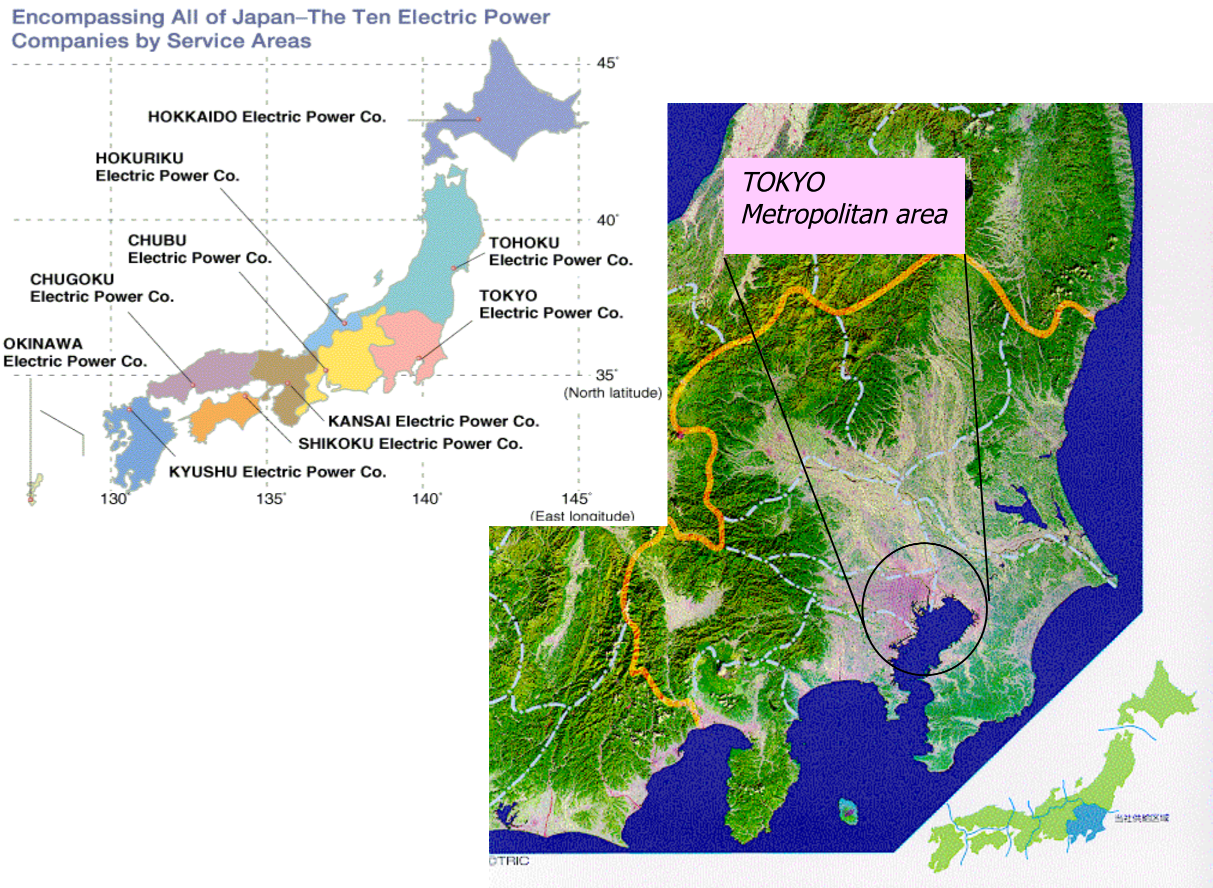


Figure 4-6 Electricity Service Area of TEPCO

4.1.2 Power System

4.1.2.1 CLP Power – Hong Kong, China

4.1.2.1.1 General Features of the Network

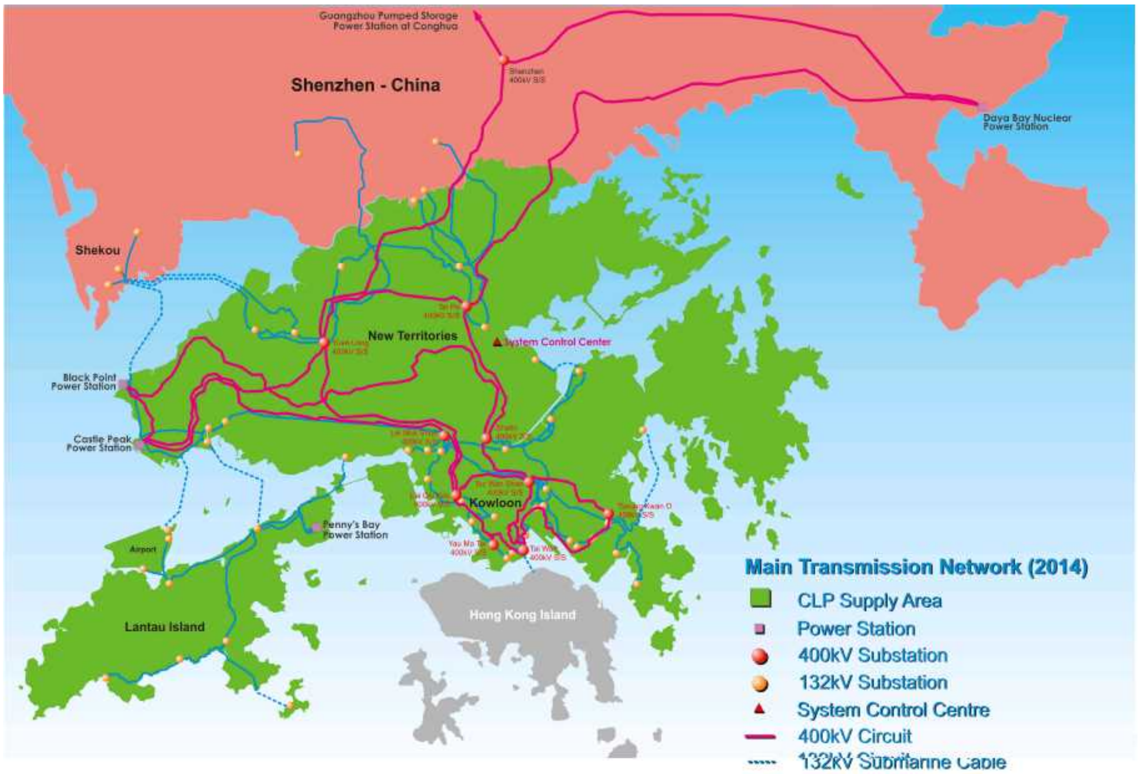


Figure 4-7 Power System Map of CLP Power

400kV Transmission Network

- 400kV transmission network serves as the backbone of our power grid to transmit electricity from various generating stations to bulk supply points within the supply territories.
- It consists of a double circuit overhead line ring, with cable sub-ring in urban area.

132kV Transmission Network

- 132kV transmission network serves as both the bulk transmission system and area transmission system.
- Each 400kV substation and its downstream 132kV network are operated as an independent group, and backed up by 132kV interconnectors with other groups.
- Area transmission networks at 132kV and 33kV supply loads through the 132/33kV, 132/11kV or 33/11kV transformer groups.

11kV Distribution Network

- In urban areas, our loads are supplied via 11kV cable closed rings spawned from a primary substation. This ring is designed to meet N-1 contingency. To achieve an even higher level of security, 11kV interconnectors are sometimes implemented between these rings.
- In the less developed areas, 11kV overhead lines are deployed. These are typically constructed with alternative supply sources, with remotely controlled pole mounted switches to speed up fault isolation and supply restoration.

Interconnectivity with Other System or Countries:

- Interconnections between CLP and South China Grid via two sets of 400kV double circuit overhead lines (1,850MVA each).

- Interconnection between CLP and HEC via three 132kV submarine cable circuits (240MVA each).

4.1.2.1.2 General Features of Installed Facilities

Generation Facilities	*Hydro [MW]* *Number of Stations*	***600*** *1*	*Short Circuit Capacity*	*400kV*	***63kA***
	Thermal [MW] *Number of Stations*	***6,908*** *3*		*132kV*	***31.5kA***
	Nuclear [MW] *Number of Stations*	***1,380*** *1*		*33kV*	***25kA***
	Renewable/Others [MW] *Number of Stations* *Type*	- - 		*11kV*	***20kA***
Network Facilities	*Substation [stations]*	***224***			
	OH line [c/c km]	***706***			
	UG Cable [c/c km]	***1,491***			

As of the end of FY2014

4.1.2.1.3 SAIDI/SAIFI

	SAIDI (*) [min./customer]	*SAIFI (*) [times/customer]*
2010	*2.43*	*0.05*
2011	*1.93*	*0.05*
2012	*3.55*	*0.06*
2013	*1.53*	*0.03*
2014	*1.68*	*0.04*

(*)SAIDI / SAIFI for unplanned outages

4.1.2.2 HK Electric – Hong Kong, China

4.1.2.2.1 General Features of the Network

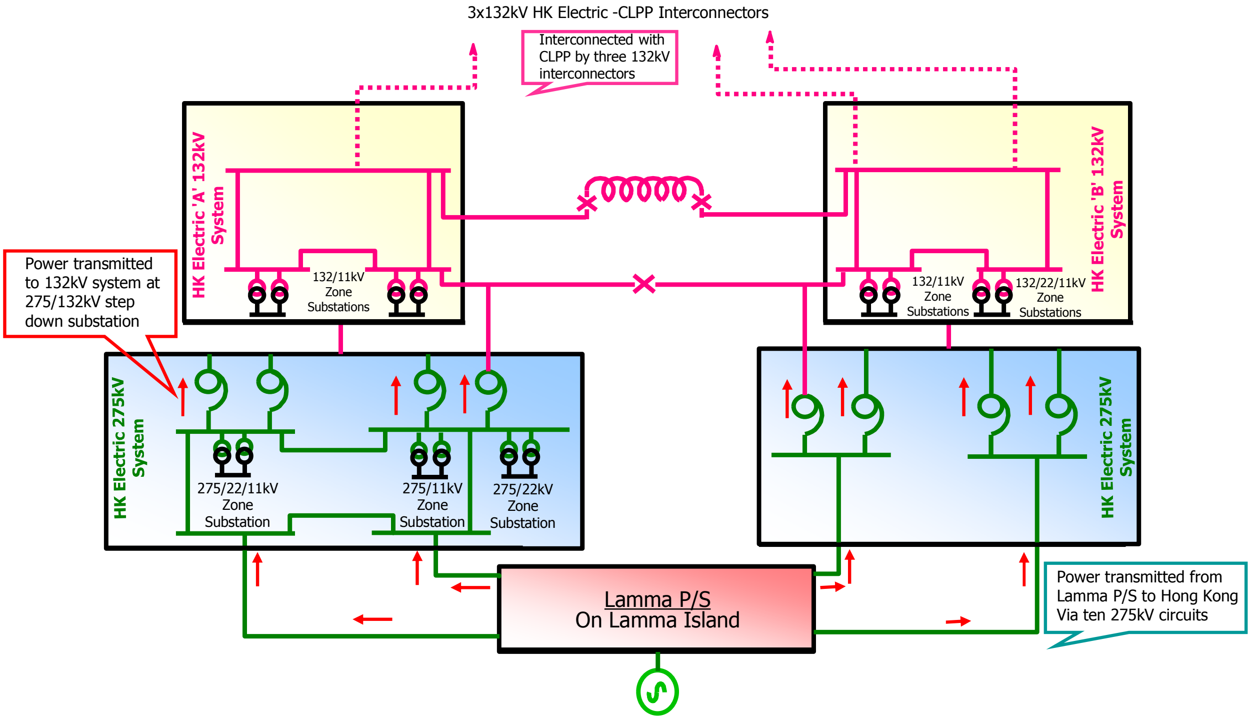


Figure 4-8 Conceptual Network Architecture of Hongkong Electric

All power generated in HK Electric's system is from Lamma Power Station, which is on the outlying Lamma Island. Generated power is transmitted at 275kV to switching stations on Hong Kong Island, where it is stepped down to 132kV before it is merged with the 132kV transmission network, or stepped down directly to 11kV or 22kV for distribution.

275kV Transmission Network

- The HK Electric 275 kV transmission network is in the form of radial as well as ring structure for transmitting power to the 132kV transmission network. It also directly supplies three 275/11kV zone substations, one 275/22/11kV zone substation and two 275/22kV zone substations.

- There are ten 275kV submarine transmission circuits transmitting power generated by the Lamma Power Station to the Hong Kong Island. Because of the geographical separation of the Lamma Island from the Hong Kong Island, each transmission circuit is composed of submarine cable section(s) across the East Lamma Channel. On the Hong Kong Island, the entire 275kV network is constructed with underground cables in the form of radial structure as well as ring structure. Two cable tunnels were also constructed to accommodate seven 275kV cable circuits for the transmission of power from the south of the Island to the Central and Eastern districts of the Island.

132kV Transmission Network

- At present, the 132kV transmission system is composed of underground cable circuits and three overhead line circuits in service in the form of ring structure. Gas insulated ring-main-units are installed in some 132/11 kV zone substations to improve the flexibility of system operation and security of supply.

- In order to contain the 132kV system fault level during system high load periods, the 132kV system can be split up into two subsystems, namely 'A' and 'B', at Apleichau Switching Station and North Point Switching Station, with the 'A' and 'B' subsystems interconnected by two series reactors to limit the system fault level.

Interconnectivity with Other System or Countries:

- HK Electric has a 132kV synchronous interconnection with CLP Power (the other power company in Hong Kong) through 3 x 240MVA submarine interconnectors across Victoria Harbour.

4.1.2.2.2 General Features of Installed Facilities

Generation Facilities	*Hydro [MW]* *Number of Stations*	*-*	*Short circuit capacity*	*275kV*	***40kA***
	Thermal [MW] *Number of Stations*	***3,735*** *1*		*132kV*	***40kA***
	Nuclear [MW] *Number of Stations*	*-*		*22kV*	***25kA***
	Renewable/Others [MW] *Number of Stations* *Type*	***1.8*** *(*)* *PV, Wind*		*11kV*	***18.4kA***
Network Facilities	*Substation [stations]*	***51***			
	OH line [c/c km]	***25***			
	UG Cable [c/c km]	***434***			

(*)Adjacent to / incorporated into the thermal power station
As of 31 Dec. 2014

4.1.2.2.3 SAIDI/SAIFI

	SAIDI [min./customer]	*SAIFI [times/customer]*
2010	*0.9*	*0.10*
2011	*0.7*	*0.05*
2012	*0.7*	*0.06*
2013	*0.7*	*0.05*
2014	*0.8*	*0.08*

4.1.2.3 SMEPC - China

4.1.2.3.1 General Features of the Network

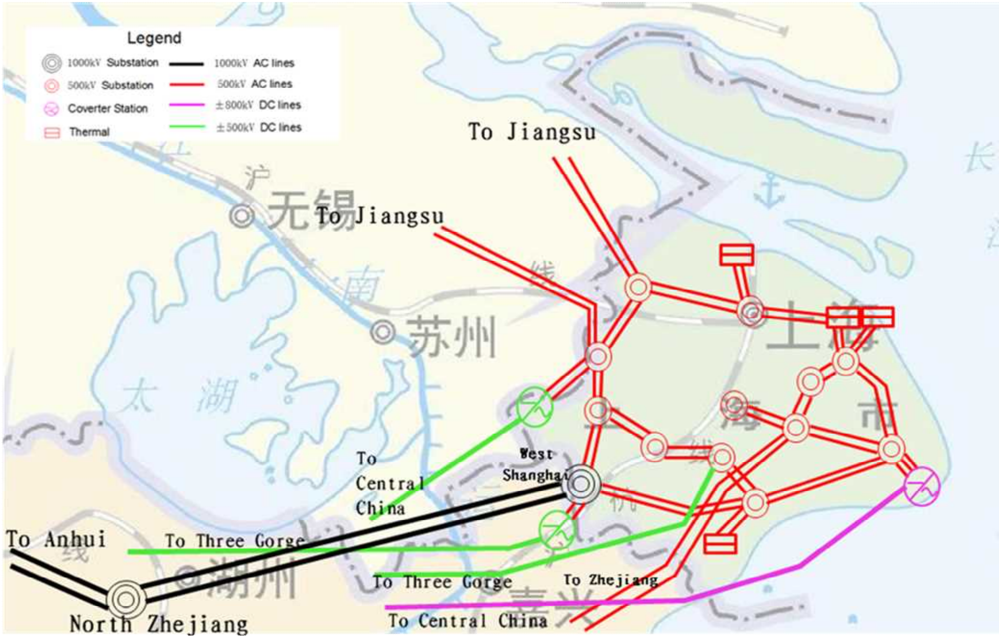


Figure 4-9 Power System Map of SMEPC

500kV Transmission Network:

- Composed of 13 500kV-substations realizing power transferred from outside regional systems to 220kV network
- Generally <u>Double loop network</u> and <u>two local double loop networks</u> to improve the transmission reliability
- Established with <u>two 500kV series reactor to restrict short circuit current</u>
- Three coal-fired generation bases with total 7GW capacity located along the south coast of Yangtse river and the north side of Hangzhou Bay ,independently

220kV Transmission Network:

- The main network distributing power to Shanghai metropolitan area
- Composed of 13 sectionalized 220kV networks, each 220kV zone network corresponding to one 500kV substation
- Established with generators in each 220kV zone network
- Strong backup interconnections between neighboring 220kV zone networks

Interconnectivity with Other System or Countries:

- *Interconnected with the East China power grid via two 1000kV and six 500kV AC tie-lines (Total capacity: 13GW)*
- *Interconnected with the Central China power grid via one ±800kV DC and three ±500kV DC transmission lines(Total capacity:13.2GW)*

4.1.2.3.2 General Features of Installed Facilities

Generation Facilities	*Hydro [MW]* *Number of Stations*	-	*Short Circuit Capacity*	*1000kV*	***63kA***
	Thermal [MW] *Number of Stations*	***21,390*** *37*		*500kV*	***63(50)kA***
	Nuclear [MW] *Number of Stations*	-		*220kV*	***50(63)kA***
	Renewable/Others [MW] *Number of Stations* *Type*	***365*** *10* *Wind*		*110kV*	***25kA***
Network	*Substation [stations]*	***932***		*35kV*	***25kA***

Facilities	OH line	[c/c km]	**9,408.2**		10kV	**20kA**
	UG Cable	[c/c km]	**10,408.8**			

As of the end of FY2014

4.1.2.3.3 SAIDI/SAIFI

	SAIDI [min./customer]	SAIFI [times/customer]
2010	15.3	0.103
2011	14.7	0.098
2012	14.6	0.14
2013	13.5	0.05
2014	13.2	0.05

4.1.2.4 KEPCO - Korea

4.1.2.4.1 General Features of the Network

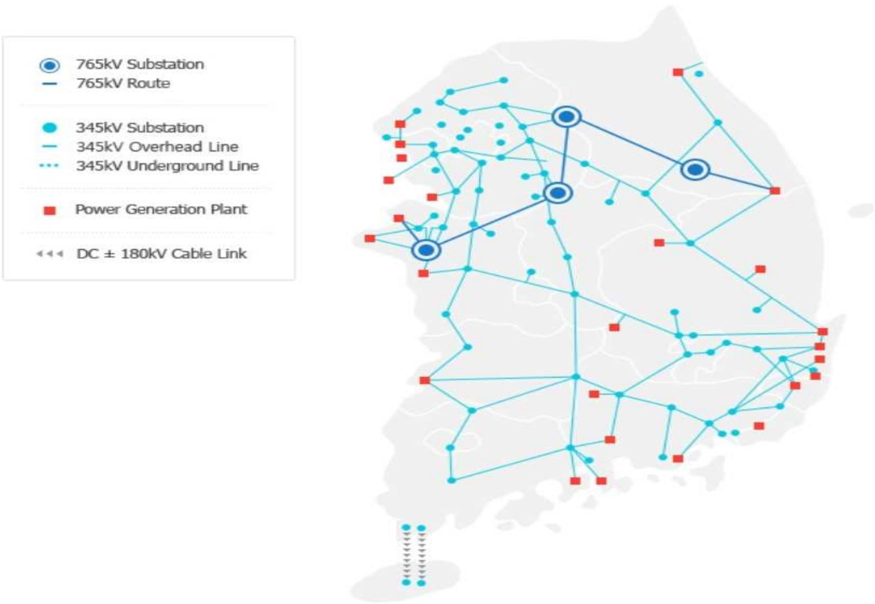


Figure 4-10 Power System Map of KEPCO

KEPCO'S transmission system voltage levels are 765kV, 345kV, and 154kV

765kV transmission Network

KEPCO has been pushing forward the 765kV power transmission voltage upgrade project to address the serious supply imbalance between high-demanding Seoul and large-sized power generation complexes and to support efficient use of national land. A 175.9km line linking Dangjin thermal power plant to Shin-seosan and Shin-anseong substation and a 154.9km line linking Shin-taebaek to Shin-gapyeong substation are already in operation. KEPCO also completed two 765kV project. One is 765kV one-circuit line which is 75km long and links Shin-anseong substation and Sin-gapyeong substation, which started operation in April, 2010. Another project is 765kV two-circuit line which is 91km long linking Shin-kori substation to North Gyeongnam substation. These two lines are expected to play a key role in improving system voltage and supply conditions in the Seoul metropolitan area and provide conditions to effectively transport electric power generated in high-capacity power plants.

345kV transmission Network

- First 345kV transmission line was built in 1975 between Yeosoo Power Plant and Shin-namwon substation
- More 345kV transmission lines are installed in order to connect the inter-regional power system
- KEPCO has 9,394 C-km long 345kV transmission lines including underground cables at present
- These 345kV trunk lines are transmitting large electric power to the mega cities such as Seoul, Busan metropolitan area and connecting power plants which are over 1,000MW to the transmission system

154kV transmission Network

- 154kV transmission lines are extensively used for regional power distribution source as a branch line inter-connecting with 345kV trunk system
- KEPCO has 22,446 C-km long 154kV transmission lines as of July, 2015
- These lines are linking substations and connecting power plants which are under 1,000MW to the transmission system

Interconnectivity with Other System or Countries:

- For the power system on Jeju Island, since power was available from larger and more efficient generator units on the mainland, a submarine connection was considered desirable. But with the distance being a 100 km, an HVAC connection was not technically feasible, because of the large charging current for the HVAC cable. An HVDC connection was chosen, to overcome this technical difficulty and additionally because of economic considerations. After testing, KEPCO began to operate the first HVDC line in 1998, which is a 300 MW bipolar link between Jeju and Hae-Nam (point from the Korean mainland). And the second HVDC was a 400MW bipolar link between Seo-Jeju and Jin-Do (point from the Korean mainland) which was installed in 2012.

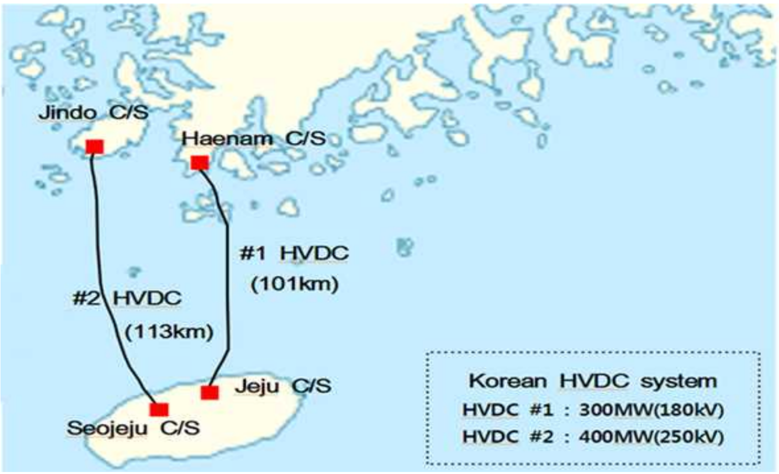


Figure 4-11 Interconnection lines between Regional Systems in KEPCO

4.1.2.4.2 General Features of Installed Facilities

Generation Facilities	*Hydro [MW]*	***6,280***	*Short Circuit Capacity*	*765kV*	***50kA***
	Number of Stations	*15*			
	Thermal [MW]	***61,560***		*345kV*	***50(63,40)kA***
	Number of Stations	*34*			
	Nuclear [MW]	***20,720***		*154kV*	***50(31.5)kA***
	Number of Stations	*8*			
	Renewable/Others [MW]			*66kV*	***20kA***
	Number of Stations	*-*			
	Type				
Network Facilities	*Substation [stations]*	***748***		*22.9kV*	***25(40)kA***
	OH line [c/c km]	***29,149***			
	UG Cable [c/c km]	***3,646***			

As of the end of FY2014

4.1.2.4.3 SAIDI/SAIFI

	SAIDI [min./customer]	*SAIFI [times/customer]*
2010	*15.6*	*0.49*
2011	*15.2*	*0.41*
2012	*12.07*	*0.27*
2013	*11.48*	*0.188*

2014	10.88	0.145

4.1.2.5 EGAT - Thailand

4.1.2.5.1 General Features of the Network

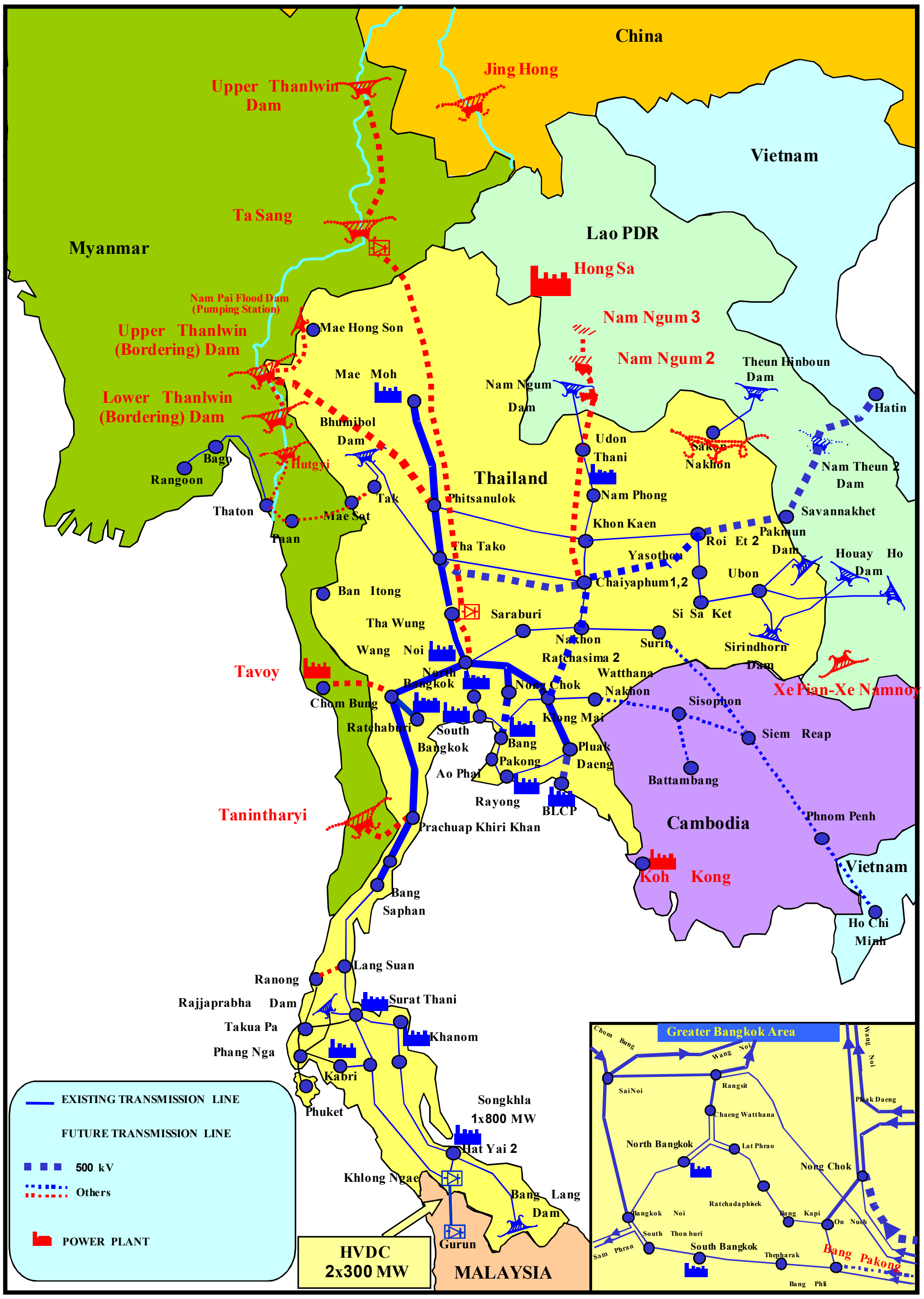


Figure 4-12 Power System Map of EGAT

4.1.2.5.2 General Features of Installed Facilities

Generation Facilities	Hydro [MW]	**3,406**	Short Circuit Capacity	500kV	**50kA**
	Number of Stations	43			
	Thermal [MW]	**12,029**		230kV	**40,50kA**
	Number of Stations	73			
	Nuclear [MW]			115kV	**31.5,40kA**
	Number of Stations				
	Renewable/Others [MW]	**47**		69kV	**40kA**
	Number of Stations	34			

	Type				
Network Facilities	*Substation [stations]*	***216***			
	OH line [c/c km]	***32,836.95***			
	UG Cable [c/c km]				

As of 30 Apr 2015

4.1.2.5.3 SAIDI/SAIFI

	SAIDI [min./delivery point]	*SAIFI [times/delivery point]*
2010	*23.85*	*0.24*
2011	*7.91*	*0.31*
2012	*6.79*	*0.30*
2013	*13.93*	*0.35*
2014	*2.32*	*0.17*

4.1.2.6 Shenzhen PSC-CHINA

4.1.2.6.1 General Features of the Network

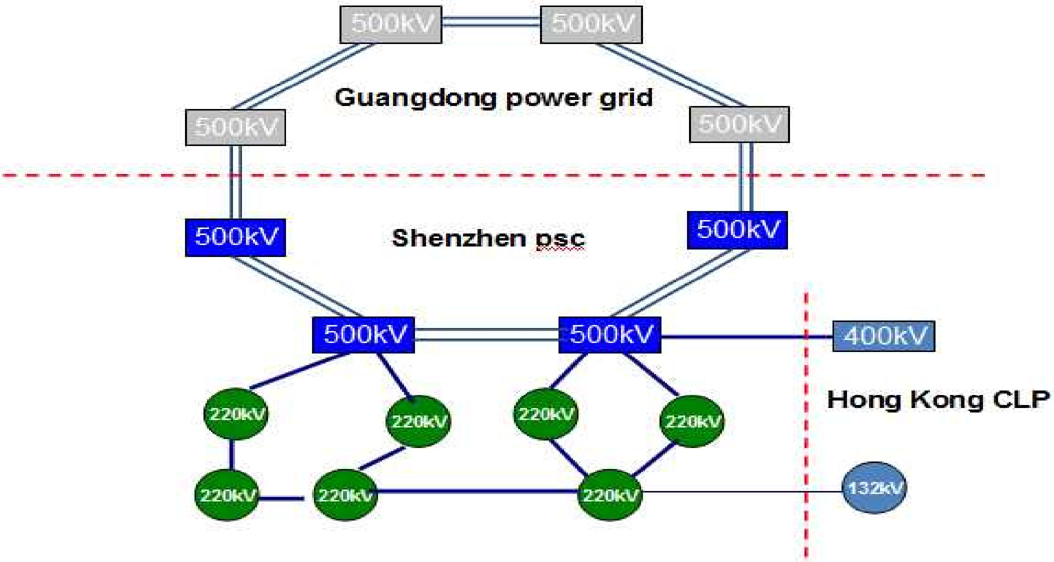


Figure 4-13 Conceptual Network Architecture of Shenzhen PSC

500kV Transmission Network:

- *Composed of 5 500kV substations realizing power transferred from outside regional systems to 220kV network。*
- *Integrated into the Pearl River Delta region network to form a double loop network to improve transmission reliability.*
- *Established with one 500kV series reactor to restrict short circuit current.*

220kV Transmission Network:

- *Each 500kV substation and its downstream 220kV network are operated as an independent group, and backed up by 220kV interconnectors with other groups.*
- *Take the double loop network.*
- *220kV transmission network serves as both the bulk transmission system and area transmission system.*

Other System or Countries:

- *Interconnected with Guangdong power grid via 500kV AC tie-lines, 500kV DC tie-lines and 220 kV AC tie-lines.*
- *A small number of 400kV & 132kV power lines connected with Hongkong power grid.*

4.1.2.6.2 General Features of Installed Facilities

Generation Facilities	*Hydro [MW]* *Number of Stations*	*/*	*Short Circuit Capacity*	***Nominal Voltage***	***Capacity***
	Thermal [MW] *Number of Stations*	*6733*		*500kV*	*63kA*
	Nuclear [MW] *Number of Stations*	*6120*		*220kV*	*50kA*
	Renewable/Others [MW] *Number of Stations* *Type*	*267.2*		*110kV*	*40kA*
Network Facilities	*Substation [stations]*	*223*		*20 kV*	*25kA*
	OH line [c/c km]	*3463*		*10kV*	*25kA*
	UG Cable [c/c km]	*743*			

4.1.2.6.3 SAIDI / SAIFI (Last 5 years):

Fiscal Year	SAIDI [min. / customer]	SAIFI [times / customer]
2010	33	0.15
2011	19.8	0.13
2012	13.2	0.1
2013	12.8	0.11
2014	12.5	0.11

4.1.2.7 TEPCO

4.1.2.7.1 General Features of the Network

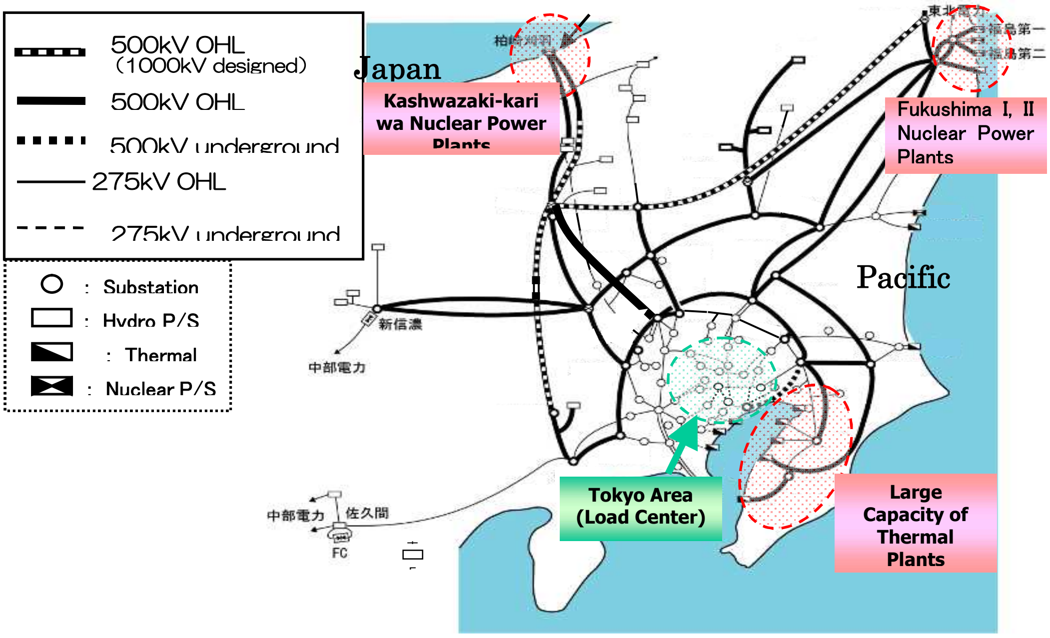


Figure 4-14 500kV Power System Map of TEPCO

500kV Transmission Network:

- 500kV transmission network has an important role of transmitting large capacity power of nuclear or thermal plants to the surrounding area of the Tokyo metropolitan.
- This network is operating in the meshed configuration for mainly synchronous or voltage stability reasons.
- Many large-capacity thermal power plants are located along the coast of Pacific Ocean and the east side of Tokyo Bay.
- The nuclear power plants are located in three locations in Fukushima and Niigata, far from large power consumption area.
- Some lines were designed as a 1000kV transmission system for future use.

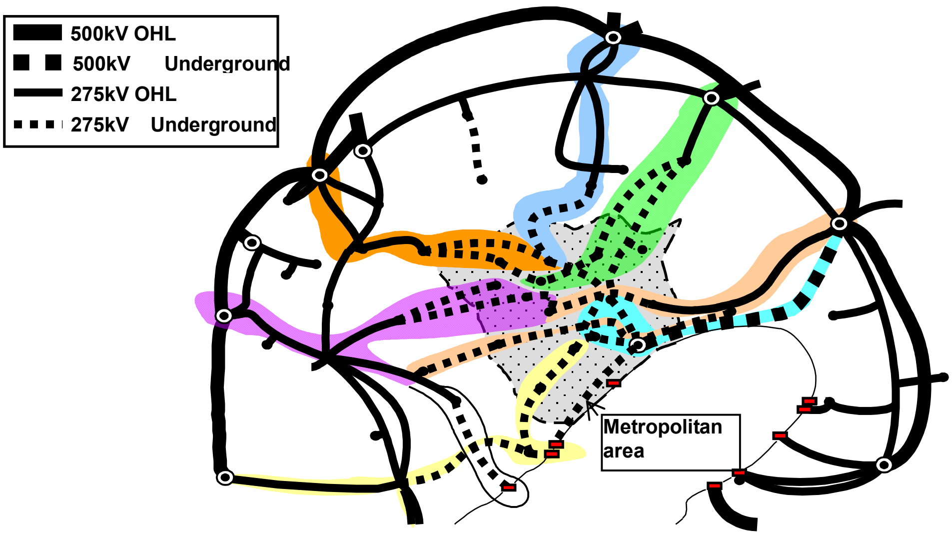


Figure 4-15 275kV Power System Map of TEPCO

275kV Transmission Network:

- Power for Tokyo metropolitan area is supplied via 275kV transmission network.
- For central part of Tokyo Metropolis, in particular, power is transmitted via underground substations and cables because of densely populated area.
- There are 7 base substations and 275kV transmission routes.

- Physically these 7 routes can be connectible each other so that the power can be supplied from both side of base substations.
- But they are usually disconnected and operated in radial configuration in order to lower the fault current, relieve the overloading, prevent cascading outages, and so on.

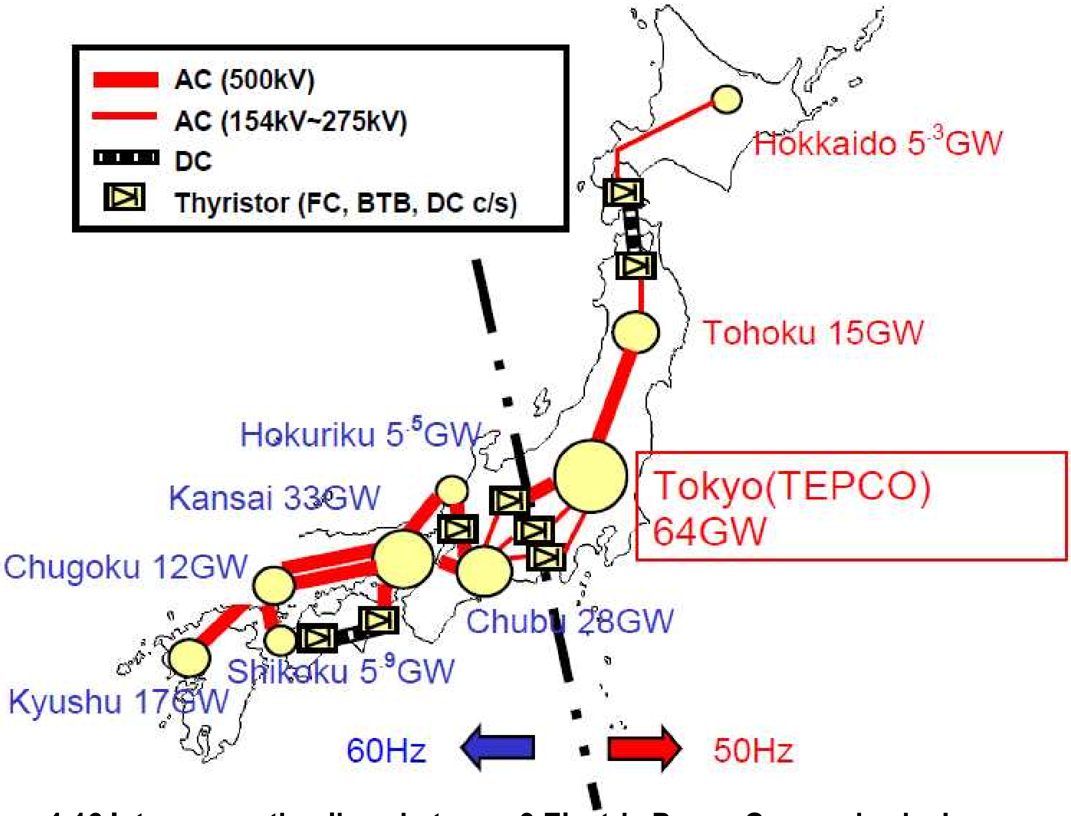


Figure 4-16 Interconnection lines between 9 Electric Power Companies in Japan

Interconnectivity with Other System or Countries:

- One synchronous interconnection between TEPCO and Neighboring Utility (Tohoku-EPCO) via 500kV double circuit OH lines (Capacity: 5GW)
- Three asynchronous interconnection between TEPCO and Neighboring Utility (Chubu-EPCO) via 275kV or 154kV double circuit OH lines and Back-to-back facilities at 50/60Hz frequency converting stations (Total capacity: 1.2 GW)

4.1.2.7.2 General Features of Installed Facilities

Generation Facilities	*Hydro [MW]*	***9,857***	*Short Circuit Capacity*	***500kV***	***63kA***
	Number of Stations	*164*			
	Thermal [MW]	***43,555***		***275kV***	***50(63)kA***
	Number of Stations	*25*			
	Nuclear [MW]	***12,612***		***154kV***	***31.5(40)kA***
	Number of Stations	*2*			
	Renewable/Others [MW]	***33***		***66kV***	***25(31.5)kA***
	Number of Stations	*4*			
	Type	*PV*			
Network Facilities	*Substation [stations]*	***1,577***		***22kV***	***25kA***
	OH line [c/c km]	***28,405***		***6.6kV***	***12.5kA***
	UG Cable [c/c km]	***12,340***			

As of the end of FY2014

4.1.2.7.3 SAIDI/SAIFI

	SAIDI [min./customer]	*SAIFI [times/customer]*
2010	*152*	*0.33*

2011	*9*	*0.10*
2012	*5*	*0.07*
2013	*15*	*0.14*
2014	*4*	*0.07*

4.2 Experiences of Past Large Scale Outages

4.2.1 Summary of Past Large Scale Outages in Member Countries

In 20 century, most of large blackouts were caused by accidental destruction by third parties and operational inaccuracy.

After greeting the 21 century, cascading blackouts due to abnormal weather occurred frequently. Besides these cases, there are many blackouts in Asian countries due to abnormal weather missing in this table; tsunami in Indonesia, typhoon in Philippines etc.

As shown in the Table 4-1, 6 cases of 10 large scale outages are cascading events due to the malfunction of islanding control or frequency instability.

This result may be caused by the long distant transportation from power stations to the load center and the vulnerability of the interconnection between them.

Table 4-1 Experiences of Large Scale Outage in Member Countries

Date	Area / Company	MW Lost / Duration	Cascading / Non-cascading	Causes/Trigger	Critical Phenomenon
Mar. 1984	Kowloon and New Territories, Hong Kong / CLP	Unknown /4 hours	Cascading	Operational inaccuracy - Power swing	Frequency instability - Cascading generator trips
Aug. 1987	Tokyo / TEPCO	8000MW /4 hours	Cascading	Operational inaccuracy - Voltage-reactive power control	Voltage instability
Nov. 1999	Tokyo / TEPCO	1600MW /3 hr 19m	Non-Cascading	Accidental destruction - Airplane crashed into OHL	Frequency instability - Significant imbalance of supply-demand in separated system
Jul. 2005	Chongmin, Shanghai / SMEPC	165MW /2 hours	Cascading	Operational inaccuracy Malfunction of relays - Directional overcurrent relays	Overloaded lines Frequency instability
Apr. 2006	Jeju / KEPCO	348MW /2 hr 34 m	Cascading	Accidental destruction - Sudden breakdown of HVDC inter-tie	Frequency instability - Cascading generator trips
Aug. 2006	Tokyo / TEPCO	2160MW /59 min.	Non-cascading	Accidental destruction - Hit by boom of crane vessel	Frequency instability - Significant imbalance of supply-demand in separated system
7 Jun. 2008	Sheung Wan District, Hong Kong Island, Hong Kong / HEC	Minimal /12 hours	Non-Cascading	Abnormal weather - Heavy rain - Squally thunderstorm	Flooding
Mar. 2011	Wide area including Tokyo / TEPCO	Unknown (Sudden 21000MW lack of power source) /Load shedding was implemented for 10 days	Cascading	Natural disaster - Earth quake - Tsunami	Frequency instability - Cascading generator trips - Significant and prolonged deficiency of power source
10 Apr. 2012	Shenzhen / Shenzhen PSC	759MW /1hr 37m	Non-Cascading	Trouble at facilities -Explosion	
21 May 2013	14 southern pr ovinces of Tha iland / EGAT	4.13GWh /4 hours	Cascading	Abnormal weather -Lightning	Frequency instability - Significant imbalance of supply-demand in separated system

4.2.2 March 1984 – Kowloon and New Territories, Hong Kong, China (CLP Power)

1. Interrupted power and duration: Interrupted power: unknown; Duration: 4 hours

2. Sequence of the events:

12:20	System power swing was observed and a major power station was instructed by System Control Center to switch the Automatic Voltage Regulator on all 3 generation units to manual control. Severe system disturbance followed and all generation units tripped almost simultaneously. All stages of the under-frequency load shedding scheme operated. The CLP system was decoupled from all other interconnected systems (i.e. HEC and South China Grid systems) due to under-frequency.
12:23	Generation units at another CLP power station tripped. The blackstart procedure to restore supply to the power stations commenced immediately after the incident.
12:57	Restoration of local supply to all 3 CLP power stations auxiliary demand was completed.
13:55	Major power station's 132kV substation was coupled to the system after successful synchronization.
15:03	400kV OHL circuits between power station and a downstream substation were restored.
16:36	The major transmission system was largely restored to normal.

3. Cause:

The initial power system swing led to the subsequent events. The blackout was triggered when the Automatic Voltage Regulators (AVR) on all 3 generation units were switched to manual mode in an attempt to damp the system power swing. The action inhibited the system's automatic response towards voltage fluctuations during the incident.

4. Countermeasures:

- Install Power System Stabilizers (PSS) on generation units to improve system stability
- Prepare a blackout procedure to allow faster system restoration

4.2.3 7 Jun 2008 – Sheung Wan District, Hong Kong, China (HK Electric)

1. Duration: About 12 hours

2. Sequence of the events:

06:30	➢ The first flooding stage 1 & 2 alarms of a distribution substation operated ➢ System control engineers proactively switched out the substation by remote switching to avoid serious equipment damage and minimize customer interruption
08:34 to 09:31	➢ 11 transformer tripped ➢ 4 distribution substations were forced to shut down ➢ 3 zone substation 11kV feeders were tripped
09:47 to 18:41	➢ 6 distribution substations were forced to shut down

In total, there were 25 distribution substation shut-down or switch-out and 51 locations had their power supply interrupted. However, of these 51 locations, only 5 had their power outage wholly caused by distribution substation problems and the resulting power loss was minimal. The remaining locations all experienced customer installation problems which contributed to the interruption. HK Electric's Customer Emergency Centre received over

1200 customer calls regarding the incident. Most of the affected distribution substations resumed operations in the afternoon.

3. Cause and nature:

The main causes of the disaster are:

- Extreme weather under the influence of an active trough of low pressure, heavy rain and squally thunderstorms
- Sheung Wan is a low-lying area susceptible to flooding during heavy rainstorms. While the Government was aware of the problem and there was a project to improve drainage system, the project had not yet completed when the incident took place

The incident is not cascading.

4. Countermeasures:

To cope with this emergency situation and the surge in service calls, standby staff were mobilized.

After the flooding, early warning of flooding was provided by the Government and HK Electric subscribed to receive the warning. Anti-flooding measures for the flooded substations and those in the vicinity were implemented or reinforced.

In 2009, a diversion chamber was constructed by Drainage Service Department (DSD) of the Government. It diverts the runoff collected from the drainage system in the low-lying area to the underground storage tank. Six submersible pumps housed within the DSD pumping station pump the storm water collected in the underground storage tank out to the Victoria Harbour.

4.2.4 Jul 2005 - Chongmin, Shanghai, China (SMEPC)

1. Interrupted power and duration: 165MW, 2hours

2. Sequence of the events:

The grid of Chongmin Island is weakly connected with the backbone grid by two 220kV transmission line in one substation (one line linked with one transformer). The whole input was 130MW corresponding to 230MW demand.

10:33	The directional over current relay issued the tripping of one transformer due to the malfunction of the directional component, which caused overload of the other. The system operator immediately transfer 10MW load to control loading within 120MW.
10:49	The remaining transformer was also tripped by the directional over current relay, which isolated the whole Chongmin grid. System frequency dropped quickly to 44.7HZ. The system operator dropped 100MW load by disconnecting 7 110kV lines, 9 35kV lines and 5 10kV lines. At the same time, low frequency devices dropped 65MW load, but some devices were blocked due to the slip setting. One generator inside Chongmin grid also tripped due to power swing. There were totally 4 110kV and 12 35kV substations losing power supply.
11:05	After the action taken by system operator, system frequency was restored to 49.9HZ
11:46	One 220kV transformer was restored as well as the 220kV transmission line. Chongmin grid was able to be connected with backbone grid.
12:02	The other 220kV transformer was also restored. The whole Chongmin grid was back to normal operation mode.
12:49	All the outage was restored, as well as the load.

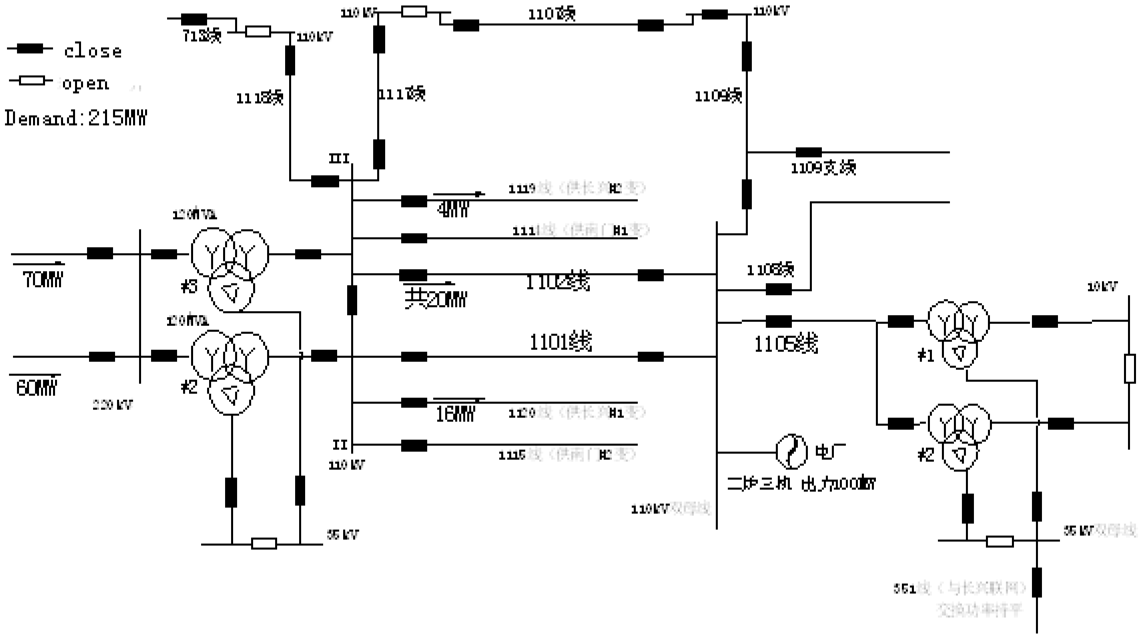


Figure 4-17 Power Flow Diagram of Chongmin Island at Pre-event State

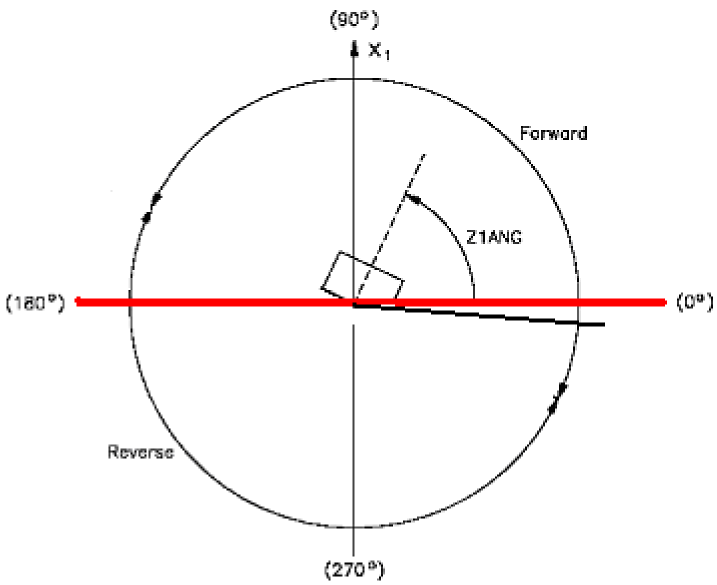


Figure 4-18 Action of Directional Over Current Relay

3. Cause:

Malfunction of directional overcurrent relay with the non-tripping of low frequency devices caused the wider load shedding.

4. Countermeasures:

- Modify the directional relay setting, as well as series with the low voltage component.
- Modify the slip setting of low frequency device
- Develop advanced analysis tool to immediately address the root cause of tripping.
- Other two 220kV transmission lines were commissioned to enhance the connection of chongmin grid with the backbone.

4.2.5 Apr 2006 – Jeju, Korea (KEPCO)

1. Interrupted power and duration: 348MW, 2hours 34min.

2. Sequence of the events:

10:36:09	HVDC trip(155MW), frequency became from 60.0Hz to 57.8Hz
10:36:29	UFR relay is operated in 1~4 level
10:36:32	Jeju diesel GEN#1 Trip(40MW), frequency became from 58.0Hz to under 57.6Hz
10:36:33	UFR relay is operated in 5 level
10:36:36	Jeju steam GEN#1 Trip
10:36:37	Nam-Jeju steam GEN#1,2 Trip
10:36:41	Jeju steam GEN#3 Trip
10:36:46	Nam-Jeju diesel GEN#1~4 Trip and Jeju became blackout(348MW) all of area

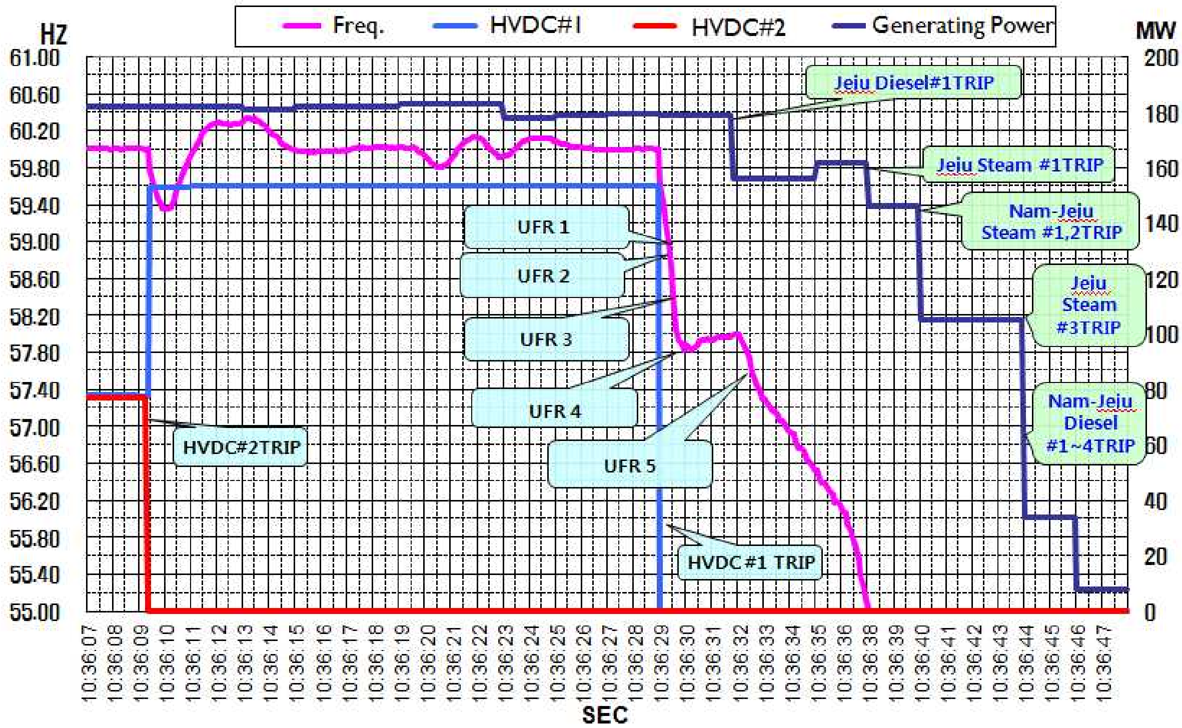


Figure 4-19 Power Flow and Frequency Chart at the Event

3. Cause:

A sharp decrease of supply of electric power caused by the breakdown of HVDC led to the collapse of frequency.

- Trouble of facility : Accidental destruction

4. Countermeasures:

- Supervising Submarine-Cable on a real time basis
- Installation of #2HVDC (400MW bipolar link between Jindo and Seo-Jeju)
- Providing adequate amounts of electric power using HVDC depending on the load amounts in Jeju (prevention of frequency collapse for contingencies)
- Enhancement of inertia by using mechanical synchronous compensator
- Enhancement of ESCR by installing FACTS equipment

4.2.6 April 2012-Shenzhen-china(Shenzhen psc)

1. Interrupted power and duration: 759 MW, 1hours37min.

2. Sequence of the events:

18: 44	An explosion occurred to phase L1 switch of 220kV AE A-wire of substation A due to an internal fault, necessitating emergency stopping of this switch.
18: 58—19: 14	To improve reliability and reduce AE B-wire load, a portion of 110kV load was shifted from substation E to substation H and in the meantime the EI wire was thrown into operation.
19: 20	At substation A, the AE B-wire was isolated using alternate circuit isolation by a by-pass switch.
20: 20	The AE A-wire switch at substation A was isolated by "hot changeover of busbar".
20: 30	In the process of busbar changeover，the 220kV AG A-wire 1M busbar-side isolation switch was pulled open, resulting in grounding of 220 kV 2M busbar; due to 220kV busbar protection action, both the 220 kV busbars lost their voltage. The incident revved up the main network frequency to 50.96Hz, resulting in loss of voltage at one 220kV substation and seven 110 kV substation. After loss of voltage of both busbars at substation A, 220kV substations E, H, G, and I and their 110kV substations, had shifted to XY line for power supply via the standby automatic transferring mechanism, thus forming a special power supply network （X-Y-Z-H-E-I-G）.
20: 31	Assisted by the dispatch automation system, the dispatcher succeeded in locating the source of power failure and found it was at the 220kV busbar at substation A.
20:33	The dispatcher realized by analysis that the 220kV substations E, H, G, and I were operating in a special mode in which power was supplied via XY lines and also realized that the lines were severely overloaded and the load was growing fast..
20: 35—20: 52	The dispatcher limited power supply and transferred the load according to the emergency brownout sequence table to control power flow growth on XY lines and, in the meantime, some generator units were put out of work and the network frequency was stabilized.
20: 53—20: 55	The dispatcher, by remote operation, restored the voltage of the busbars at substations J, K, and X and restored the voltage of the main substation and substation S. Three 110kV transmission routes were added: SY line, and JN double lines. By now, overloading was alleviated significantly on XY lines.
21: 25—21: 56	The 220kV busbar at substation A had its voltage restored, so did the 220kV substation F, and the special power supply network restored its normal power supply mode.
20: 59—22: 07	Voltage was restored at all the affected 110kV substations, and the main network of Shenzhen returned to normal power supply.

3. Cause:
The two equipment failure causes an important substation bus to lose voltage.

4. Countermeasures

- Control rigorously the acceptance of equipment for incorporation in the network, and intensify the maintenance of critical node equipment, particularly the maintenance of switch devices.
- Regarding electricity network operation, any switching operation involving sensitive

equipment or sensitive period shall, if at all possible, take place in the night when the load is low.

- The 220kV busbar structure at substation A is changed from "double-busbar with by-pass" to "double-busbar and double-section".
- Optimize the layout of local power source points, tap into clean energy sources like waste power and wind power generation, expedite the installation of pump storage power generation units, and improve the reserve capability of the electricity network.
- The stabilization control equipment for any regional electricity network likely to become an isolated one shall be augmented and be regularly checked so as to improve its adaptability to various operation modes and reduce the probability of large-scale power failure.
- A refined and well-established emergency plan system shall be created so that the dispatchers are familiar with the mutual support channels among different electricity networks in the event of an extreme network fault.

4.2.7 21 May 2013 – 14 southern provinces of Thailand (EGAT)

1. Interrupted power and duration: 4.13 GWh, 4hours

2. Sequence of the events:

1	Disconnected 500 kV central and southern transmission line link, circuit 2, for routine maintenance transmission system
2	Line fault at 500 kV central and southern transmission line link, circuit 1
3	Disconnected HVDC link between Thailand and Malaysia
4	Disconnected 230 kV and 115 kV remaining system
5	Power link between Central region and Southern region were completely separated
6	Load shedding with under frequency scheme was not fully operated as setting
7	Power plants in Southern region tripped out
8	14 southern provinces were interrupted

3. Cause:

Abnormal weather

4. Countermeasures:

Short Term Countermeasures to Prevent the Problems in

- Review the scheme for the operation of the Under Frequency Relay
- Review and practice the operation of the control system during system crisis
- Review the Blackout Restoration plan with regular training to reduce the duration of power outage
- Review the maintenance plan of transmission system and power plants in the Southern region of Thailand.
- Set guidelines for situations where it is necessary to have power off in the area to maintain the system stability and prevent extensive power outage.

Long Term Countermeasures to Prevent the Problems in

- Power Development Plan in the Southern region of Thailand must be considered that the reserve margin is sufficient for the operation of the Southern power system.
- Accelerate the implementation of transmission system improvement project in Western and Southern Regions to enhance system security
- Review the overall development plans for both generation and transmission focusing on the system security of the country. If any area is considered risky and vital to the main grid, it should be increased the system security to avoid the extensive power outage.

5. Detailed description

5.1 General Background on Blackout in Southern Thailand on 21 May 2013

Lightning hit the 500 kV central and southern transmission line circuit #1 at the same time that the other 500 kV line was under maintenance. The power system was operated to control more power flow from the central region to the southern region.

However, the power demand in the southern region was increasing from 2,200 megawatts while only 1,600 megawatts power were generated at that time and parts of the power supply were from the existing 230 kV and 115 kV transmission lines. Some 480 MW of electricity was still unsupplied to meet the increasing demand during the evening time. Load shedding scheme was not fully operated as setting up in distribution systems.

To make up for the power shortage after the incident, the power purchase from Malaysia under the power purchase agreement was made which can be up to 450 MW. During a short period, Thailand received 380 MW of power, but the power was later unsupplied after only short period due to some limits.

For security reason, power plants in the south automatically released themselves from the power system and all 14 provinces of the southern region were then hit by the blackout.

During the blackout period, the power system can be restored by 13 - 80 minutes, and all southern customers can use electricity after the southern region is electrified within 13 - 285 minutes.

Goal

To prevent the risk from causing power outage in wide area in the future, especially the southern region which is the long distance power grid of Thailand

Achievement under development

1. Technologies on voltage control such as: various sizes of static var compensator (SVC) are being applied to the transmission grid to enhance system security in the southern region.

2. Power development plan in the southern region of Thailand is planned to have sufficient reserve margin to ensure the solely operation of the southern power system with southern region power plants. However, the excess power can be fed back from the southern to the central region via 500 kV transmission lines

3. Acceleration of the implementation of transmission line link between the central and southern regions to enhance system security.

5.2 General Background on Bangkok and Vicinity Area of Thailand

Bangkok and vicinity has consumed about 30 % of electricity generated in Thailand, and it is well recognized that this area has a very high important load, both in terms of central business of Thailand but also many industrial zones are within this area.

The power systems in Bangkok and vicinity area has both power plants and transmission line link that can supply electric power from other regions of Thailand to meet the power consumption in Bangkok and vicinity area.

However, the retirement of the existing power plants shall be more during year 2019 – 2022; therefore, EGAT plans for the power plant replacement at the existing site location because the infrastructure is already existing.

Moreover, the system in the mega city like Bangkok and vicinity has seen the problems on high short circuit current level. EGAT and MEA have a collaboration plan to maintain the most appropriate system configuration on transmission and distribution systems respectively.

EGAT has developed the 500 kV upgrades to decrease the system high short circuit current level and maintain the system reliability at the same time.

Goal

To prevent the risk from causing power outage in wide area in the future, especially mega cities such as Bangkok and vicinity area with high power demand

Achievement under development

1. Review of the overall transmission focusing on the system security of the country. If any area is considered risky and vital to the main grid, it should be increased the system security to avoid the extensive power outage, for example, EGAT has planned to

- Construction of the 500 kV transmission line link to feed the power consumption in the north Bangkok, and the eastern Bangkok.
- Upgrading of the 500 kV transmission line link, initially operated at 230 kV, to be operated at 500 kV to feed the power consumption in the western Bangkok.

2. Balancing the proportion on the power supply to mega city such as: Bangkok and vicinity area by considering two aspects of system reliability:

   1) System reliability on sufficient power plants within mega city area
   2) System reliability on enhancing the transmission system capability to transmit electric power from other regions into the mega city area
      The proportion of those two aspects shall be approximately 45 % and 55 % respectively.

5.3 Future Achievement

Technologies on blocking the short circuit current level such as: high voltage direct current (HVDC) shall be applied to the transmission grid to enhance system security in the future.

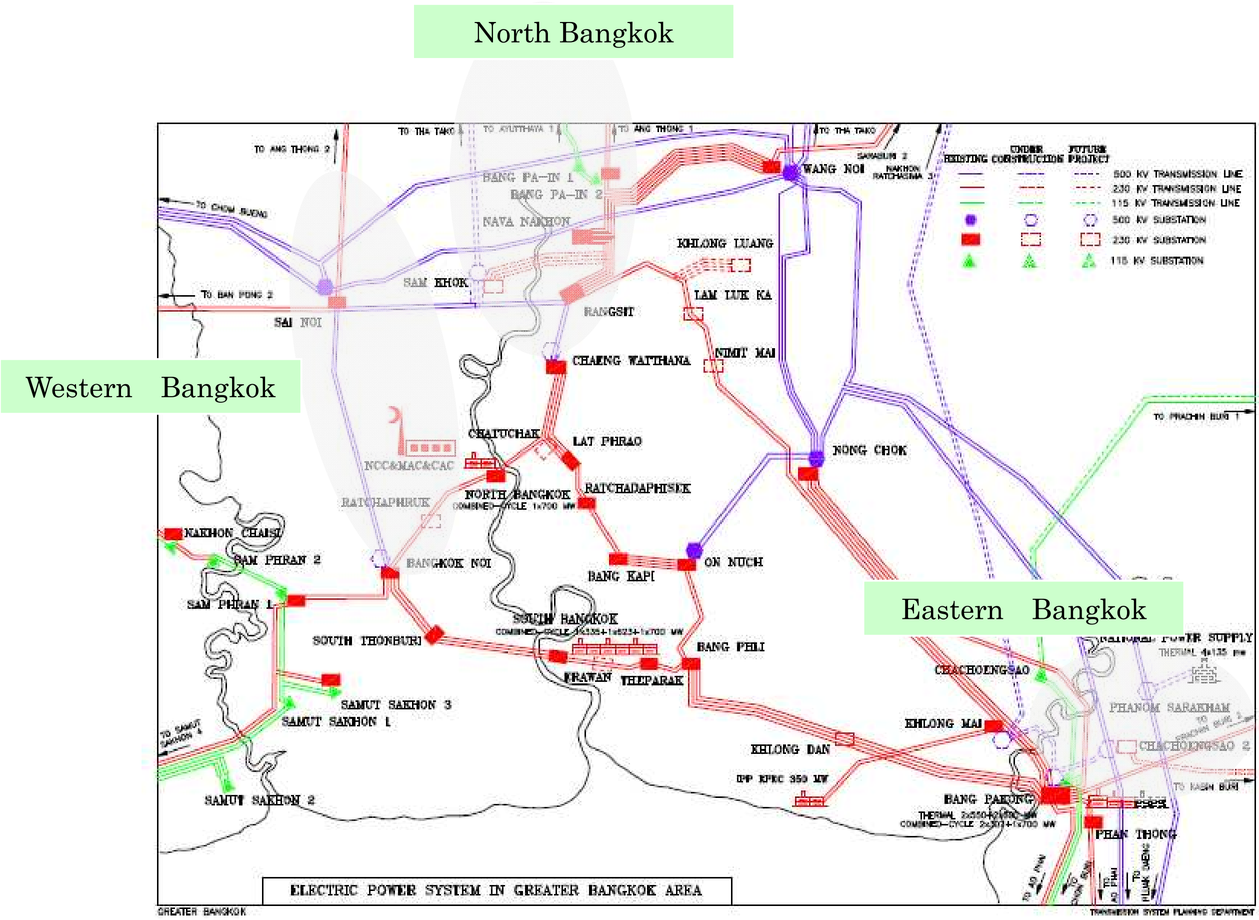


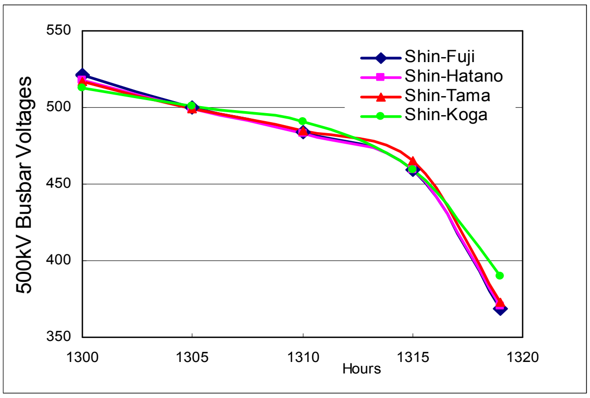
Figure 4-20 Power System Map in Bangkok Area

4.2.8 Aug 1987 – Tokyo, Japan (TEPCO)

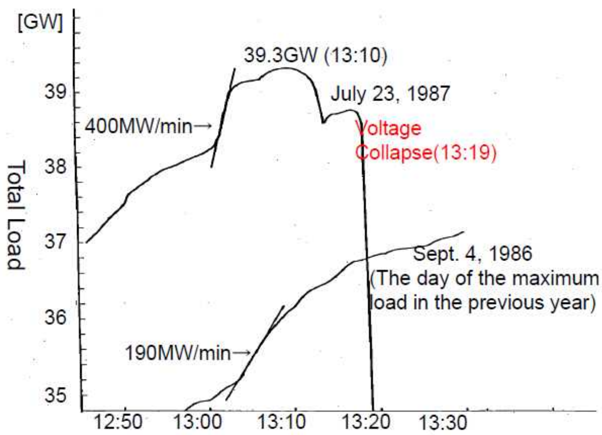
1. Interrupted power and duration: 8,000MW, 4 hours

2. Sequence of event:

13:00 -13:10	The load increased at 400MW/min., which was much steeper than forecast. Even though all available capacitors were put into the system, voltages at 500kV substations gradually fell
13:15	Voltages at the 500kV substations close to the Tokyo metropolitan area decreased to around 460kV
13:19	Voltages at the 500kV substations fell rapidly to about 370kV in the western area, 390kV in the central area. Protective relay operations due to the voltage fall caused three substations to shut down.
13:23 -13:35	The three substations restored
13:36	4,700MW of the outage load restored
14:30	6,300MW restored
16:40	All the outage was restored



(a) Bus-bar Voltage of 500kV substations



(b) Total demand at the incident

Figure 4-21 Bus-bar Voltage of 500kV substations and total demand at the incident

Figure 4-21 (a) shows voltages of 500kV bus-bars and Figure 4-21 (b) shows load curve from 12:50pm to 1:20pm in the event of voltage collapse.

At 12:40, the total demand has reached 36.5GW, and then started to rapidly increase after lunch break toward 13:00. In response to the steep rise of the demand, shunt capacitors were put in service and reactive power supply from generators were increased to meet the increasing var consumption in the network or load.

However, from 13:00 to 13:10, the load increased at rate of 400MW/min., which was twice the rate at the day of the maximum load in the previous year.
Although all available capacitors were put into the system by 13:07, voltages at 500kV substations gradually fell down.

After the load has reach to the peak demand of 39.3GW at 13:10, the voltage at the 500kV substations close to Tokyo metropolitan area decreased to around 460kV. At last, voltages fell down rapidly down to about 370kV at the western area, and 390kV at the central area.
Protective relays operated due to the voltage fall, consequently three substations were shut down and about 8,168MW load was interrupted.

Frequency in power system rose to 50.74Hz due to this load shedding, and that resulted in No.6 generator of Kawasaki thermal power station (350MW), No.4 (600MW) and No.6 (1,000MW) generator of Kashima thermal power station were tripped or manually stopped.

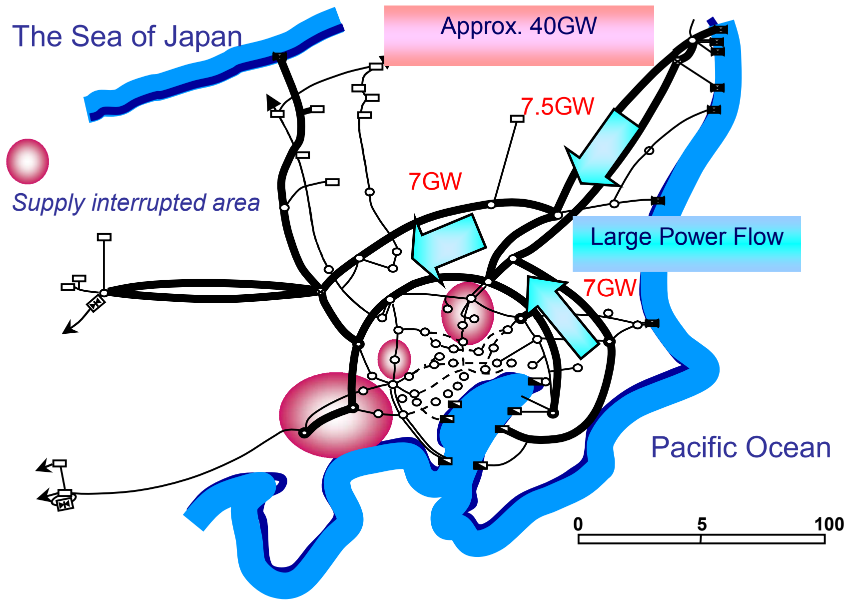


Figure 4-22 Power flow and Outage area when voltage collapse occurred in 1987

The Figure 4-22 illustrates transmission Network, power flow, and outage areas in 1987. There were 7.5GW of large power flow from Fukushima nuclear power station, 7.0GW from eastern thermal power stations, and 7.0GW from eastern area to western area.

3. Cause:

Insufficient reactive power supply for the high rate of load demand increase causing significant voltage collapse.

4. Countermeasures:

- Higher voltage profile
- Installation of shunt capacitors to the network
- Development of sophisticated automatic voltage controllers (VQC) and its simulation tool.
- Development of under-voltage load shedding as wide area protection scheme

4.2.9 Nov 1999 – Tokyo, Japan (TEPCO)

1. Interrupted power and duration: 1,600MW, maximum of 3 hours 19minutes

2. Sequence of event:

(1) A double-circuit line was lost when a small airplane crashed into a 275kV overhead transmission line. The area with a total load of 2,000MW and local operating generation of 400MW was separated from the main power system.

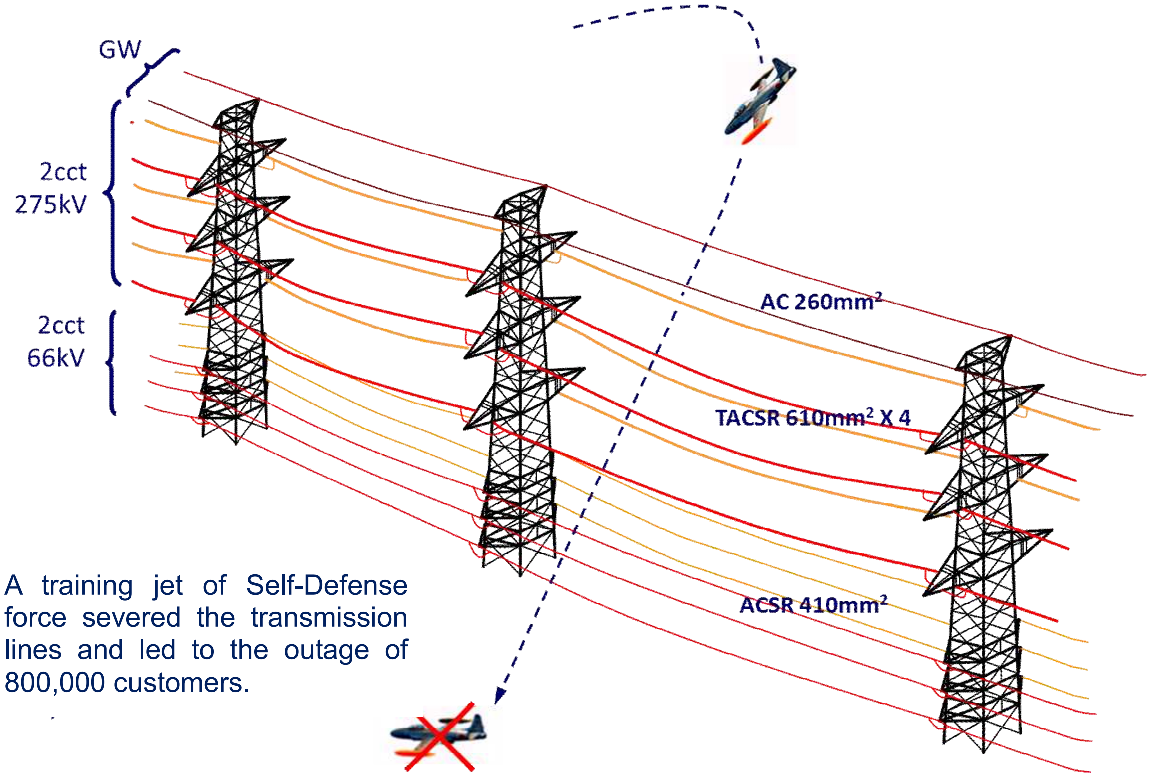


Figure 4-23 Cause of the Trouble

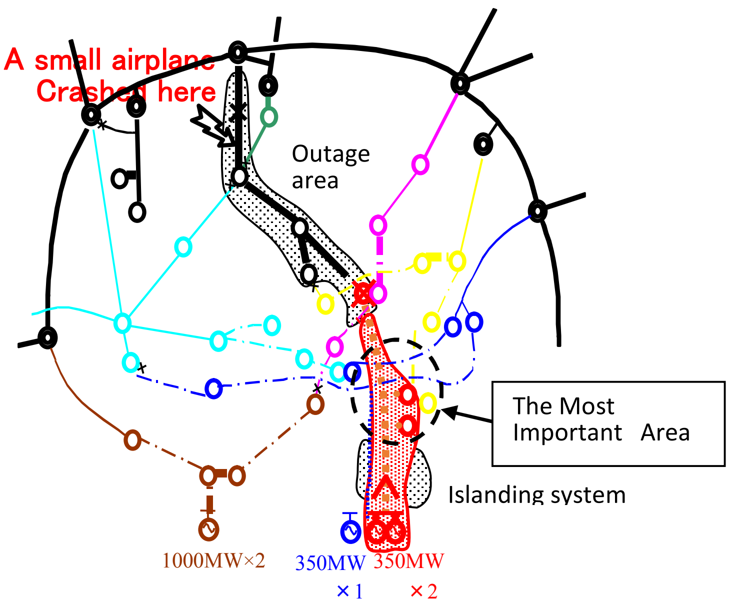


Figure 4-24 Interrupted Area and Islanded Area

(2) The frequency of the separated area started dropping at a rate of 5.2Hz/sec due to a severe imbalance between the supply and demand.

(3) The System Islanding Controller (UPSS) successfully identified the separation from the main grid by detecting an excess of phase angle difference between designated nodes from the predetermined value. Then, it took the appropriate actions to form an island with a better power balance by shedding loads and switching shunt capacitors, which were completed within 500ms after the fault.

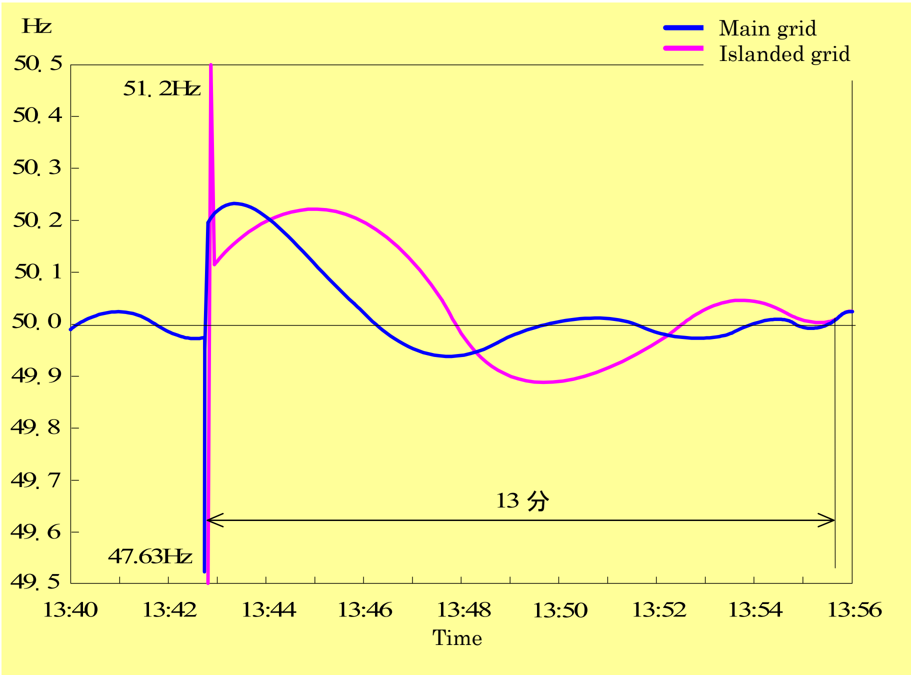


Figure 4-25 Frequency Fluctuation of Main Grid and Islanded Grid

(4) The islanded area was re-synchronized with the main grid about fifteen minutes after the incident occurred. Consequently, power was restored to 94 % within 30 minutes.

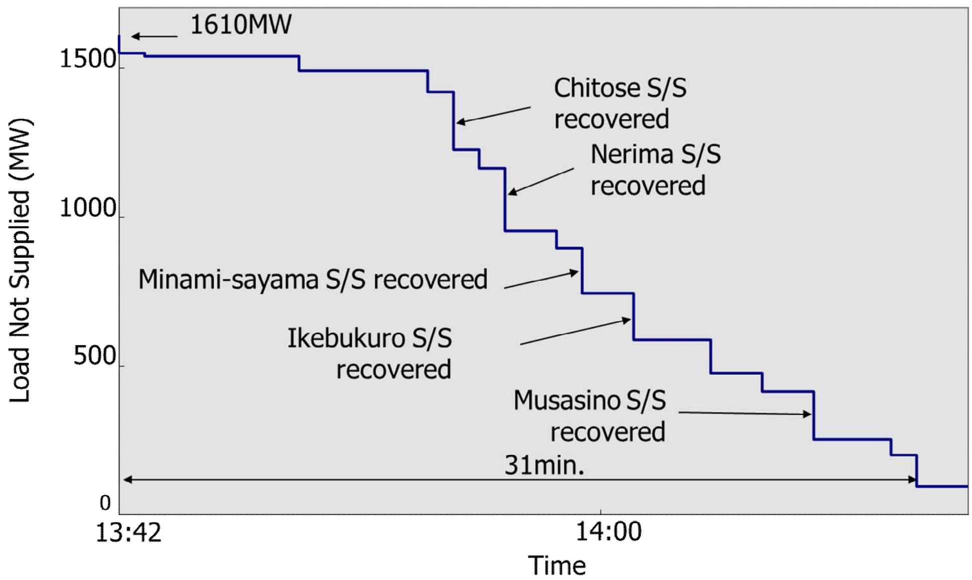


Figure 4-26 Restoration Process of Interrupted Load

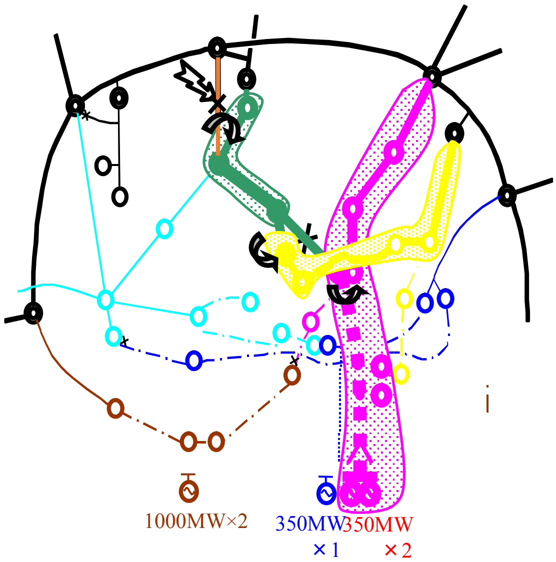


Figure 4-27 Power System Configuration at Post-event State

3. Cause:

Accidental destruction by third party

- Loss of a double circuit line due to a small airplane crashing into a 275kV overhead transmission line.

4. Countermeasures:

This case is one of the best practices that the important or vital loads were successfully prevented from interruption caused by accidental destruction - the System Islanding Controller (UPSS) could successfully operate and islanded the important area in the center of Tokyo metropolitan area.

TEPCO recognized the importance of the automatic control scheme.

4.2.10 Aug 2006 – Tokyo, Japan (TEPCO)

1. Interrupted power and duration: 2,160MW, maximum of 59minutes

2. Sequence of event:

(1) A double-circuit line was lost when a raised construction crane hit a 275kV overhead transmission line. The area with a total load of 2,160MW and local operating generation of 620MW was separated from the main power system.

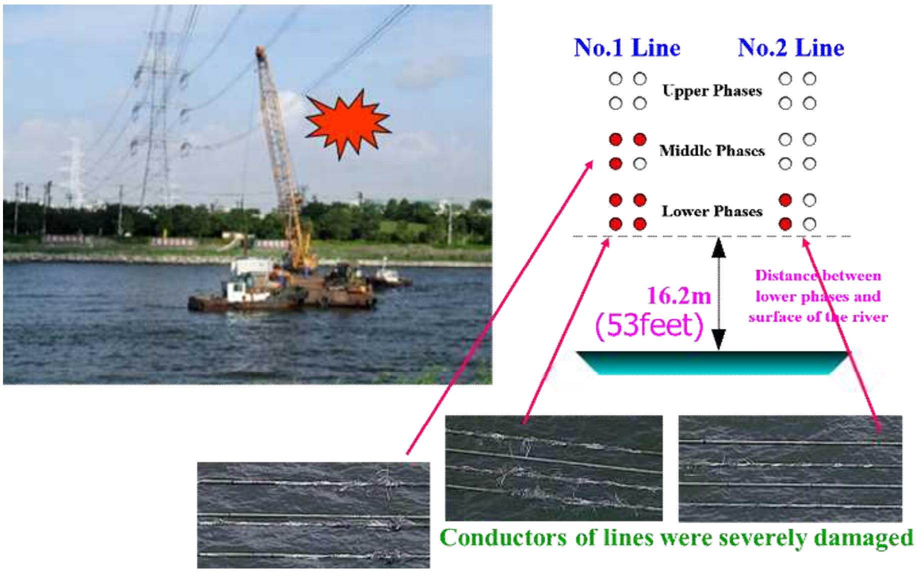


Figure 4-28 Cause of the Trouble

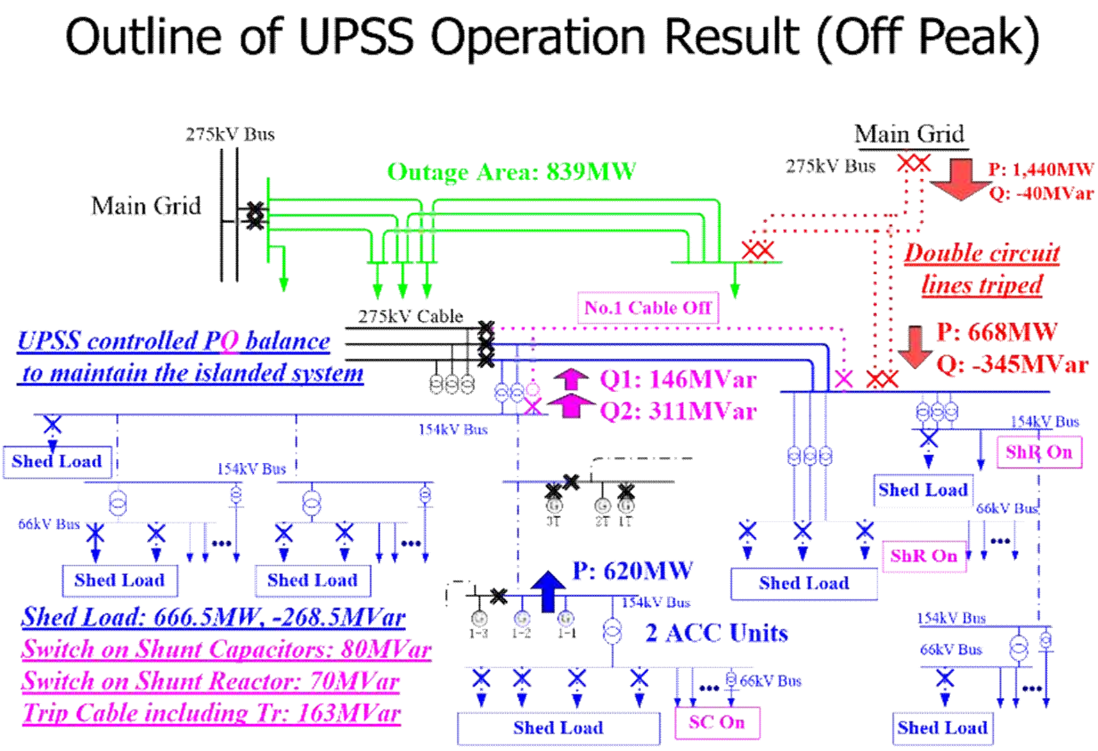


Figure 4-29 Power System Diagram after the UPSS Operation

(2) The frequency of the separated area started dropping at 1.2Hz/0.4sec due to a severe imbalance between the supply and demand.
(3) The System Islanding Controller successfully identified the separation from the main grid by detecting an excess of phase angle difference between designated nodes from the predetermined value. Then, it took the appropriate actions to form an island with a better power balance by shedding loads and switching shunt capacitors, which were completed within 500ms after the fault.

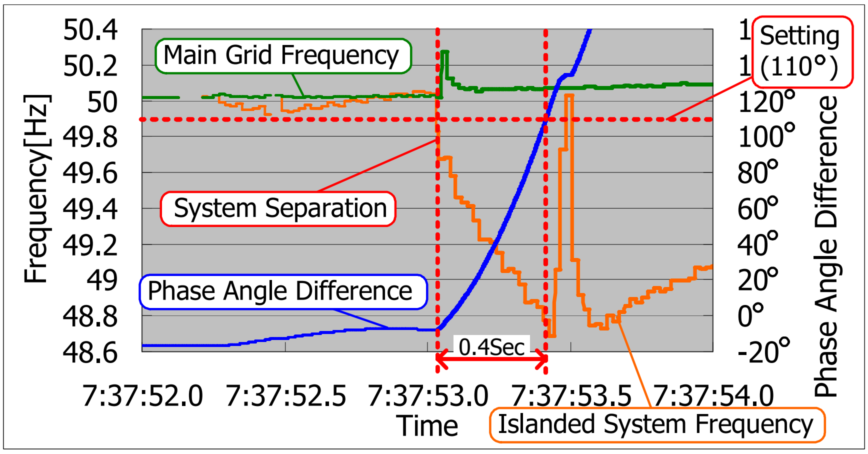


Figure 4-30 Voltage Phase Angle and Frequency Fluctuation at around the Event

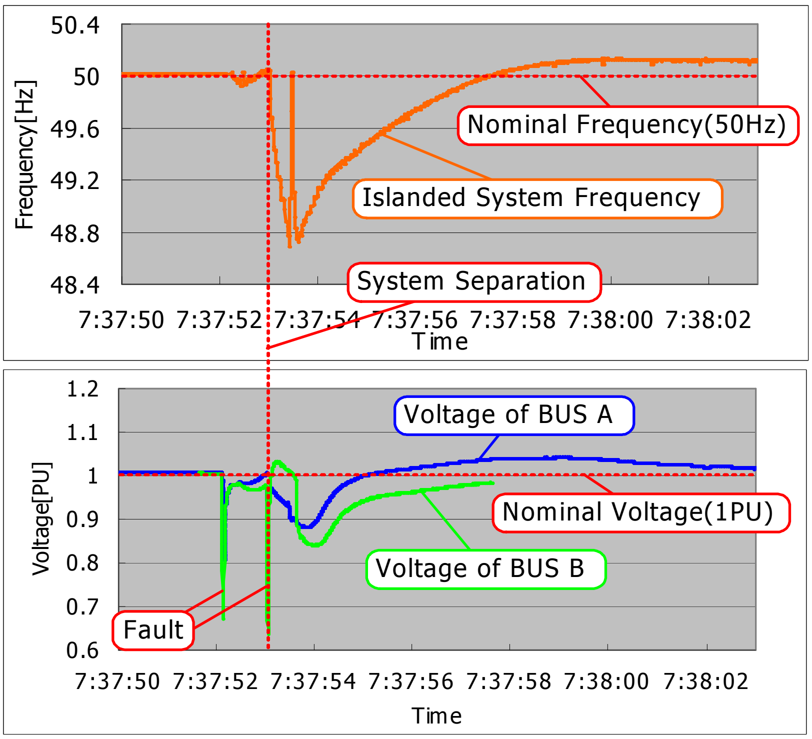


Figure 4-31 Voltage and Frequency Diagram at around the Event

<u>3. Cause:</u>

Accidental destruction by third party

- Loss of a double circuit line as the result of a raised construction crane hitting circuit No. 1 and No.2 of a 275kV overhead transmission line.

4. Countermeasures:

The islanded system that maintains stable operation thanks to the islanding relay can't hold long period because the islanded system scale is so small and adjustability is quite limited. Therefore, the islanded system must be reconnected in a short time.

Islanded System Automatic synchronizer (ISAS) performs emergency system re-synchronize operation automatically when the islanded system is separated from the main grid.

TEPCO applied some ISAS devices in Tokyo metropolitan area just after this incident.

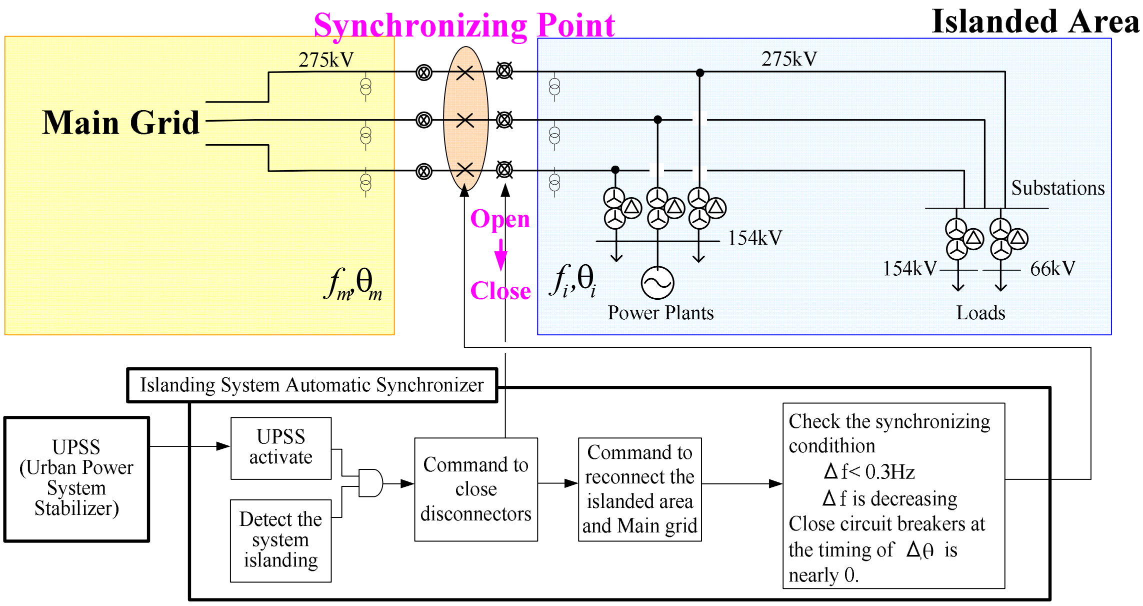


Figure 4-32 Fundamentals of Islanded System Automatic Synchronizer (ISAS)

4.2.11 Mar 2011 – East of Japan including Tokyo (TEPCO)

1. Interrupted power and duration: 9,100 MW, maximum of 1 week

Date: Friday, March 11, 2011
Time: about 14:46
Epicenter: off the coast of Sanriku
(38.00 degrees N, 142.90 degrees E)
Magnitude: 9.0 (depth 10km)
(The strongest earthquake ever recorded in Japan)
Seismic Intensity on the Japanese scale of zero to seven:

North Miyagi: 7
South Miyagi: strong 6
Fukushima Hamadoori: strong 6
North Ibaraki: strong 6
South Ibaraki: strong 6
North Tochigi: strong 6
South Tochigi: strong 6
South Gunma: weak 6
South Saitama: weak 6
North West Chiba: weak 6

TSUNAMI came after the earthquake and caused big damage

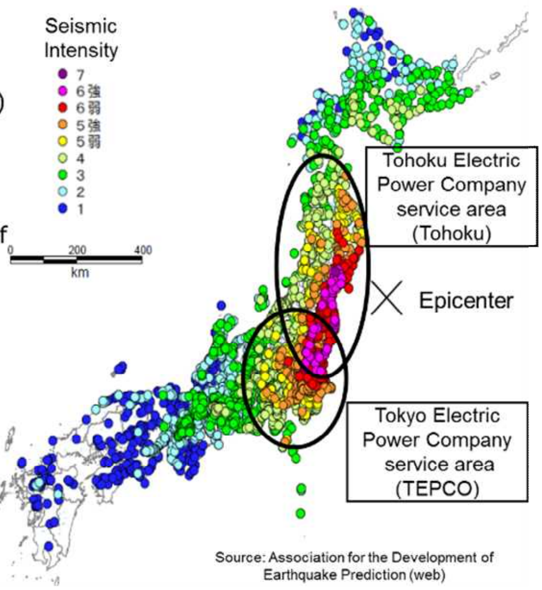


Figure 4-33 Facts of East Japan Earthquake in March 2011

Table 4-2 Facts of Outage in the East Japan Earthquake

Power Outage	Approx. 7,900 MW in Tohoku (60% of loads before the earthquake) Approx. 9,100 MW in TEPCO
Number of Customers Out of Power	Approx. 4.66 million households in Tohoku Approx. 4.05 million households in TEPCO
Power Stations Shut Down	Approx. 7,300 MW in Tohoku Approx. 21,000 MW in TEPCO

2. Sequence of event (in TEPCO's service area):

(1) Due to the earthquake and tsunami, approximately 21,000MW of power supply was damaged, resulting in a significant supply deficiency.

(2) Frequency sharply went down to 48.44Hz, which activated Under-frequency Relays (UFR) and about 5,700MW of loads were automatically shed.

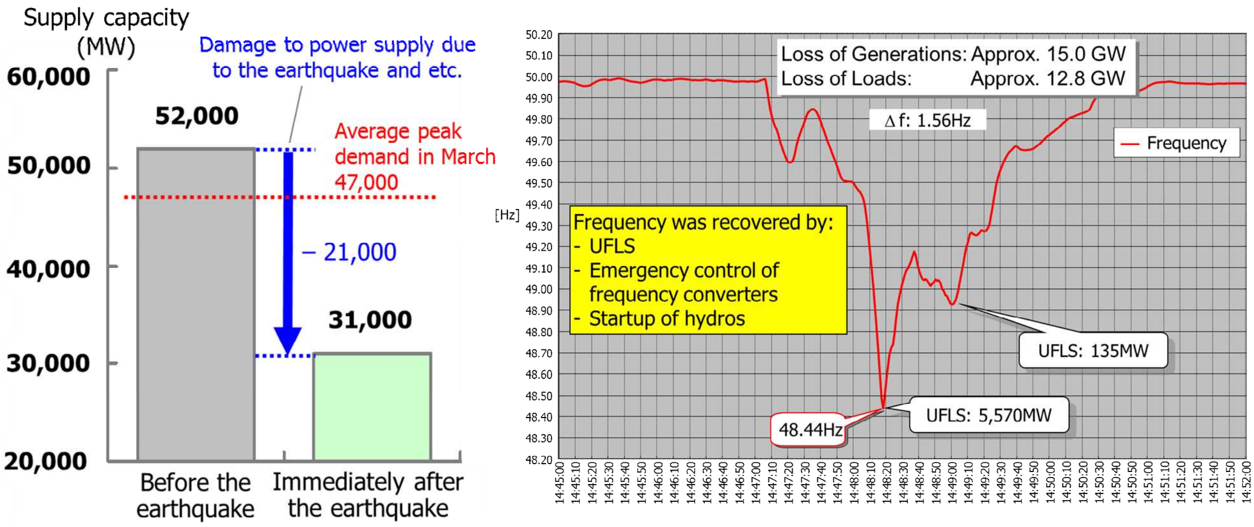


Figure 4-34 Sudden Degradation of Power Supply Capacity and Frequency Deviation

(3) By March 18th, all power outages were restored, but the rolling blackout was conducted on 10 days between March 14th and March 28th.

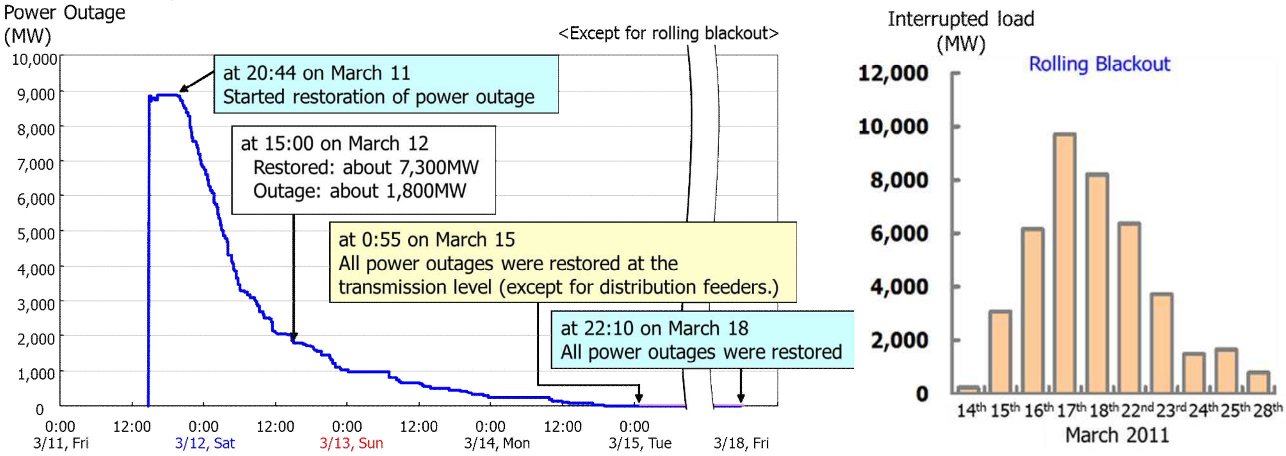


Figure 4-35 Restoration Process of the Outage and Interrupted Load by Rolling Outage

(4) Supply capacity of 57,200MW was secured by the end of July through the restoration of thermal power stations and the installation of gas turbines.

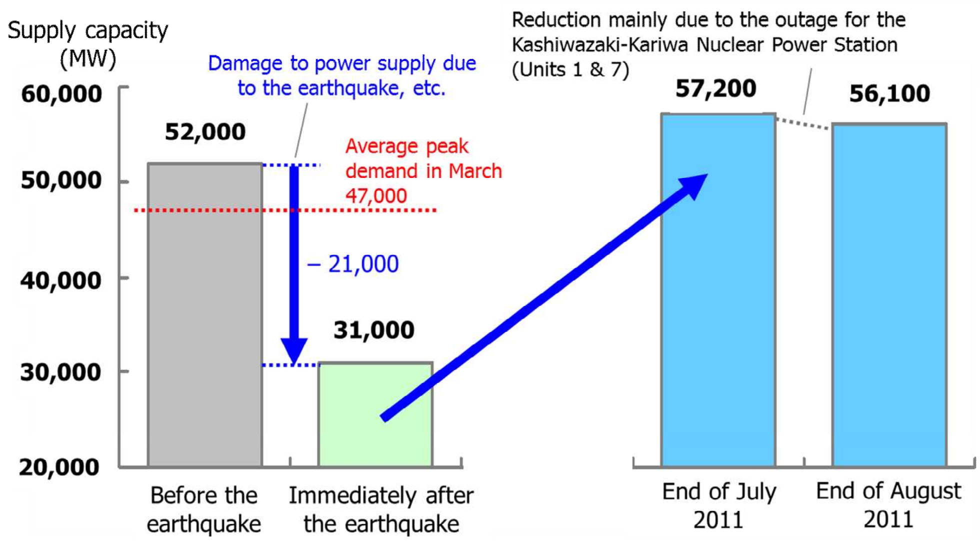


Figure 4-36 Rapid Recovery of Significant Deficiency of Power Supply Capacity

(5) Power flow in the EHV system has changed mainly due to the loss of nuclear power plants. Countermeasures were taken for issues caused by the change of power flow.

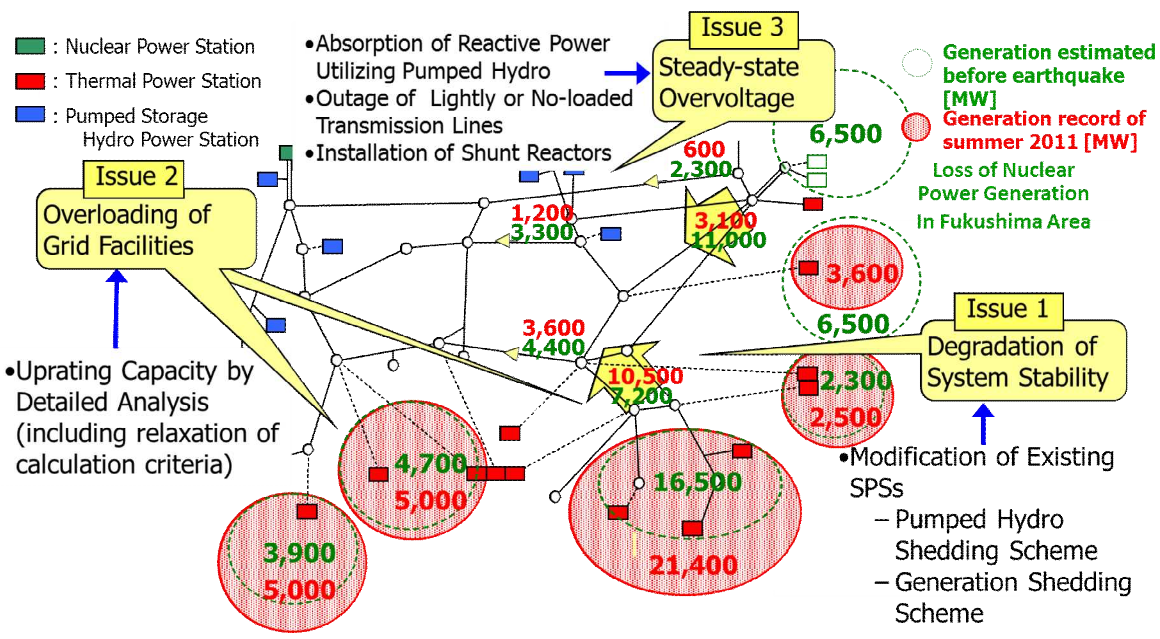


Figure 4-37 Drastic Change of Power Flow between Pre- and Post-event

3. Cause:

Natural disaster (Earthquake and tsunami)

4. Countermeasures:

(1) Preparation of Rolling Blackout Scheme

- A rolling blackout scheme must be prepared, in case for a loss of a large share of the generation capacity due to a large disturbance, such as big earthquakes.
- Public should be informed of the scheme in advance as it has a significant influence on social activities when enforced.
- Each primary substation was divided into five groups each of which has five sub-groups. Time slot for each group was rotated everyday so that customers would experience an outage during a different time slot from the last day.

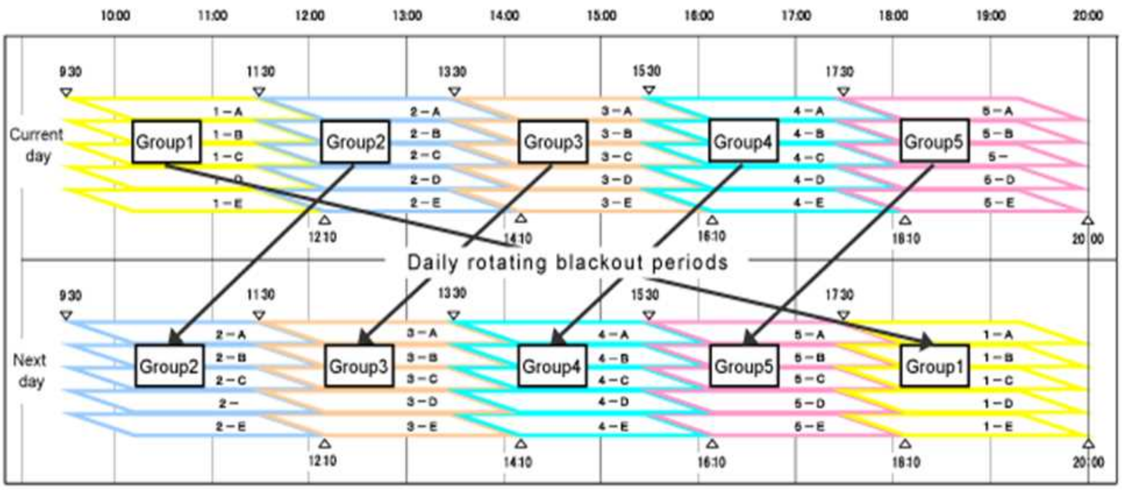


Figure 4-38 Schedule of the Rolling Blackout Scheme

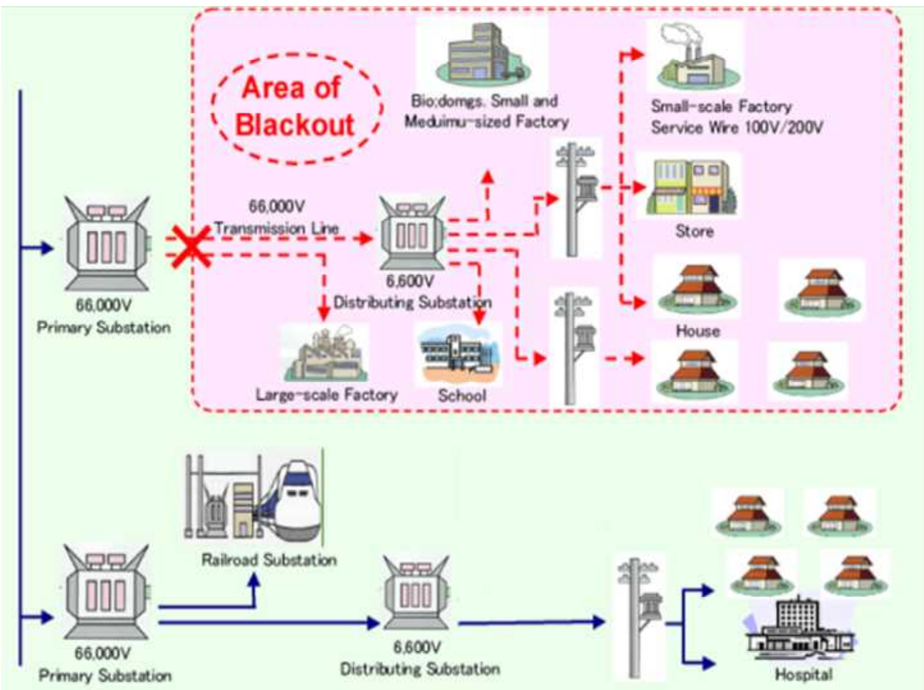


Figure 4-39 Conceptual Diagram of the Operation for Rolling Outage

(2) Improvement of EMS (Energy Management Systems)

- When a large disturbance occurs, a lot of information is sent to EMS of control centers. We are planning to upgrade a function of EMS in order to allow system operators to quickly grasp the system condition, including the operation of protection relays and special protection schemes.

(3) Training of System Operators

- System conditions during the Great East Japan Earthquake were reproduced in the real-time simulator of the operator training system, using recorded data.
- We have been using the reproduced event in the operator training system for system operators to experience the event and improve their skills in the restoration procedure.

Figure 4-40 Training Center for Power System Operators

4.3 Risks and Measures for Large Scale Outage in Mega Cities

4.3.1 Introduction

As described in sec. 3.2.2, identifying and prioritizing resilience-enhancement measures prior to cost/benefit analysis is important step for long-term planning.
In this project, we conduct a survey through a questionnaire regarding decision-making procedures in order to optimally allocate limited resources including capital investment in member companies/countries.
The results of survey are as follows:

CLP Power

This company has implemented the "Investment Ranking and Benefits Tracking System" to consistently evaluate all non-mandatory projects. They are ranked based on their impacts in 5 key result areas including financial, customer impact, internal business, innovation & growth, Government & communication. Justifications are vetted by a central team and benefits of projects are tracked to confirm its effectiveness. We also conduct risk assessment by a structured approach which identify, assess, prioritize and mitigate risks. All significant risks are registered and corresponding owners are accountable for the development of mitigation plans.

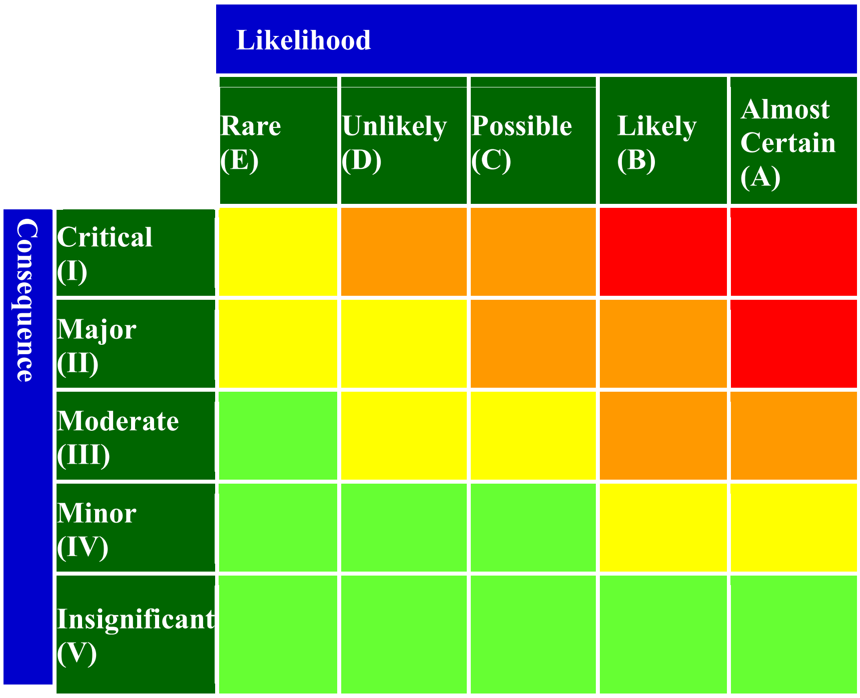


Figure 4-41 5 x 5 Matrix for Risk Assessment

Figure 4-42 Plan, Do, Check, Act – Risk Assessment

Hongkong Electric

All improvement items identified under periodic system security review will be prioritized into difference categories based on their;

- failure consequence,
- effectiveness of the items to eliminate/reduce the risk/failure,
- impact to our network as well as customers.

For those items related to health and safety, higher priority will be given. Then the items will be implemented based on their categories.

Risk management is integrated into HK Electric's day-to-day activities and is an ongoing process that flows through the organisation. Risks are categorised into different categories to facilitate analysis. Each risk identified is analysed on the basis of likelihood and impact. Action plans are in place to manage risks. The risk assessment process also includes a review of the control mechanisms for each risk and the effectiveness of each control is rated. A risk register is compiled and the company updates and monitors the risk register on an on-going basis by taking into account emerging issues.

Shanghai Municipal EPC

- This company has applied condition-based maintenance (CBM) strategy to all assets from 10kV to 500kV which is the main criteria for facility replacement and investment decision making.
- This company has applied CBM to facility maintenance and replacement decision making for nearly 10 years and set up both management and technical systems for CBM. And also has fixed inspecting teams to perform site condition monitoring tests (such as Infrared Ray, Partial Discharge, Dissolved Gas Analysis) and professional engineers and research experts in EPRI to analyze data and make proper maintenance strategy.

KEPCO

This company operates "a committee for the large scale projects" as below

- Purpose : To minimize the social discord caused by the development of transmission and substation construction projects
- Scope : Determination of the optimal direction of large scale projects at the planning and location selection level
- Composition
  - Planning & Budget Department
  - Procurement & Contract Department
  - Grid Planning Department
  - Transmission & Substation Construction Department
  - Other related departments
- Resolution : By a vote of two-thirds of the board member present and a two-thirds majority or more
- Mission
  - How to configure power grid
  - Construction method (overhead power line, underground power cable)
  - Project scale & Time of completion
  - Location Selection and so on

TEPCO

- This company yearly conducts a risk assessment from the viewpoint of "Probability" that each risk scenario is realized and "Impact" on our business when each risk scenario is realized
- Then, the risk is visualized with the Risk Impact/Probability Chart as shown in the figure below and share the results of assessment and priority of mitigation measures against the risks on the company-wide basis
- When formulating the specific capital investment, repairs or removal plan, following

points should be noted:

- Necessary repairs for ensuring the personal safety, legal compliance or equipment maintenance should be properly included
- Necessary measures to keep the reliability of power supply or soundness of equipment in good conditions should be prioritized from the viewpoint of details, necessity and period.
- The plan should be well harmonized with regional circumstances, man power and maintenance outage planning

● The PDCA (Plan-Do-Check-Action) cycle will be repeated every year for continuous improvement.

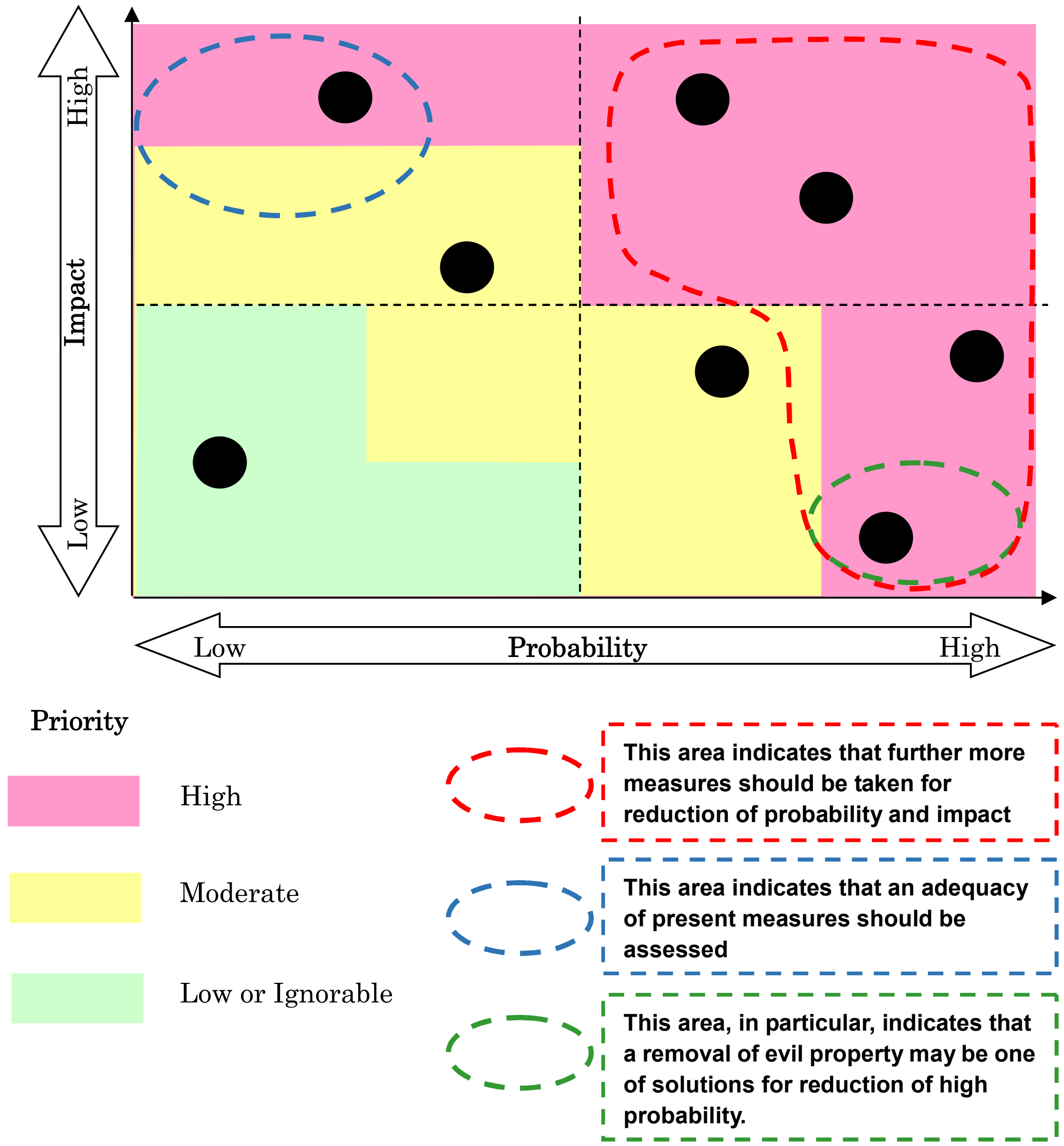


Figure 4-43 Probability/Impact Chart for Risk Assessment

4.3.2 Method of Survey

4.3.2.1 Probability/Impact Chart Risk Assessment

In this report, we adopt a “Probability/Impact Chart” method in order to visualize and simplify the risk assessment and the decision-making/prioritizing process.

In order to provide informative charts, following steps are taken:

Step 1

Each member company selects the disturbances from the following categories and items, and consider a worst-case scenario which results in a *severe outage*.

"Severe Outage"

Blackout of whole service area or wide area outage including whole / important part of "Mega Cities" in each company. (In terms of "Mega Cities", refer to each table in section 4.1.1)

Table 4-3 Categories and Items of Disturbance

Categories	Items
Abnormal weather	Typhoon/Rain storm, Lightning strike, Flooding, Tornado, Blizzard/Ice-storm, Drought/Heat wave, Others
Natural disaster	Earthquake, Tsunami/Tidal wave, Volcanic eruption, Landslide/Avalanche, Forest fire, Wildlife/Tree contact, Geomagnetic storm, Others
Trouble at facilities	Aging, Defects, Explosion/Fire, Accidental destruction, Intentional destruction (Conflict, Terrorism, Cyber-attack), Others
Operational inaccuracy	Demand-forecasting, Deficiency of power source, Supply-demand control (Deficiency of reserves), Voltage-reactive power control, Miss-operation/Malfunction of facilities/control systems/relays, Others
Others	Pandemic, Others

Step 2

Each member company scores the ***probability*** the worst-case scenario occurs, and the ***impact*** on the power supply if the scenario occurred according to the following tables:

"Probability"

Grade	Definitions	Score
H (High)	"Severe Outage" will happen within 3 years. "Severe Outage" will happen once in 3 years. "Severe Outage" will frequently happen.	4
M (Medium)	"Severe Outage" will happen within 10 years. "Severe Outage" will happen once in 10 years. "Sever Outage" will not frequently but possibly happen.	3
L (Low)	"Severe Outage" seldom happen	2
U (Unknown)	Unknown, Unpredictable	1

"Impact"

Evaluation process has two sub-steps:

(1) Grade 4 indices ; (a) – (d) and calculate the sum.

Point	A. Interruption		B. Influence on the facilities	
	(a) Proportion of affected service area or number of customers	**(b) Time to complete recovery**	**(c) Proportion of total expense for complete restoration to annual capital investment +repair cost (*)**	**(d) Time to complete restoration or measures**
4	More than 40%	More than 1 month	More than 50%	More than 1 month
3	20-40%	1 week – 1 month	30-50%	1 week – 1 month
2	10-20%	1 day - 1 week	10-30%	1 day - 1 week
1	Less than 10%	Within 1 day	Less than 10%	Within 1 day

(*): Annual (capital investment + repair cost) for the whole company

(2) Select the final evaluation in the table below.

Total Point	Grade	Score
13~16	VH	4
9~12	H	3
5~8	M	2
~4	L	1

Example of valuation

	(a)	(b)	(c)	(d)	Total → Grade(Score)
Ex1	3	1	3	4	11 → H (3)
Ex2	3	4	4	4	15 → VH (4)

Step 3

The highest score of the probability and impact are adopted every disturbance and placed in the probability/impact distribution chart for every category.

If there is a company who sets multiple risk scenarios and probability/impact in one disturbance, only the highest grade/score is adopted.

Step 4

As show in Figure 4-44, the countermeasures for each disturbance are prioritized into 3 degrees – "high", "moderate", "Low/Ignorable" according to 3-color-classification of the Probability/Impact Chart.
"Low probability high impact" zone (enclosed in red thick line) should be closely watched to enhance the "resilience" of the power system.

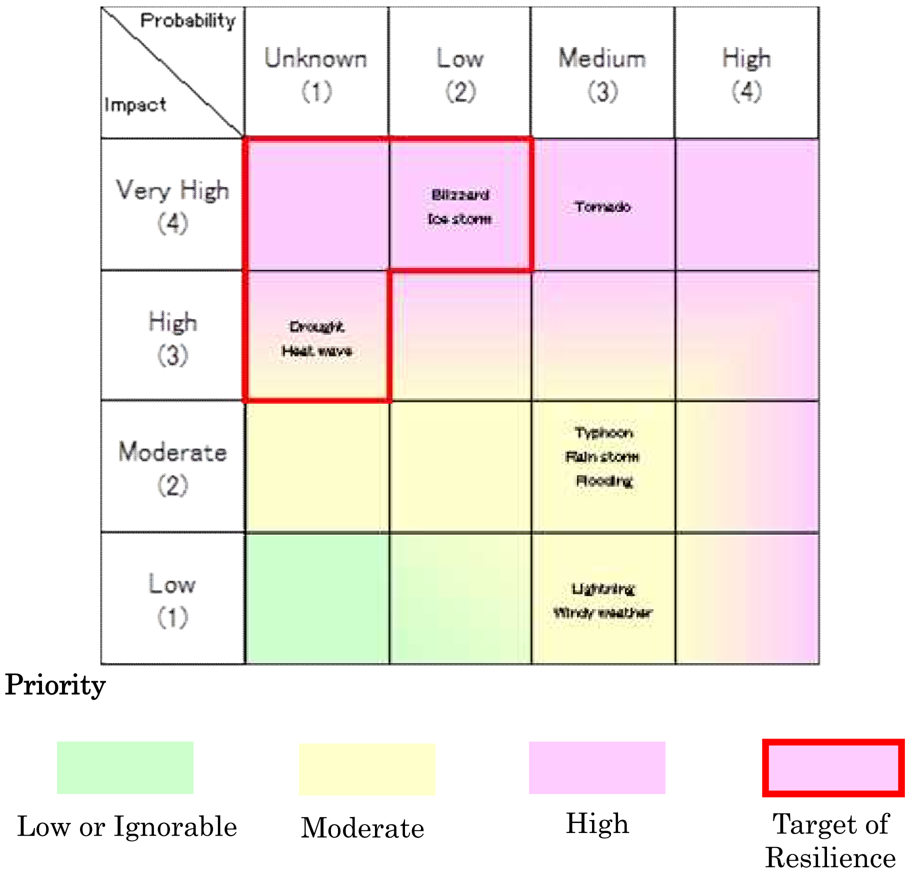


Figure 4-44 Conceptual Priority Assessment Method with the Probability/Impact Chart

4.3.2.2 Survey of existing countermeasures for disturbances

In addition to the risk assessment, existing measures (Mitigation, Hybrid, and Adaptation measures) for each disturbance are surveyed

In order to mitigate the risks, hardening measures such as strengthening of the transmission network may be effective, but there are some issues concerning high costs and long construction periods, which may induce a time lag between the installation rate of facilities for electricity supply and the high rate of economic growth and electricity demand increase in Asia.

Therefore, hybrid measures, between mitigation and adaptation ones such as protection and control systems for power system stabilization, may be effective to complement the issues above and adapt to various situations.

4.3.3 *Results of the Survey*

4.3.3.1 *Abnormal Weather*

In recent years, wide-area and prolonged outages occur in many countries of the world caused by the abnormal weather like super-typhoon, terrible flooding, or others.

Utilities have been experienced many normal-grade typhoons, lightning strikes, flooding, and so on, and facilities have been damaged by them in many times in the past. Therefore, utilities supposed to consider that countermeasures for such frequent incidents have already been taken to some extent.

However, more careful considerations will be required from the viewpoint of the climate change in the future.

It should be noted there is a strong likelihood that the drought/heat wave or Blizzard/Ice storm, which is considered to be low or unknown probability of occurrence, may cause following troubles:

- Steep electricity demand rise that results in significant deficiency of power source
- Wide area collapse of towers that results in Overload of multiple network facilities and cascading trips

Impact \ Probability	Unknown (1)	Low (2)	Medium (3)	High (4)
Very High (4)		Blizzard Ice storm	Tornado	
High (3)	Drought Heat wave			
Moderate (2)			Typhoon Rain storm Flooding	
Low (1)			Lightning Windy weather	

Typhoon/Rainstorm

(1) Risk scenarios that lead to a severe outage

Likely events	**Scenarios**
● Overhead lines breakage ● Tower collapse ● Landslide ● Tree touching	Multiple tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines.
● Overhead ground wires breakage	Malfunction of the protection system will induce; ● wide area outage with remote backup protection

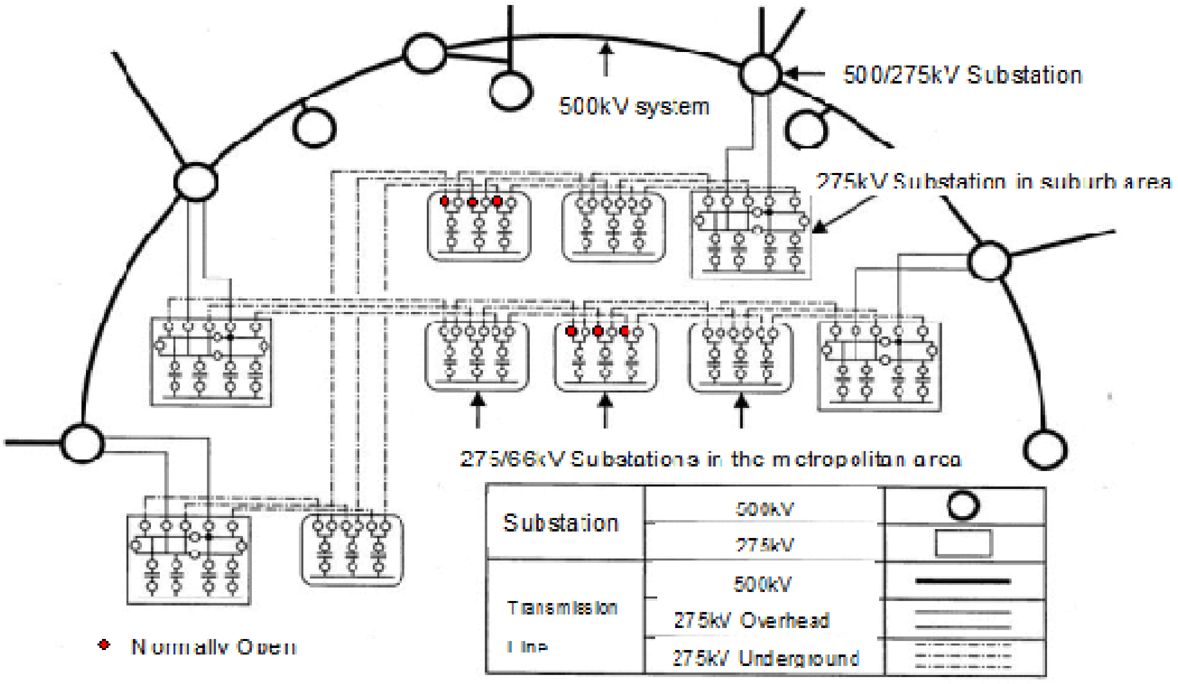
	• delay of fault clearing which results in multiple step out of generators
• Flooding	Malfunction of multiple substations will causes prolonged and wide area outage.

(2) Countermeasures

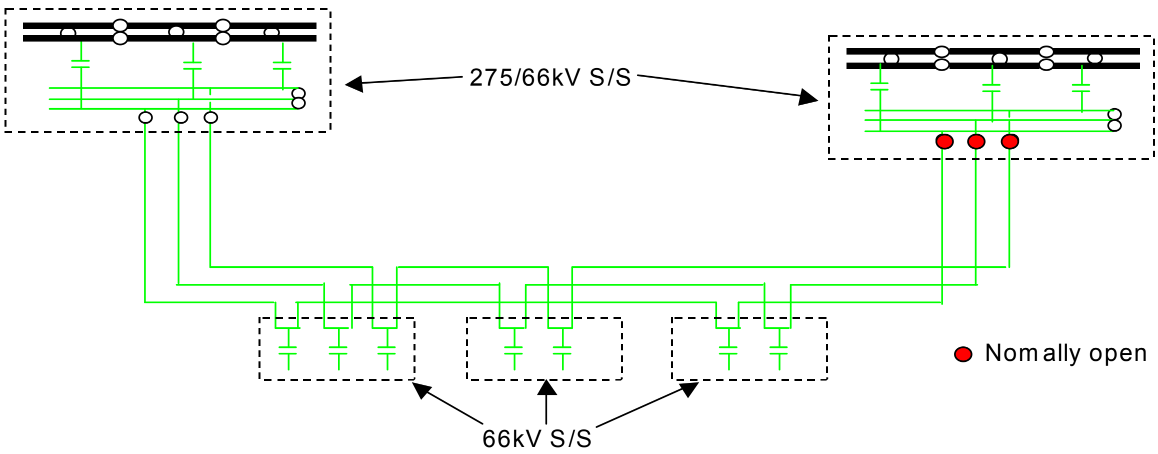
Mitigation	Hybrid	Adaptation
<Power stations> • Strengthening of the structures **<Transmission lines>** • Reinforce tower structures and foundations • Replaced with underground cables **<Substations>** • Transform into indoor types • Installation of GIS • Installation of insulator washing equipment • Installation of bund wall, especially for those substations with a high risk of flooding. • Transform into double-ended substation (*)	**<Strengthening of support system>** • Emergency restoration system (ESR) **<Substations>** • Installation of flooding alarm system, especially for those substations with a high risk of flooding.	**<Strengthening of support system>** • Incorporate additional manpower into typhoon response teams • Yearly updated typhoon contingency plan • Declaration of emergent status or release risk alarming **<Inspection/testing and maintenance>** • Special assets inspection before typhoon arrives in order to find and eliminate potential external damage sources against OHL and cables, such as diggers, big trees, billboards, and greenhouse made of plastic film, etc. • Regularly carry out routine inspection and maintenance before rainfall season • The stations located on low-lying areas should work out an emergency package **<Stock of spare materials/parts>** • Stores of materials or parts for prompt restoration of damaged facilities. **<Operational action>** • Change of power system configuration **<Periodic drill for rapid restoration>** • Periodic drill for setting up the ESR to speed up the restoration of overhead lines under contingency

(*) Example of a double-ended substation (TE)

System configuration in the metropolitan area



66kV underground cable system in the metropolitan area



Lightning strike

(1) Risk scenarios that lead to a severe outage

Likely events	**Scenarios**
● Multiple strokes	Multiple strokes will cause; ● reduction of power quality (interruptions, voltage dip) ● circuit breaker failures, resulting in expansion of outage area.

(2) Countermeasures

Mitigation	**Hybrid**	**Adaptation**
<Transmission lines> ● Installation of Surge arresters or line arresters ● Replaced with	**<Transmission lines>** ● Installation of intelligent switches to minimize supply interruption	**<Inspection/testing and maintenance>** ● Testing OHL insulators to avoid zero insulation

underground cables **<Substations>** ● Installation of lightning arresters ● Transform into double-ended substation	duration ● Application of high-speed and/or multi-phase reclosing scheme **<Substations>** ● Application of Circuit Breaker Failure (CBF) Protection Scheme **<Strengthening of support system>** ● Implement lightning strike tracking and locating system	resistance ● Testing grounding resistances to verify good connection **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities. **<Operational action>** ● Carry out special operation strategy of OHL during lightning season (15 Mar. – 15 Oct.)

Flooding

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
● Malfunction of multiple substations	Malfunction of multiple substations in flood prone areas will causes prolonged and wide area outage.
● Malfunction or tripping of multiple power stations	Malfunction or tripping of multiple power stations which results in significant/prolonged deficiency of power supply and; ● Load shedding by UFR ● rolling blackout
● Malfunction of the load dispatching office	Malfunction of the load dispatching office due to loss of power source causes wide-area outage

(2) Countermeasures

Mitigation	Hybrid	Adaptation
<Risk assessment> ● Study of the possible impact on transmission and distribution equipment for a flooding level of +5.0mCD under extreme weather conditions. (HEC) ● Equipment shall be set above the highest recorded flood level **<Strengthening of anti-flooding measures>** ● flood gates, bund wall ● sealing of cable inlets ● sump pumps ● relocation to elevated ground	**<Strengthening of anti-flooding measures>** ● flood alarms **<Inspection/testing maintenance>** ● Implemented flood calculator for flooding assessments	**<Strengthening of support system>** ● Emergency response plan **<Inspection/testing maintenance>** ● Routine inspection and maintenance before rainfall season. **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities.

Tornado

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
● Tower collapse ● Wire breakage ● Short circuit ● External touching (kites, unfixed bill board, etc.)	Multiple tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines.
● Overhead ground wires breakage	Malfunction of the protection system will induce; ● wide area outage with remote backup protection ● delay of fault clearing which results in multiple step out of generators

(2) Countermeasures

Mitigation	Adaptation
<Transmission lines> ● Replaced with underground cables **<Substations>** ● Transform into double-ended substation	**<Strengthening of support system>** ● Request the interconnection parties for emergency support **<Operational action>** ● A change of power system configuration ● Utilization of our Spinning Reserve and available hot standby generator units **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities

Blizzard/Ice-storm

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
● tower collapse ● wire breakage	Multiple tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines.
● galloping ● sleet jump	These disturbances will induce the malfunction of protection relaying system for transmission lines and wide-area outage

(2) Countermeasures

Mitigation	Adaptation
<Transmission lines> ● Underground installations ● Spacers between each phase lines ● Snow resistant rings to OHL[(*)] ● Melt ice device or mobile melt ice car **<Substations>** ● Transform into double-ended substation	**<Strengthening of support system>** ● Request the interconnection parties for emergency support **<Operational actions>** ● Utilization of our Spinning Reserve and available hot standby generator units ● Take remedial actions to stabilize the

	system ● A change of power system configuration **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities **<Inspection/testing maintenance>** ● Regularly carry out routine inspection and maintenance before winter season

(*) Tolerant design against snow storm for transmission facilities (TE)

Snow resistant ring

Drought/Heat Wave

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
● Over load or burned out of network facilities (transmission lines, transformers)	Multiple tripping of transmission lines or transformers will cause overload of other lines which results in cascading
● Significant deficiency of power source	Demand rise days and nights may cause significant deficiency of power supply by multiple tripping of generators infeed lines.
● Voltage instability	The Voltage of local area grid is lacking which caused to voltage instability

(2) Countermeasures

Mitigation	Adaptation
<Risk assessment> ● Comprehensive review is conducted to ensure the performance of the equipment would not be affected under extreme weather. **<Substations>** ● Installation of adequate reactive power compensation capacity	**<Strengthening of support system>** ● There are reservoirs for storing water in our Lamma Power Station. (HEC) **<Operational actions>** ● A change of power system configuration ● Implement radiation configuration. ● Preparation for the rolling outage plan **<Inspection/testing and maintenance>** ● Monitoring of the soil temperature of the major transmission cable corridors. ● Infrared Ray (IR) inspection for

	over-loaded facilities/parts ● Sag inspection for over-loaded OHLs.

Windy Weather

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
● external damages	External damages to the overhead lines by kites and unfixed bill boards tripping of the HV OHLs will cause interruption. (SG)

(2) Countermeasures

Mitigation	Adaptation
	<Inspection/testing and maintenance> ● Shorten inspection period of high-voltage OHLs and cables from 1 month to 1 week by setting up local cooperation mechanism (SG)

4.3.3.2 Natural disaster

Totally, probability of severe outage caused by the natural disaster is considered to be lower. (Earthquake is scored “medium”, but this may be influenced by the hazardous result of the east Japan earthquake in 2011.)

On the other hand, the impact of many of disturbances in this category is considered to be very high on the power supply.

Tsunami, which may wipe out the many facilities including power stations along the coast, causes significant and prolonged deficiency of power source. In addition, tsunami destroyed power supply system to the house-load of the nuclear power stations, which resulted in the core meltdown, when the East Japan Earthquake occurred in 2011.

Big eruption of volcanos located very close to the mega cities may cause dielectric breakdown at many open air sites. If big eruption occurs at Mt. Fuji in Japan, not only electricity supply but also many civic functions of Tokyo metropolitan area will be hamstrung.

Geomagnetic storm, which caused wide area outage in the past due to the induced over current in the electric facilities in Canada, should be paid attention. Especially influence of the storm caused by the Super-flare should be carefully considered.

Probability / Impact	Unknown (1)	Low (2)	Medium (3)	High (4)
Very High (4)		Tsunami Tidal wave Volcanic eruption Geomagnetic storm	Earthquake	
High (3)				
Moderate (2)		Landslide Avalanche		
Low (1)		Forest fire Wildlife Tree contact		

Earthquake

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Multiple destructions or tripping	Multiple destructions or tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines. Multiple destructions or tripping of power stations causes; ● load shedding by UFR

	● rolling blackout
Mega-quake directly below a populated area	Mega-quake directly below a populated area will causes devastating destructions of facilities, especially power stations and bulk power system which result in prolonged outage and rolling blackout
Malfunction of the load dispatching office	Malfunction of the load dispatching office due to destruction of building or computer system causes wide-area outage

(2) Countermeasures

Mitigation	Adaptation
<Power stations> ● Being connected in different voltage class grid **<Transmission lines>** ● Strategically replace transmission overhead line with underground cable **<Substations>** ● Transform into double-ended substation ● Transform into indoor types ● Installation of GIS **<Comprehensive Network design>** ● Reinforcement of the seismic design. ● The size of stations on the earthquake-prone area should not be too large	**<Strengthening of support system>** ● Request the interconnection parties for emergency support ● Black start procedure was prepared with periodic drill on the procedure to improve the response under the black-out scenario ● Preparation for the rolling outage plan **<Operational actions>** ● Utilization of our Spinning Reserve and available hot standby generator units ● Take remedial actions to stabilize the system ● A change of power system configuration **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities

Tsunami/Tidal wave

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Malfunction, multiple destruction or tripping caused by long and high destructive wave	Malfunction or tripping of multiple power stations results in significant/prolonged deficiency of power supply and; ● Load shedding by UFR ● rolling blackout Multiple tower collapse or tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines.

(2) Countermeasures

Mitigation	Hybrid	Adaptation
<Risk assessment> ● Study of the possible impact on transmission and distribution equipment for a flooding level of	**<Strengthening of anti-flooding measures>** ● flood alarms	**<Strengthening of support system>** ● Request the interconnection parties for emergency support ● Preparation for the

+5.0mCD under extreme weather conditions. (HEC) ● Equipment shall be set above the highest recorded flood level **<Strengthening of anti-flooding measures>** ● flood gates, bund wall ● sealing of cable inlets ● sump pumps ● relocation to elevated ground		rolling outage plan **<Operational actions>** ● Utilization of our Spinning Reserve and available hot standby generator units ● Take remedial actions to stabilize the system ● A change of power system configuration **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities

Volcanic eruption

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Multiple tripping due to dielectric breakdown caused by large quantity of ash falling in wide area	Multiple tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines. Multiple tripping of power stations causes; ● load shedding by UFR ● rolling blackout

(2) Countermeasures

Mitigation	Adaptation
<Transmission lines> ● Underground installations **<Substation>** ● Transform into double-ended substation	**<Strengthening of support system>** ● Preparation for the rolling outage plan **<Operational actions>** ● A change of power system configuration **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities

Landslide/Avalanche

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Multiple tower collapse or tripping of transmission lines	Multiple tower collapse or tripping of transmission lines cause; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines which results in;

	- Load shedding by UFR - rolling blackout

(2) Countermeasures

Mitigation	Adaptation
<Transmission lines (Stability of slope)> ● Slope improvement ● Hillside cultivation activities ● Underground installations ● Appropriate right-of-way selection **<Substations>** ● Transform into double-ended substation **<Comprehensive network design>** ● Periodic network security review and reinforcement of network, if necessary.	**<Strengthening of support system>** ● Emergency Restoration System for prompt restoration of damaged OHL tower ● Comprehensive crisis management plan has been prepared and periodic drills are arranged **<Operational actions>** ● A change of power system configuration if landslide or avalanche occurs ● Take remedial actions to stabilize the system ● Use of mobile generators ● Arrange temporary supply from adjacent supply sources **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities.

Forest fire

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Line tripping or breakage	Line tripping or breakage causes; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines which results in; - Load shedding by UFR - rolling blackout

(2) Countermeasures

Mitigation	Adaptation
<Transmission lines> ● Cutting down of the plant or removal of objects ● Underground installations **<Substations>** ● Transform into double-ended substation ● Reformation into Indoor type or GIS	**<Operational actions>** ● A change of power system configuration ● Proactively switch out transmission overhead lines if there is a fire case reported from Fire Service Department. **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities. **<Inspection/testing and maintenance>** ● Enhance patrol of transmission lines in high level forest fire warning area

Wildlife/Tree contact

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Flashover	Flashover causes; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines which results in; - Load shedding by UFR - rolling blackout

(2) Countermeasures

Mitigation	Hybrid	Adaptation
<Transmission lines> ● Vegetation management (trimming the trees or removal of objects) and patrols ● Installation of wild-life anti-climb guard protection device ● Underground installations **<Substations>** ● Transform into double-ended substation ● Reformation into Indoor type or GIS	**<Transmission lines>** ● Install intelligent switches in overhead line system to minimize supply interruption duration	**<Operational actions>** ● A change of power system configuration ● Proactively switch out transmission overhead lines if there is a report for wildlife/tree contact. **<Stock of spare materials/parts>** ● Stores of materials or parts for prompt restoration of damaged facilities. **<Inspection/testing and maintenance>** ● Enhance patrol of transmission lines

Geomagnetic storm

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Over current induced by electromagnetic induction	Over current induced by electromagnetic induction causes; ● overload of transformers which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines which results in; - Load shedding by UFR - rolling blackout

(2) Countermeasures

Mitigation	Adaptation
<Substations> ● Transform into double-ended substation	**<Strengthening of support system>** ● Request the interconnection parties for emergency support **<Operational actions>** ● Utilization of Spinning Reserve and available hot standby generator units

	- Take remedial actions to stabilize the system - A change of power system configuration **<Stock of spare materials/parts>** - Stores of materials or parts for prompt restoration of damaged facilities

4.3.3.3 Trouble at Facilities

In this category, the “Intentional destruction” should be closely watched from the viewpoint of “low probability high impact” incident because the “cyber terrorism” is now called “the war in the fifth domain” and is drastically growing into a threat to the stable power system operation.
Therefore, from the viewpoint of the “resilience”, countermeasures against the cyber attack should be taken as rapidly as possible.

Impact \ Probability	Unknown (1)	Low (2)	Medium (3)	High (4)
Very High (4)	Intentional destruction	Explosion Fire		
High (3)				
Moderate (2)		Aging Defects		
Low (1)		Accidental destruction		

Aging

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Equipment failure	Equipment failures, especially sudden shut off the large capacity power stations, HV transformers cause wide-area interruption.
Bankruptcy/Withdrawal of manufacturer/constructor	Inability to periodic replacement due to bankruptcy/withdrawal of manufacturer / constructor

(2) Countermeasures

Mitigation	Hybrid	Adaptation
<Replacement/maintenance> ● Strategic Refurbishment/replacement	**<Strengthening of support system>** ● Adopt condition monitoring for specific assets to detect incipient [beginning to happen] fault	**<Strengthening of support system>** ● Preparation for rolling outage plan **<Operational action>** ● N-1 contingency is applied ● Awareness of coordinated remedial actions in case of security violations, in order to avoid the deterioration of the operational conditions

		towards emergency ● A change of power system configuration **<Inspection/testing and maintenance>** ● Early inspection ● Apply condition monitoring tests ● Maintenance/retrofit to extend their service lives **<Stock of spare materials/parts>** ● Adequate contingency spare for prompt restoration of faulty equipment

Defects

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Malfunction or miss-function of equipment	Malfunction or miss-function of equipment, especially large capacity power stations, HV transformers cause a sudden damage and then a wide-area interruption
Deterioration of the products or skills	Deterioration of the products or skills due to a drastic shift in the management policy of manufacture / constructor

(2) Countermeasures

Mitigation	Adaptation
<Replacement/maintenance> Strategic replacement or repair of the same model/type equipment	**<Operational actions>** ● N-1 contingency is applied ● Awareness of coordinated remedial actions in case of security violations, in order to avoid the deterioration of the operational conditions towards emergency ● A change of power system configuration ● Preparation for rolling outage plan **<Inspection/testing and maintenance>** ● Operational test ● Comprehensive network reliability and operation review will be carried out every 3 years to review the failure cases in the period to improve the asset performance ● Condition monitoring tests, such as; ➢ Dissolved Gas Analysis (DGA) ➢ Partial Discharge (PD) of bushings ● Shorten inspection and test period when slight defects found (C_2H_2 slightly rises) ● Apply strict standards in commissioning tests and routine

	periodic tests ● Early inspection **<Stock of spare materials/parts>** ● Adequate contingency spare for prompt restoration of faulty equipment

Explosion/Fire

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Multiple tripping of transmission lines	Multiple tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines.
Multiple tripping of power stations	Multiple tripping of power stations causes; ● load shedding by UFR ● rolling blackout
Explosion of high voltage transformers	Explosion of high voltage transformers extent to forced outages of almost substation that results in blackout for a long period.
The fire in the culvert (utility-tunnel) for power cables	The fire in the culvert (utility-tunnel) for power cables causes damages and trips that result in the wide-area and prolonged outage in the metropolitan area.
Huge fire or oil-spill disaster	Huge fire or oil-spill disaster extends to forced outages of almost all thermal power stations, which results in the load shedding by UFR or prolonged rolling blackout for a long period.

(2) Countermeasures

Mitigation	Hybrid	Adaptation
<Transmission lines> ● Using the fire retardant material cable ● Adoption of oil free transmission and distribution equipment, such as XLPE cable, GIS and GIT, to reduce the fire risk	**<Substations>** ● Fire alarm/fighting systems are installed in substations **<Control center>** ● Fire alarm connected to EMS to alert System Control Engineers for preventive actions	**<Strengthening of support system>** ● Request the interconnection parties for emergency support **<Operational actions>** ● Utilization of Spinning Reserve and available hot standby generator units ● Take remedial actions to stabilize the system ● A change of power system configuration **<Inspection/testing and maintenance>** ● Periodic inspection of transmission facilities to prevent the accumulation of explosive gas inside the

		cable shaft/chamber ● Early inspection **<Stock of spare materials/parts>** ● Adequate contingency spare for prompt restoration of faulty equipment

Accidental destruction

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Third party damages	Third party damages, especially; ➢ Diggers ➢ other heavy construction machines will cause; ➢ damage multiple our underground cables / overhead lines. ➢ malfunction or miss-function of equipment

(2) Countermeasures

Mitigation	Adaptation
<Transmission lines> ● Plans for cables instead of OHL **<Substations>** ● Adoption of Indoor type. ●	**<Inspection/testing and maintenance>** ● Regular construction site inspections **<Information sharing>** ● safety talks to road work contractors ● keeping construction company informed the route of underground cable and responsible for the external damage ● A change of power system configuration **<Operational actions>** ● N-1 contingency is applied ● Awareness of coordinated remedial actions in case of security violations, in order to avoid the deterioration of the operational conditions towards emergency **<Stock of spare materials/parts>** Adequate contingency spare for prompt restoration of faulty equipment

Intentional destruction (Conflict/Terrorism/Cyber-attack)

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
● Physical destructions of critical facilities ● Cyber-attack, illegal access, virus infection to the operation control system	Multiple tripping of transmission lines induce; ● overload of other lines which results in cascading ● significant deficiency of power supply by multiple tripping of generators infeed lines.

	Multiple tripping of power stations causes; ● load shedding by UFR ● rolling blackout

(2) Countermeasures

Mitigation	Hybrid	Adaptation
	<Countermeasures for physical attack> ● Monitoring/Surveillance system ● An authentication system **<Countermeasures for cyber-attack>** ● Dedicated telecommunication network **<Strengthening of support system>** ● Raise cyber security awareness of SCE ● Local security system are installed for S/S monitoring	**<Strengthening of support system>** ● Physical security for critical cyber assets ● Request the interconnection parties for emergency support **<Operational actions>** ● Utilization of Spinning Reserve and available hot standby generator units ● Take remedial actions to stabilize the system ● A change of power system configuration ● Conduct drills to prepare for contingencies **<Stock of spare materials/parts>** Adequate contingency spares for prompt restoration of damaged or faulty equipment **<Others>** ● Requirement of strengthening of punishment and regulations on criminals ● Ensuring confidentiality of facilities

4.3.3.4 Operational Inaccuracy or others

"Operational Inaccuracy" which results in a wide area outage is a forbidden incident because we, power system engineers, make continuous effort to eradicate such troubles and take measures for them. Therefore, it is a matter of course that the probability is considered to be lower.

On the other hand, the impact may be higher because a miss-demand forecasting, a malfunction of supply-demand control or a frequency control will immediately result in the cascading and wide area outages.

Especially, exponential increase of renewable energy power sources such as photovoltaic or wind power should be carefully watched because they will definitely affect the predictability of the power system operators.

In addition, Pandemic is identified as future possible risk to be prepared from the viewpoint of BCP (Business Continuity Plan).

Impact \ Probability	Unknown (1)	Low (2)	Medium (3)	High (4)
Very High (4)		Deficiency of gen.		
High (3)	Pandemic	Voltage control		
Moderate (2)		Demand forecast Balancing Miss operation		
Low (1)				

Demand forecasting

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Increase of distributed (embedded) PV or Wind power source	An inaccuracy of whole power system demand forecast will causes considerable deviation or collapse of frequency that results in; ● load shedding by UFR ● rolling blackout

(2) Countermeasures

Mitigation	Hybrid	Adaptation
	<Substations> ● Load shedding scheme with under-frequency relay is applied and regularly reviewed and optimized to minimize	**<Operational actions>** ● Sufficiency in generation capacity is closely monitored. ● Improvement of demand forecast accuracy

	impacts in cases of generation loss	● Securing adequate reserve by bilateral contract or market trade ● Request the interconnection partner to provide its share of spinning reserve or provide emergency support ● Preparation for performing rolling blackout

Deficiency of power source

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Blockade of the transportation route of fuel (LNG)	Deficiency of power source will leads to supply-demand imbalance which causes considerable deviation or collapse of frequency that results in; ● load shedding by UFR ● rolling blackout

(2) Countermeasures

Mitigation	Hybrid	Adaptation
	<Substations> ● Load shedding scheme with under-frequency relay is applied and regularly reviewed and optimized to minimize impacts in cases of generation loss	**<Operational actions>** ● Sufficiency in generation capacity is closely monitored. ● Improvement of demand forecast accuracy ● Securing adequate reserve by bilateral contract or market trade ● Request the interconnection partner to provide its share of spinning reserve or provide emergency support ● Preparation for performing rolling blackout

Supply-demand control/Deficiency of reserves

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Supply-demand imbalance caused by increase of PV and Wind power source, for example.	Supply-demand imbalance which causes considerable deviation or collapse of frequency that results in; ● load shedding by UFR ● rolling blackout

(2) Countermeasures

Mitigation	Hybrid	Adaptation
<Power Stations> ● Installation of adjustable speed Pumped storage	**<Substations>** ● Load shedding scheme with under-frequency	**<Operational actions>** ● Sufficiency in reserves is closely monitored.

hydropower (*)	relay is applied and regularly reviewed and optimized to minimize impacts in cases of generation loss	● Improvement of demand forecast accuracy ● Securing adequate reserve by bilateral contract or market trade ● Request the interconnection partner to provide its share of spinning reserve ● Startup the hot standby units to recover the reserve ● Preparation for performing rolling blackout

(*) Adjustable speed Pumped storage hydropower (AS-PSHP)

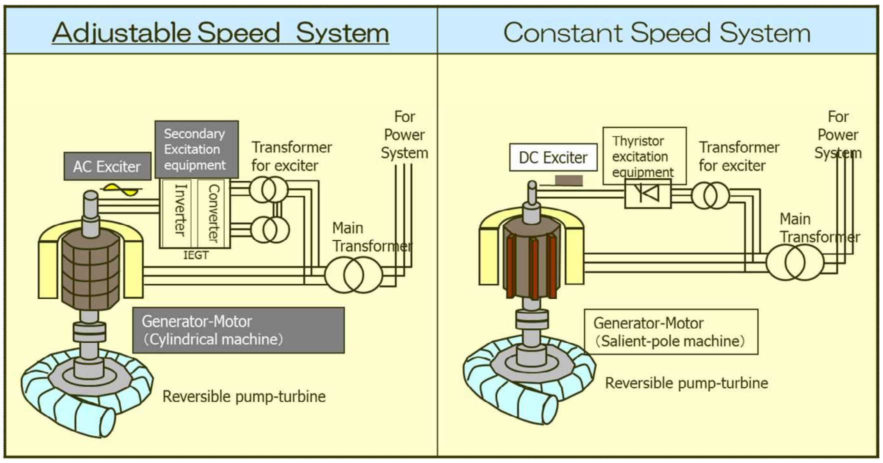


Figure 4-45

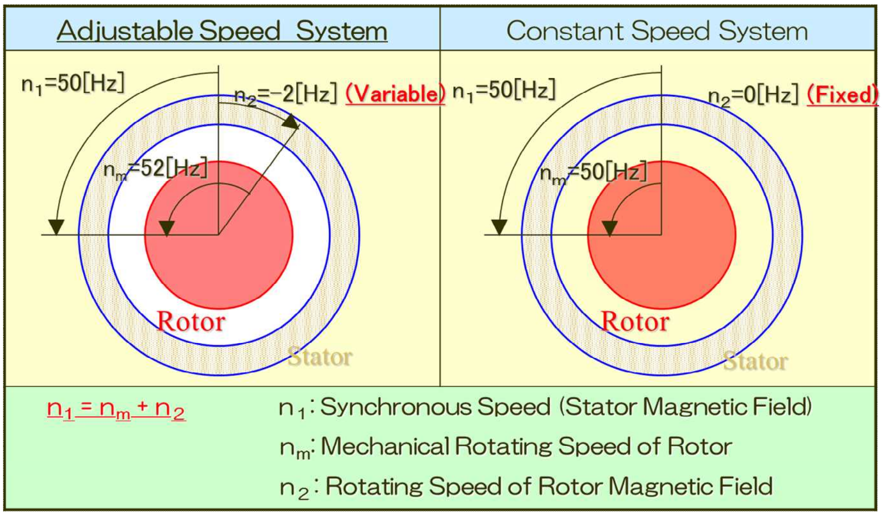


Figure 4-46

Figure 4-45 and Figure 4-46 illustrates the difference between AS-PSHP and conventional PSHP. Rotor of AS-PSHP is excited by AC current with variable frequency within ±2Hz, while the rotor of conventional PSHP is excited by DC current.

Therefore, the rotor speed of AS-PSHP can be variable, while that of the conventional PSHP must be fixed to the rated speed.

With these characteristics, AS-PSHP has following advantages over the conventional one.

- Input power for pumping up water can be changeable without constraints of power system frequency.
- On generating mode, rotating speed of hydraulic turbine can be adjust so as to generate with the highest efficiency. 5-10% improvement of efficiency can be expected.

Voltage-reactive power control management

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
Deficiency of reactive power reserves	Deficiency of reactive power reserves will lead to; ● the collapse of voltage ● power swing (step out) of generators ● operation of the under-voltage /over-voltage protection that results in blackout.

(2) Countermeasures

Mitigation	Hybrid	Adaptation
<Substations> ● Improve the planning rule of reactive power	**<Power stations>** ● Install Power System Stabilizers (PSS) ● Installation of Power System Voltage Regulators (PSVR) **<Substations>** ● Implement AVC to enhance online operation (*) ● Installation of VMS(**), shunt type FACTS devices(***) ● Installation of VQC (Voltage-Q(var) Controller)	**<Operational actions>** ● Sufficiency in reactive power capacity is closely monitored. ● Take remedial actions to alleviate the impacts, e.g. switching in/out shunt reactors or capacitor banks. ● Preparation for performing rolling blackout ● High voltage profile operation

(*) AVC (automatic voltage controller) (SG)

Unman substation and central supervision scheme was implemented in SMEPC 3 years ago. To accommodate with this change, AVC system is a must since hundreds of reactive power devices need to be operated for voltage control.

Another advantage brought by AVC is minimizing the power loss by controlling the power factor. The optimization algorithm is provided by the following picture and table.

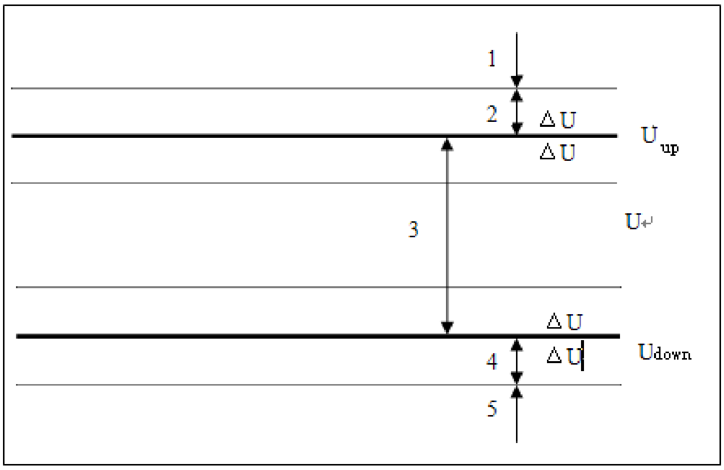
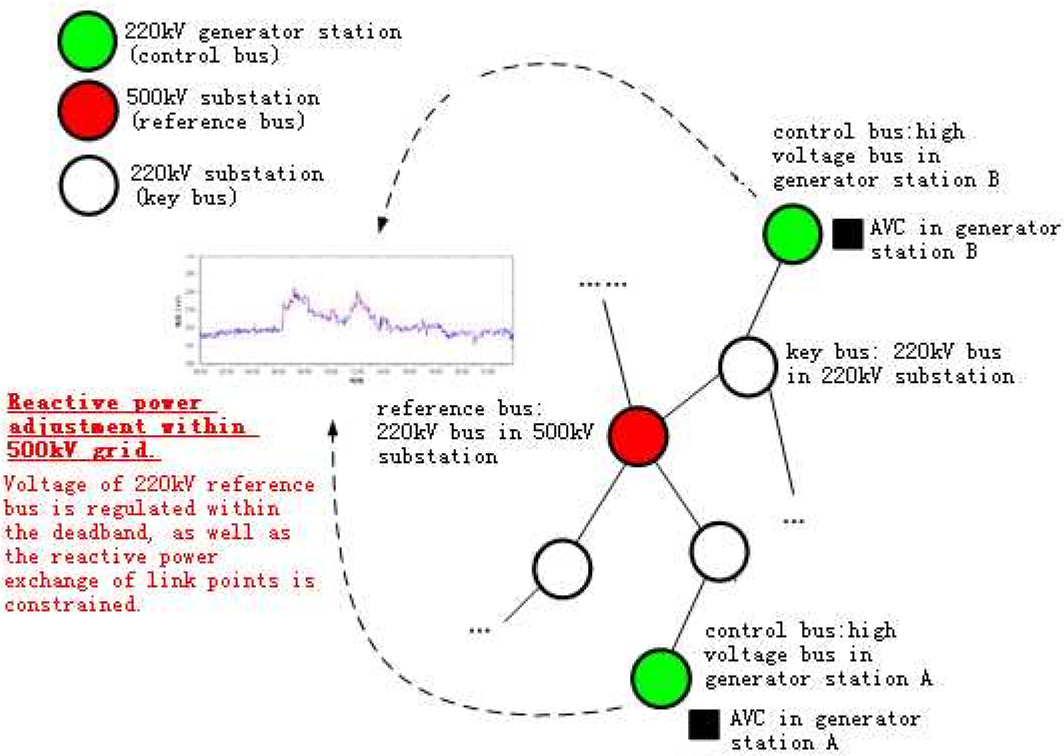


Table 4-4 Optimization algorithm for AVC to control reactive power devices

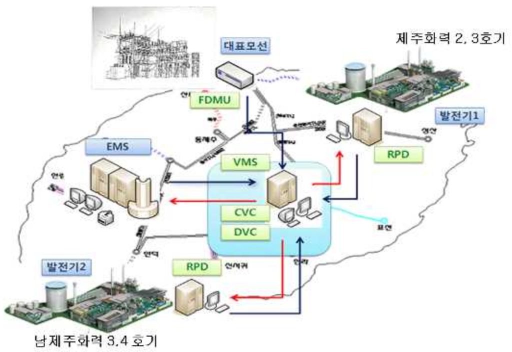
Type	Range of the Voltage	Controlling of Power Factor	Measures	Control target
1	U＞Uup＋ΔU	Not considered	switch off the capacitors, switch on the reactors	U≤Uup+ΔU
2	Uup＋ΔU ≥ U ＞ Uup	Cosϕ ＜Cosϕ up	Cosϕ < Cosϕ up no action, Cosϕ >Cosϕ up switch off the capacitors, switch on the reactors	Cosϕ ＜Cosϕ up
3	Uup ≥ U ≥ Udown	Cosϕ down≤Cosϕ ≤ Cosϕ up	switch off or switch on the capacitors	Cosϕ down≤Cosϕ ≤ Cosϕ up
4	Udown－ΔU ≤U＜ Udown	Cosϕ ＞Cosϕ down No maxium, allow little inverse transmission	Cosϕ >Cosϕ down, no action, Cosϕ <Cosϕ down, switcht off the reactors. switch on the capacitors	Cosϕ ＞Cosϕ down
5	U＜Udown－ΔU	Not considered	switch off the reactors. Switch on the capacitors	U≥Udown- ΔU

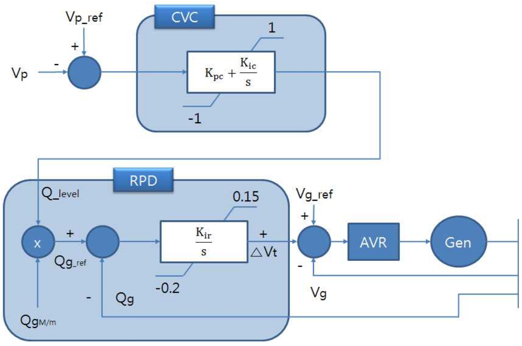
Both the reactive power output of generator and the substation reactive power equipment are used by AVC to regulate voltage profile. A comprehensive optimization method should address both by using sensitivity data from online simulation. Furthermore, AVC for different grids categorized by voltage level shall be coordinated to minimize the switching number and reactive power exchange among the link points.



(**) Voltage Management System (VMS) (KEPCO)

- KEPCO proposes the enhanced voltage management system (VMS) which is a coordinate voltage control system between the hierarchical voltage control system and the slow voltage control system. It is installed on Jeju Island. VMS consists of a master controller, Continuous Voltage Controller (CVC) and Discrete Voltage Controller (DVC). The CVC consists of a main controller, Field Data Measurement Unit (FDMU) and several Reactive Power Dispatchers (RPDs). The CVC has a control scheme with AVRs of the generator to maintain the voltage of a pilot bus in a power system. The DVC has a control scheme with static reactive power sources, like a shunt capacitor, a shunt reactor, ULTC and so on, to maintain the reactive power reserve of a power system and a master controller is executed to recover the reactive power margin of a power system through coordinated control between CVC and DVC.





(***) Multi-FACTS Cooperative System (MFCS) (KEPCO)

- The on-line system schemes for a coordinated control system of multiple FACTS were introduced to enhance the voltage stability around the metropolitan areas. In order to coordinate the control system of FACTS devices, the MFC on-line system calculates the optimal set points (Vref, Qrev) of FACTS devices using the coordinated control algorithm with real time network data which is transferred from SCADA/EMS system. If the system is unstable after contingencies, the new operation set-points of FACTS are determined using bus sensitivity from tangent vector at the voltage instability point. According to the test results, MFC(Multi-FACTS Coordinated control) on-line system was installed in Korea power system

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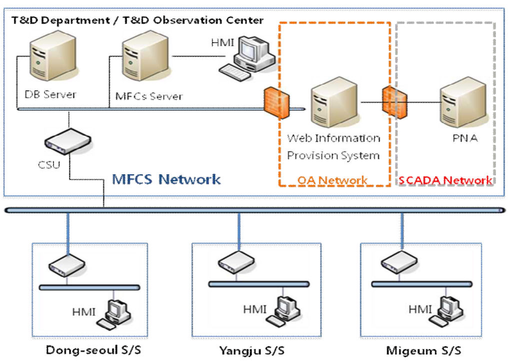
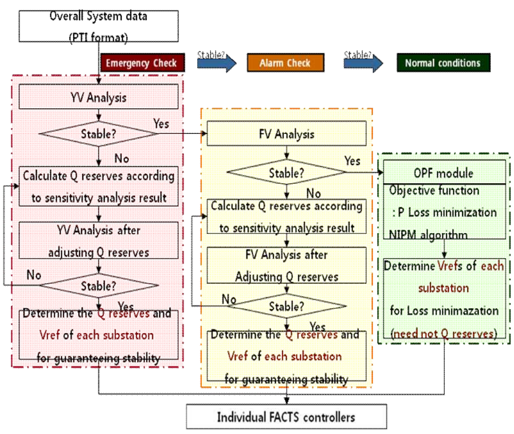


MFCS Network Map



Miss-operation/Malfunction of facilities, control systems, relays, etc.

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
DC block induced by some severe faults in AC transmission lines	DC block induced by some severe faults in AC transmission lines will cause a sudden loss of power supply through DC lines which will leads to; ● overload of other AC lines which results in cascading ● significant deficiency of power supply
Incomplete update / bug of program or data in dispatching control system	Miss-operation or control induced by incomplete update / bug of program or data in dispatching control system causes wide-area interruption.

(2) Countermeasures

Mitigation	Hybrid	Adaptation
	<Protection & Control System> ● Duplication of system/circuit ● Automatic self-testing/monitoring scheme ● High speed CBF (Circuit Breaker Failure) protection scheme ● Other SPS (Special protection scheme) to prevent cascading out-of-step of generators.	**<Inspection/testing and maintenance>** ● Regular inspection, maintenance and refurbishment ● Maintenance of the asset is under an accredited asset management system complying ISO 55001 ● Comprehensive network reliability and operation review will be carried out every 3 years to study past failure cases in the period to derive means to improve asset performance ● Revisit setting of relay regularly ● Testing relay function strictly **<Operational actions>** ● Take remedial actions to alleviate the impacts. ● Making contingency plan considering relay failure or DC block

Pandemic

(1) Risk scenarios that lead to a severe outage

Likely events	Scenarios
➢ Avian Influenza / new strain flu virus ➢ Middle East Respiratory Syndrome ➢ Ebola Virus Disease	Wide spread of ; ➢ Avian Influenza / new strain flu virus ➢ Middle East Respiratory Syndrome

	➢ Ebola Virus Disease may significantly affects performance of control center.

(2) Countermeasures

Mitigation	Hybrid	Adaptation
	<Vaccination / Hygiene management> ● Safety guidelines for the handling and disposing of carcasses of dead birds or animals was established ● Influenza vaccination for employees ● Maintain personal and environmental hygiene	**<Strengthening of support system>** ● A reporting procedure for Avian Influenza/Middle East Respiratory Syndrome/Ebola Virus Disease has been formulated ● Influenza Pandemic Contingency Plans for operational and non-operational divisions have been established to deal with different situations. ● Formulation of the BCP (Business Continuity Plan)

4.4 Other Remarkable Measures for Large Scale Outage in Mega Cities

As a result of survey, many of the remarkable measures can be categorized into the hybrid measures.

4.4.1 Mitigation Measures

Expansion of high voltage network	- Planning for main grid: 500kV transmission lines to cover all regions of Thailand's power system to ensure system reliability and system security (EG)
Meshed network	- Construction of loop ring power system (KE)
Double-ended substations	- Double-ended substations (TE)
Redundancy (N-1 or more criteria)	- N-1 contingency criterion is rigorously followed in network design. (CLP) - Higher security standards such as N-1-1 are applied in cases where the loss of supply will expose our customers to significant risks. (CLP) - The N-1 design criterion under regular grid mode is applied to 35kV above substation and transmission line. In addition, considering the load location, the N-1 rule under maintenance mode is applied for the central city. (SG)
Decentralization of power sources	- Enlargement of distributed resources (KE) - Planning with the concept to maintain a balance proportion on the power supply to mega city such as: Bangkok and vicinity area by considering two aspects of system reliability (EG): 1) System reliability on sufficient power plants within mega city area 2) System reliability on enhancing the transmission system capability to transmit electric power from other regions into the mega city area - The proportion of those two aspects shall be approximately 45 % and 55 % respectively.
Standardization	- State Grid Corporation of China (SGCC, the mother company of Shanghai Electrical Power Company) has issued standardized transmission and distribution designs which include typical substations layouts, OHL modules, and forms of cable piping to fit in with the needs of all different provinces and conditions. Based on this standard design, SMEPC will do some minor modification according to local meteorological conditions. (SG)
Grouping/sectionalize the downstream network	- Each 400kV substation and its downstream network are operated as an independent group. The demand of each 400kV group is limited to 100MVA. (CLP) - 220kV network is sectionalized and linked to 500kV grid backbone, which is used to mitigate the short circuit issue and restrict outage area. (SG)

	- Normally 220kV network is operated with several sections, and each of them can be connected to adjacent one under emergent status if short circuit is allowed. (SG)
Mutual backup by interconnectors	- The 400/132kV groups are backed up by 132kV interconnectors with other groups. (CLP) - Similar concept is applied at the MV level (11kV) to provide mutual backup between different load groups. (CLP) - The third transformer is required for 220kV substation. In addition, hand in hand grid configuration for 110kV and dual power supply for 35kV are adopted to avoid load interruption during 220kV grid maintenance. (SG)
Assessment or review of planning	- Regular system stability review (HEC) - Regular review on interconnection issues with neighboring power utilities for maintaining the overall integrity of interconnected system (HEC) - Network reliability reviews of the entire system are regularly carried out based on N-1 and/or more stringent criteria (e.g. switchgear/bus coupler fault) to ensure system security (HEC)

4.4.2 Hybrid Measures

Health monitoring	- Online Condition Monitoring Systems for Transmission Switchgears (CLP)[1)] - Advanced cables or switchgears diagnostic techniques are deployed to identify and replace weak components (e.g. Partial Discharge Monitoring) (HEC)[2)]
Identification system	- Automatic Vessels Identification System (AIS) is used to improve cable damage prevention of the 275kV and 132kV submarine cables East Lamma Channel and Victoria Harbour (HEC)
Remote Inspection	- As a good supplement to helicopter, we apply remotely piloted aircrafts to inspect high voltage OHLs (200kV and above) because there are some 'blind' segments of in civil regulated area when using helicopter. Renting service is provided by aircraft manufacturers at present, and we plan to buy two within this year. (SG) - We have applied remotely controlled robots to do regular inspection job in a 500kV substation and a 1000kV substation. The robots are equipped with cameras to take picture and video of assets, IR to detect temperature of desired parts of assets and diagnose over-heating defects. The additional functions include sound detection function, environmental information detection (temperature, humidity, wind speed, etc.), route optimization, historical data analysis and reporting, etc. We plan to use robots in all HV substations (220kV and above) at the end of 2016. (SG)
Deployment of advanced control scheme	- UPSS (TE)[3)] - ISAS (TE)[4)] - Pilot project of feeder automation (FA) with self-healing features to quickly detect faults, isolate the affected line segments and restore the unaffected segments.(SG) [5)] - Various forms of automatic switching schemes are adopted to speed up outage recovery (CLP, EG): ✧ Auto-Reclose features on overhead lines (transmission & distribution) ✧ Automatic switching scheme at primary substations (for restoration of supply due to the failure of a primary transformer) ✧ Automatic fault detection, isolation and restoration systems are being tested and implemented in our MV OHL networks, - Highly sophisticated and constantly enhanced computer programs are used to automate supply restoration and reduce restoration time (e.g. automatic bus-bar reconfiguration upon 11kV faults via SCADA System / automatic capacitor bank switching/ Automatic Load Restoration (ALR) feature is available for speedy recovery/ DMS Fault Identification Expert System (DIFES) is employed for fault isolation & supply restoration) (HEC)

Operator Training / Training System	- Real Time Simulator for power system operator training - PGS (APGS) (TE) [6)]
Increase Visualization, situational awareness, and controllability	- Development of integrated intelligent precaution module in EMS to improve the observation and decision making capability of system operator (SG)[7)] - Wide-Area Monitoring And Control (WAMAC) (KE)[8)] - Implementation of the 275kV/132kV 3-phase Fault Detection Scheme in SCADA system to uphold HEC system stability (HEC) - Distribution automation provides our system control center with complete visibility and remote control capability of our network (CLP) - Fast 220kV network reconfiguration between adjacent networks and reclosing of the tripping breaker after incident, are through remote breaker operation in control center. Previous 80 minutes duration was required for the switching operation, now it is reduced to 10 minutes. (SG) - Energy Management System (EMS) & Distribution Management System (DMS) are equipped with SCADA functions for remote switching and alarm handling (HEC) - A gigantic scale of SCADA function is implemented in distribution system where all substations are installed with RTUs (HEC) - Dual RTUs are employed in strategic and important substations (HEC)

1) Online Condition Monitoring Systems for Transmission Switchgears (CLP)

Background: Transmission switchgears are critical assets in the network. Real-time asset condition information helps facilitate incipient fault detection, condition-based maintenance and capital investment optimization. Online condition monitoring systems provide real-time asset condition data.

Objective: To install online equipment condition monitoring systems for transmission switchgears to allow real-time monitoring and detection of incipient fault conditions.

Achievement: Online Condition Monitoring Systems are being installed at 10 x 400kV and 35 x 132kV GIS switchboards. These systems carry out both Partial Discharge Monitoring and Switchgear Monitoring. Up to April 2015, 40% of the installation has been completed. Data processing and sampling, and PD identification using Pattern Recognition will be tested.

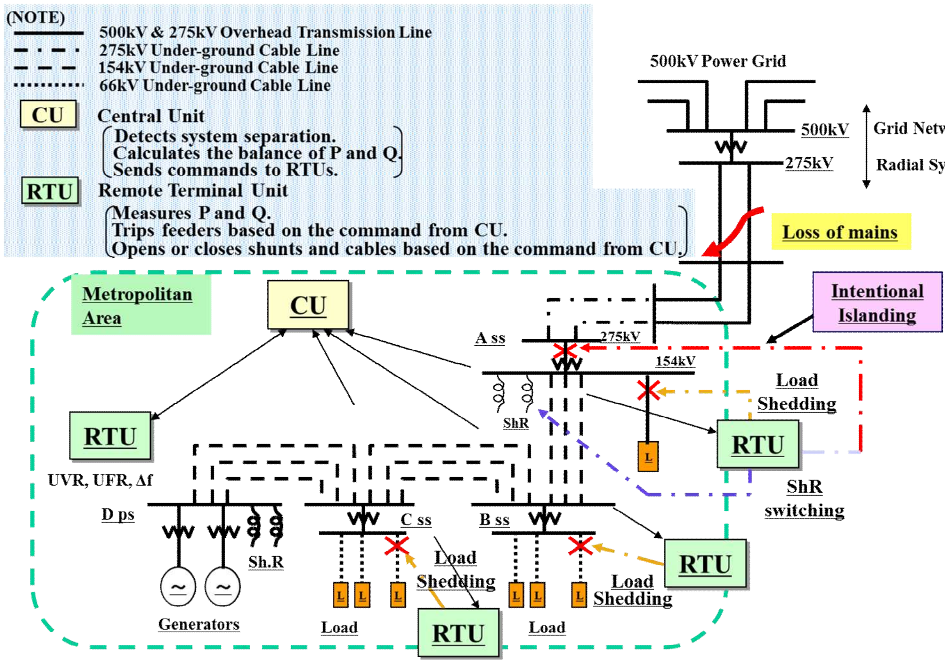
2) Advanced cables or switchgears diagnostic techniques (e.g. Partial Discharge Monitoring) (HEC)

To enhance the reliability of the plants in transmission network, all 275kV and 132kV gas insulated switchgears are monitored by **online partial discharge monitoring systems**. In addition, the conditions of the oil-insulated transmission transformers are monitored by **online dissolved gas analysis or total combustion gas systems**. Trial application of online partial discharge monitoring system was kicked off for gas insulated transformers. As a further step, HK Electric installs the online partial discharge monitoring system progressively to all 11kV switchgears in zone substations.

Very Low Frequency (VLF) Tangent Delta (TD) measurement and partial discharge (PD) mapping have been adopted for diagnostic testing of 11kV distribution cables since 2010 with the aim to assess the cable circuit conditions and pin-point weak components prior to failure. To further enhance the effectiveness in identifying the weak components in a tested cable circuit, VLF monitored withstand testing technique was introduced in November 2013. Based on the diagnostic test results, recommendations were timely made for replacement of identified weak components to enhance the circuit reliability. The distribution cable circuit failure rates have been on a decreasing trend since the introduction of VLF diagnostic testing.

Besides the offline PD cable testing, with the introduction of online partial discharge monitoring systems at zone substations and application of the portable online PD measurement and locating equipment, the condition of the 1st leg 11kV distribution cable (the section closest to the source transformer) as well as the other cable identified with incipient fault can be monitored 24 hours continuously.

3)UPSS (TE)



Purpose

- A severe accident such as loss of double circuit lines could separate an islanded system that contains both generators and load from the main grid.
- If the produce and consumption of active power (P) and reactive power (Q) in the islanded system is not well balanced, the islanded system can't continue stable operation because of abnormal system frequency or voltage.
- The islanding relay performs some operations to keep islanded system stable operation.

Principle

The relay performs following operation to recover the balance of P and Q.

- Generator shedding.

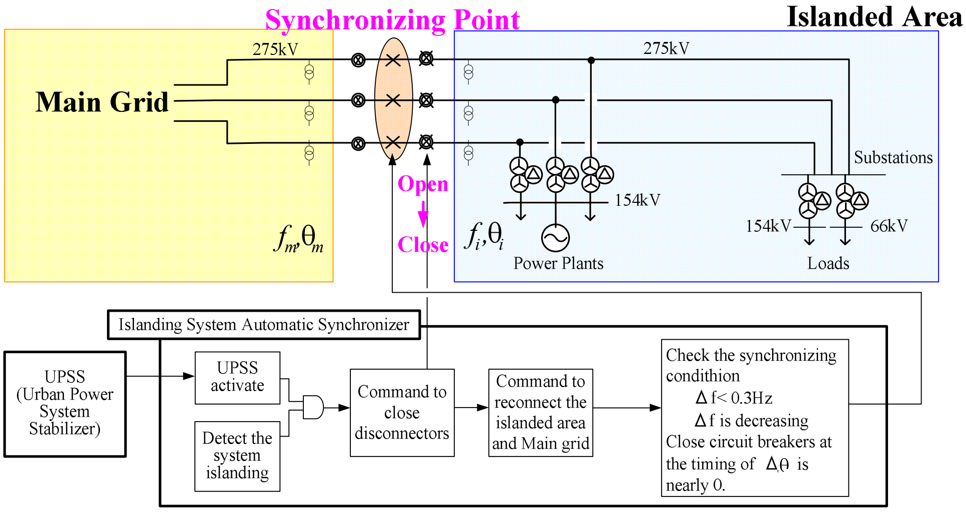
- Load shedding.
- Switch on and off shunt capacitors and reactors.
- Switch off cables that produce big amount of reactive power (Q).

4)ISAS (TE)

Background
UPSS mentioned above is the system to keep providing power to the most important area in Tokyo by islanded system automatically. When the islanded system is built, it has to be reconnected to the main grid as soon as possible. Though we relied on manual operation for system reconnection, it would cause risks for blackout of the islanded system.

Goal
System reconnection is done automatically and rapidly, not manually and slowly.

Study and Achievement
When UPSS activates and islanded system is detected, ISAS starts and commands to close disconnectors and circuit breakers automatically and as quickly as checking the synchronizing condition of frequency.



5)Pilot project of feeder automation (FA) with self-healing features (SG)

Background
Shanghai is a one of the largest cities in China and has been growing to be the most important financial and center. Almost all top 500 global companies have established their factories, Asian headquarters and R&D centers in Shanghai. Therefore, high power supply reliability is required to meet the need of such economic development.

Goal
- Enhance power supply reliability to 99.999% in core urban area of Shanghai
- Automatic operations in fault isolation and restoration to shorten restoration time.

Study and Achievement

- We apply Distribution Automation (DA), especially Feeder Automation (FA) with self-healing features to quickly detect faults, isolate the affected line segments and restore the unaffected segments.
- We have implemented pilot project of Feeder Automation (FA) with self-healing features in CBD area (10km2) of Pudong and planned to achieve 100% penetration for central city area (within inner-ring elevated road, 150km2) by 2018 and the rest of city area (within outer-ring elevated road, 600km2) by 2020.
- With self-healing functions, fault isolation and restoration are all automated (centralized or decentralized) without any manual operation and it will takes no more than 1 minute to restore the un-faulted customers.

6)Real Time Simulator for power system operator training - PGS (TE)

The PGS (Power Grid Simulator), developed by TEPCO's Research and Development Center in 1998, has enabled us to precisely perform the power plow calculation, dynamic analysis or contingency analysis in real time and continuously.
TEPCO adopted the PGS to the training simulator which enables it to generate "current, voltage, system stability, and frequencies," very close to the actual power system phenomena, so as to compute the wide varieties of power system behaviors of the power system on the real time basis.

7)Development of integrated intelligent precaution module in EMS (SG)

Background
After centralizing of substation supervision, traditional system operation business is evolving into a new scheme that equipment supervision is integrated with grid operation in the control center. Data transferred from substation not only serve the needs of grid operation, but also include the alarming signal of primary and secondary equipment, which improve the observation capability of system operator. On the other hand, a large amount of data increases the working pressure of operator and would interfere with the operator's judgment if not properly organized, especially during incident.

The purpose of this study is to visualize the data by different categorization, such as relay data, fault recorder data, PMU data, real time SCADA data, and conduct analysis to submit an incident report. Through this brief report system operator can address the root cause instead of reviewing all the data piece by piece. Then the faster and better decision could be made to restore the outage and load.

Goal
- Friendly visualize the fault data in one interface.
- Integrate the fault data and conduct analysis.
- Make the brief fault report.

Study and Achievement
To achieve the goal, SMEPC started a project to develop a module inside the EMS. Following items are considered within the research and implementation.
- Integrate all the data in one platform

Besides the SCADA, there are several kinds of devices which can capture incident information in the substation, such as relay, PMU, and fault recorder. We developed the common communication protocol to gather all the data, which make it available to access these data in one platform

・ Research on the analysis method

All these data may or may not be related. We need to identify these data and study on the exact information related to the incident. A filter was designed for the analysis purpose.

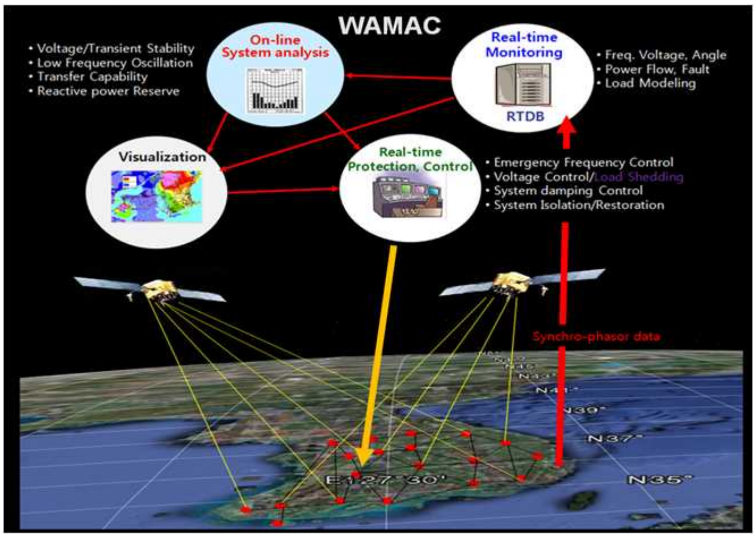
・ Visualize the data in one interface

A brief report regarding the incident, as well as the support information needs to be friendly visualized. System operator can easily confirm the conclusion in one interface.

SMEPC has already applied this new module, which functioned well and did help the system operator quickly focus on the root cause of incident and reduce the restoration time.

8)Wide-Area Monitoring And Control (WAMAC) (KE)

Recent technology advancements related to computer & communication and measuring devices allow system operators to adopt more intelligent monitoring and control systems to their power systems in order to prevent massive system blackout. Among them, the WAMAC system based on synchro-phasor technology has been widely applied to power systems.



4.4.3 Adaptation Measures

Preparation for rapid restoration stabilization plan	- Various supply scenarios with outages of different system elements are considered and contingency plans are devised (HEC) - Establishment and Review of black-start procedure and contingency plans for other high impact network events (CLP, EG) - Yearly reviewing Black-start procedure. Fast speed black-start gas-fired generator is used to restore the grid in 30 minutes. (SG) - Power failure recovery procedures are in place (e.g. black-start procedures) (HEC, KE, TE) - Prioritization of load and establishment of recovering order (e.g. power restoration plan) (HEC, KE, TE, EG) - Setting up of the guidelines for situations, if necessary, to have power off in the area to maintain the system stability and prevent extensive power outage. (EG)
Operator Training / Training System	- Company-wide drills for blackout recovery (e.g. Regular drills on black-start procedures by System Control Engineers) (HEC) - System Operation Training Simulator to train system control staff (CLP)
Continuous cycle of assessment or review	- Daily operation of the system (generation, network configuration and outages) is carefully planned and reviewed to ensure all relevant reliability standards are met. (CLP) - A formal risk management process is adopted to consistently handle probable network risks. (CLP) - Review of maintenance plan for transmission system and power plants in the southern region of Thailand. (EG) - Reviews of operational processes for the entire system are regularly carried out (e.g. contingency plans for transmission forced outage) (HEC)
Spare equipment or parts	- Reviews of spare capacity for the entire system are regularly carried out (HEC) - Universal spare transformers are readily on hand to shorten the restoration time under the power transformer failure scenario (HEC)

4.5 Future Technologies under development

As a result of survey, there are 3 remarkable challenges for future technology, and 2 of 3 can be categorized into the hybrid measures.

Equipment health monitoring

- New Ageing Marker for Power Transformers (CLP)

  Background: Methanol can detect power transformer's insulation ageing earlier than the traditional method. The innovative methodology was developed by Hydro-Quebec in Canada. To better understand the universal applicability of the new methodology and its effectiveness, CLP participated in a joint R&D programme established by International Electric Research Exchange.

  Objective: To investigate the effectiveness of methanol as a new ageing marker for power transformers.

  Achievement: CLP, with utilities and manufacturers from Japan, Mexico, Taiwan and India, are conducting trials since 2012 and sharing the results. The knowledge and experience gained will help detect potential ageing problems and hot spots in transformers earlier than conventional methods. This could increase the efficiency and effectiveness of our equipment health monitoring programme.

Securing Network flexibility (transmission capacity)

- Development and Verification of Superconducting Power Devices (KE)

  Technology overview

  Superconducting power devices are devices made of superconductors, whose electrical resistance disappears at around –180℃. Superconducting cables have a loss rate that is half of that of conventional cables, and a transmission capacity of five times more. Large-capacity transmission is made possible by replacing cables with superconducting cables without building additional tunnels in already-saturated underground areas or adding substations in city centers. Superconducting fault current limiters (SFCLs) are devices that reduce fault current occurring in the power systems to smaller current. They can limit fault current rapidly within 2 milliseconds, have nearly zero impedance, and hence low loss rate.

  Background

  Construction of more power facilities are needed due to increasing power demand, but this is hampered by difficulties in securing land for new transmission lines and in using overly-dense underground space of urban areas. In order to solve this problem, development and grid application of superconducting cables, which enable high efficiency and large-capacity transmission, has been carried out, as a priority projects. In addition, SFCLs have been developed and applied to grids, as a promising alternative to conventional measures to solve fault current problems such as replacement of circuit breakers and bus split.

  Development status

  For nearly a decade since 2002, the industry, academia, and research laboratories led by KEPCO, backed by the support of the government, succeeded in developing and demonstrating through actual grid application, the AC 22.9 kV 50 MVA and DC 80 kV 500 MW commercial-level superconducting cable systems, each of which consist of superconducting cables, terminals, joints, cooling systems, and control systems, Currently, tests on the world's largest capacity 154 kV 600 MVA superconducting cables are under way with a goal for grid application next year. In addition, development of a cryocooler system with a 10 kW cooling capacity below -200□ is being carried out for home-production of cryocooler systems, which are the core of cooling systems for superconducting cables. As for SFCLs, a 22.9 kV 630 A class was developed and successfully applied to a distribution line at Icheon Substation, first time in Korea. In parallel, a large capacity 22.9 kV 3,000 A class SFCL was also developed. Currently, the world's largest capacity 154 kV 2,000 A class SFCL is under development. In the first phase, a single-phase SFCL was designed, fabricated, installed on a field-test site and tested. In parallel with these development and field tests, a pilot project is being planned for commercial operation of superconducting power devices in domestic power systems.

Expected benefits

Through successful development of superconducting devices, Korea is expected to possess world class superconductivity technology. Based on this, it will gain an edge to lead the fast growing global superconductivity power industries, in cooperation with domestic industries. It will be able to apply technology of environmentally-friendly large capacity power transmission and fault current limitation to grids extensively. KEPCO also saw significant accomplishments in HTS technology and will strengthen the R&D to obtain the outstanding core technology and commercialize them successfully through strategic investment.

Decentralization of equipment

- Development of new predictive step out prevention relay that requires no telecommunication (TE)

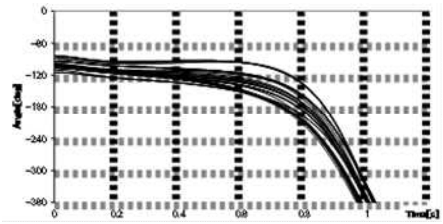
Background

On Mar. 11th 2011, TEPCO experienced historically large scale outage and generation loss caused by "The Great East Japan Earthquake" of magnitude 9.0 and accompanied tsunami that wiped out vast area of eastern Japanese coast. Since the loss of generation reached 15GW, TEPCO ran into significant deficiency of power source and had no choice but to perform planned outage immediately after the disaster. TEPCO could cease the planned outage in several weeks but was still short in generation, which meant heavy dependence on around 11GW of pumped storage hydro in daytime, and forced TEPCO to use large amount of electricity for pumping up water throughout the night.

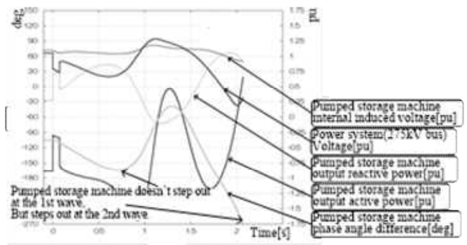
In overall TEPCO's transmission system, thermal and nuclear generation is predominant in the eastern area while majority of pumped storage hydro is located in the western area. Therefore, the power flow from the east area to the west grows significantly at midnight depending on the amount of pumping, which causes transient instability problem.

According to our dynamic simulation study, a severe fault such as 3 phase fault or loss of both double circuit lines in the condition of heavy pumping at midnight could cause pump decelerated or generator accelerated step out which might result in large scale outage.

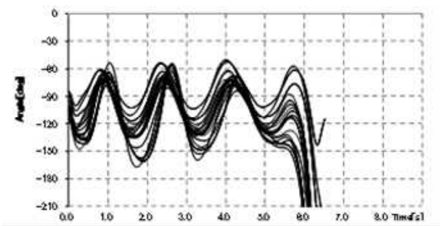
Through this study, we found various mode of step out phenomena, 1st wave step out, 2nd wave step out, Nth wave step out and poor damping phenomenon. TEPCO managed to find the way to prevent these step out phenomena by using old and almost abandoned step out prevention relay system, but this experience motivated us to develop and apply new step out prevention relays.



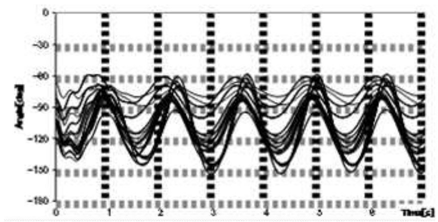
Example of 1st wave out of step phenomena



Example of 2nd wave out of step phenomena



Example of Nth wave out of step phenomena



Example of poor damping phenomena

Goal

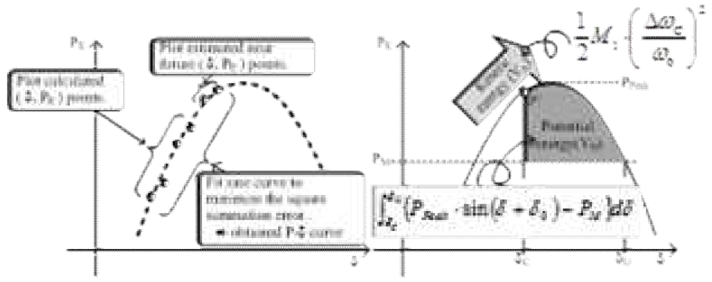
- Predict step out phenomena and shed some pumped storage hydro machines before step out to keep the entire system stable.
- Handle all step out phenomena, 1st wave step out, 2nd wave step out, Nth wave step out and poor damping phenomenon.
- Do not require complicated setting that varies by power system condition.
- Do not require telecommunication channel considering cost.

Study and Achievement

To achieve the goal, TEPCO and MELCO launched the collaborative research based on dynamic simulation study. The research shows that the combination of following methods achieved good result.

- P-δ curve estimation method

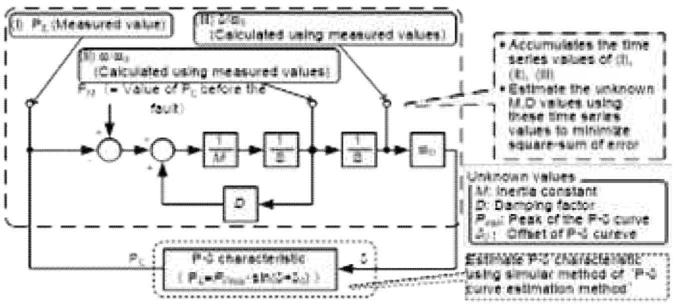
  The relay calculates angle difference (δ) between the pumped storage hydro station and center of the entire grid from measured active power (P) and voltage (V) using swing equation, and predicts near future P and δ values. Then the relay estimates P-δ curve from time series of P and δ values and foresees step out phenomenon using estimated P-δ curve. This method is utilized for 1st wave step out and 2nd wave step out.



• On-line modeling method

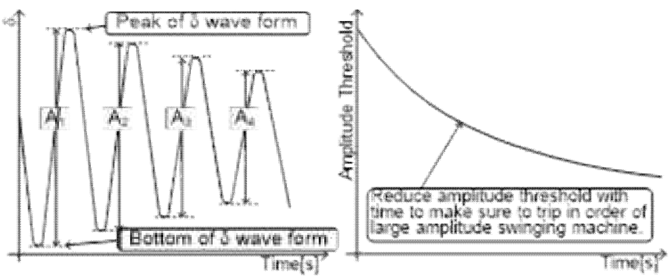
The pumped storage hydro station and the entire system can be represented as single machine – infinite bus model. However, some parameters in the swing equation of this simplified model cannot be determined in advance.

The relay accumulates the time series values of measured or calculated P, V, δ and δ, estimates the unknown parameters using these time series values, and foresees step out phenomenon. This method is utilized for N^{th} wave step out.



• Angle wave form peak-bottom detection method

The relay extracts peak and bottom values from oscillating time series of δ values, and obtains time series data of peak to peak values. Then, the relay calculates the damping ratio from peak to peak values and discriminates the poor damping phenomenon. This method is utilized for poor damping phenomenon.



TEPCO has started to apply this new type predictive step out prevention relay and will complete installation to all pumped storage hydro station in several years.

4.6 Summary of the Measures for Large Scale Outage in Mega Cities

4.6.1 Mitigation measures

This category can be summarized as follows:

<Hardening facilities>

- Reinforce;
  - The power system(*)
  - The structures and foundations
  - With duplication
  - With taking special measures (**)

(*) Typical hardening measures for power system
- Expansion of high voltage network
- Double-ended Substation
- Meshed or redundant (N-1 or more criteria) network
- Decentralization of power sources
- Interconnectors for mutual backup
- Superconducting Power Device

(**) Remarkable example of the special measures for hardening
- For typhoon
  - Insulator washing equipment
- For flooding
  - Flood gate, Bund wall, Sealing of cable inlets, Sump pumps
- For blizzard risk
  - Snow resistant rings, Spacers
  - Melt ice device, mobile melt ice car
- For fire or explosion
  - Oil free equipment, Fire retardant material
- For adequate reserve
  - Adjustable speed Pumped storage hydropower
- For Wild-life risk
  - Wild-life anti-climb guard protection device

- Relocation;
  - To underground
  - To indoor
  - To elevated ground
  - To no disturbance-prone area
  - With the aim of decentralize

- Strategic replacement
  - Repair of the same model/type equipment, a part of which found to have defect.

<Strategic power system planning>

- Grouping/sectionalize the downstream network

<Quality enhancement activities>

- Periodic network security review and reinforcement planning of network
- Standardization

4.6.2 Hybrid and Adaptation measures

These categories can be summarized as follows:

<table>
<tr><th>Ability</th><th>Hybrid</th><th>Adaptation</th></tr>
<tr><td>Anticipating</td><td>Predictability Observability/Visibility
● Condition monitoring system
● Alarm system
● Lightning strike tracking and locating system
● Monitoring/Surveillance system
● An authentication system
● Remote inspection tool
● WAMAC, Dual RTU
● New aging marker</td><td>Predictability Observability/Visibility
● Manage inspection
➢ Perform special inspection,
➢ Shorten inspection period
● Condition Monitoring Test
➢ Insulation or grounding resistance test
➢ Infrared Ray (IR) inspection</td></tr>
<tr><td rowspan="6">Rapidly recovering</td><td>Automatic recovery system
● Emergency restoration system (ESR)
● Intelligent switch
● Auto-reclosing scheme
● Automatic self-testing/monitoring scheme</td><td></td></tr>
<tr><td>Backup/Alternatives
● Use of mobile generators
● Preparation of spare parts, Universal parts</td><td>Backup/Alternatives
● Securing adequate reserve
● Arrange temporary supply from adjacent supply sources</td></tr>
<tr><td>PACS for localization of the disturbance
● CBF protection scheme
● Load shedding scheme with under-frequency relay
● PSS, PSVR, VQC, AVC, VMS
● UPSS, ISAS</td><td>Operation for localization of the disturbance
● Change of power system configuration
● Implement radiation configuration.
● Proactively switch out
● High voltage profile operation</td></tr>
<tr><td></td><td>Preparation of emergency plan
● Preparation of Black-start procedure, Rolling outage procedure</td></tr>
<tr><td></td><td>Emergency support
● Request for emergency support, manpower</td></tr>
<tr><td colspan="2" style="display:none"></td></tr>
<tr><td>Absorbing lessons</td><td>Quality enhancement
● Calculator for assessment
● Real-time simulator for shift operators' drill (PGS)</td><td>Quality enhancement
● Establish and periodical review of;
➢ Comprehensive network reliability and operation plan
➢ Comprehensive crisis management plan
● Periodic drill</td></tr>
</table>

4.6.3 Remarkable Measures against the low probability high impact incidents

Following tables are the sampled measures from the tables in section 4.3.3, which is specialized in each low-probability high-impact incident.

As shown in the tables below, there is less remarkable measusres in the category of “volcanic eruption”, “geomagnetic storm”, and “deficiency of power source”.
Probability of occurrence of “mega eruption of volcanos” or “super-flare” may be very low but not zero, and if they occur, whole power system can be damaged and humstrung for prolonged period.
In addition, exponential increase of renewable energy power source such as photovoltaic or wind may increase the uncertainty of demand forecast and instability of supply demand balance.

Therefore, more energetical activities and breakthrough of technology in these categories are desired.

Blizzard/Ice-storm

Mitigation	Hybrid/Adaptation
<Transmission lines> ● Spacers between each phase lines ● Snow resistant rings to OHL(*) ● Melt ice device or mobile melt ice car	

Drought/Heat Wave

Mitigation	Hybrid/Adaptation
	<Strengthening of support system> ● Reservoirs for storing water **<Inspection/testing and maintenance>** ● Monitoring of the soil temperature of the major transmission cable corridors. ● Infrared Ray (IR) inspection for over-loaded facilities/parts ● Sag inspection for over-loaded OHLs.

Tsunami/Tidal wave

Mitigation	Hybrid/Adaptation
<Risk assessment> ● Study of the possible impact on transmission and distribution equipment for a flooding level of +5.0mCD under extreme weather conditions. **<Strengthening of anti-flooding measures>** ● flood gates, bund wall ● sealing of cable inlets ● sump pumps ● relocation to elevated ground	

Volcanic eruption

Mitigation	Hybrid/Adaptation

Geomagnetic storm

Mitigation	Hybrid/Adaptation

Explosion/Fire

Mitigation	Hybrid/Adaptation
<Transmission lines> ● Using the fire retardant material or oil-free equipment, such as XLPE cable, GIS and GIT.	**<Substations>** ● Fire alarm/fighting systems

Intentional destruction (Conflict/Terrorism/Cyber-attack)

Mitigation	Hybrid/Adaptation
	<Countermeasures for physical attack> ● Monitoring/Surveillance system ● An authentication system **<Countermeasures for cyber-attack>** ● Dedicated telecommunication network **<Others>** ● Requirement of strengthening of punishment and regulations on criminals ● Ensuring confidentiality of facilities

Deficiency of power source

Mitigation	Hybrid/Adaptation

Pandemic

Mitigation	Hybrid/Adaptation
	<Vaccination / Hygiene management> ● Safety guidelines for the handling and disposing of carcasses of dead birds or animals was established ● Influenza vaccination for employees ● Maintain personal and environmental hygiene **<Strengthening of support system>** ● A reporting procedure for Avian Influenza/Middle East Respiratory Syndrome/Ebola Virus Disease has been formulated ● Influenza Pandemic Contingency Plans for operational and non-operational divisions have been established to deal with different situations. ● Formulation of the BCP (Business Continuity Plan)

5. Conclusion

5.1 Summary of Survey

In 20 century, most of large blackouts were caused by accidental destruction by third parties and operational inaccuracy.
After greeting the 21 century, cascading blackouts due to abnormal weather occurred frequently. Besides these cases, there are many blackouts in Asian countries due to abnormal weather missing in this survey; India, Philippines etc.

5.1.1 Results of Assessment with the Probability/Impact Chart

In terms of the results of the survey with the Probability/Impact Chart assessment, the following disturbances are identified as the threats to "resilience":

- **Abnormal weather**: Blizzard/Ice storm, Drought/Heat wave
- **Natural disaster**: Tsunami/Tidal wave, Volcanic eruption, Geomagnetic storm
- **Trouble at facilities**: Intentional destruction, Explosion/Fire
- **Operational inaccuracy or others**: Deficiency of power supply, Pandemic

Most of them are difficult to predict, and they may cause significant damage to the power supply facilities, once they occur.
Therefore, the survey this time has reached a reasonable conclusion.

However, there were several issues relating to the methodology of this survey that affected the result:

- Each member country was able to choose freely the disturbance which would cause the wide area outage, and was not required to provide answers to all disturbances.

- Each member country was able to describe freely the worst case scenarios which would lead to wide area blackout in the mega city.

- In addition, we faced difficulties in setting the proper scaling of the "impact" for all member countries

These processes caused a gap in the interpretation and severity of each disturbance between affected countries and non-affected countries, which resulted in a wide range of scores between member countries, and the final scores in each disturbance became relatively featureless results if they were averaged.

This time, we adopt the highest scores among responses from member countries concerning the "impact" scores, as described in section 4.3.2.

Therefore, it is to be desired that the survey is properly reviewed on the basis of common understanding and severity of the disturbance.

5.1.2 Results of Measures for Wide Area Outages

As summarized in section 4.6.1, the typical mitigation measures found to be properly and thoroughly taken in member countries, as follows:

<Hardening facilities>

- Reinforce a power system, structures and foundations
- Duplication or taking special measures for abnormal weather or natural disaster
- Relocation to underground, indoor elevated ground, or other less disturbance-prone area
- Strategic replacement of the same model/type equipment, a part of which found to have defect.

<Strategic power system planning>

- Grouping/sectionalize the downstream network

<Quality enhancement activities>

- Periodic network security review and reinforcement planning of network
- Standardization

However, the knowledge of a power system and its main resilience threats is often partial and incomplete, as it is almost impossible to accurately and precisely predict the future extreme events that would compromise power system resilience.
In many times, it is difficult or almost impossible to qualify all aspects of resilience when mitigation measures are planned. For example, moving transmission/distribution lines or substation facilities underground is considered one of the most effective measures for reducing a vulnerability to wind damage, lightning, and vegetation contact, but then if the cable is damaged it may take much longer to repair it than an overhead line. Moreover, this measure will rather increase a cost to eliminate a threat to the extreme weather.
Therefore, we think that the adaptive management including “hybrid measures” and continuous review is very important and effective approach in order to develop a resilient power system.
In addition, affordability is also important aspect to keep the power system resilient. In other words, it is important to take an economically minimum necessary amount of measures for the “low-probability high-impact” incidents. We think that the hybrid or adaptation measures may be suitable for the viewpoint of this economical efficiency.

We described in section 3.3.4 the three (3) points of view in order to conduct an appropriate assessment of the “Resilience” of a power system .

As summarized in section 4.6.2, it can be said that the hybrid/adaptation measures are properly and thoroughly taken from the three viewpoints in member countries at least, and the hybrid measures may, especially, occupy an influential position and will keep the majority for future technology.

5.2 Recommendations

5.2.1 Correct Understanding of the Difference between Reliability and Resilience

It is important to know that resilience is a concept which mainly focuses on low probability and high impact events and that it not only includes destruction of infrastructure itself but also needs to be evaluated by achievement of a relatively “slow” and possibly controlled degradation and reduction of its recovery time.

Reliability	Resilience
High probability, low impact	Low probability, high impact
Static	Adaptive, ongoing, short and long
Evaluates the power system states	Evaluates the power system states and transition times between states
Concerned with customer interruption time	Concerned with customer interruption time and the infrastructure recovery time

Table 5-1 Reliability versus resilience

5.2.2 PDCA Cycle of Risk Assessment using the Probability/Impact Chart

Alike some Asian electric power companies have already installed, utilities owing infrastructure for power supply to the mega cities are highly recommended to have “Probability/Impact Risk Assessment” so that they can give a priority of measures to be taken. Of course, this assessment process should be repeated every year in a manner of PDCA (Plan-Do-Check-Action) cycle.

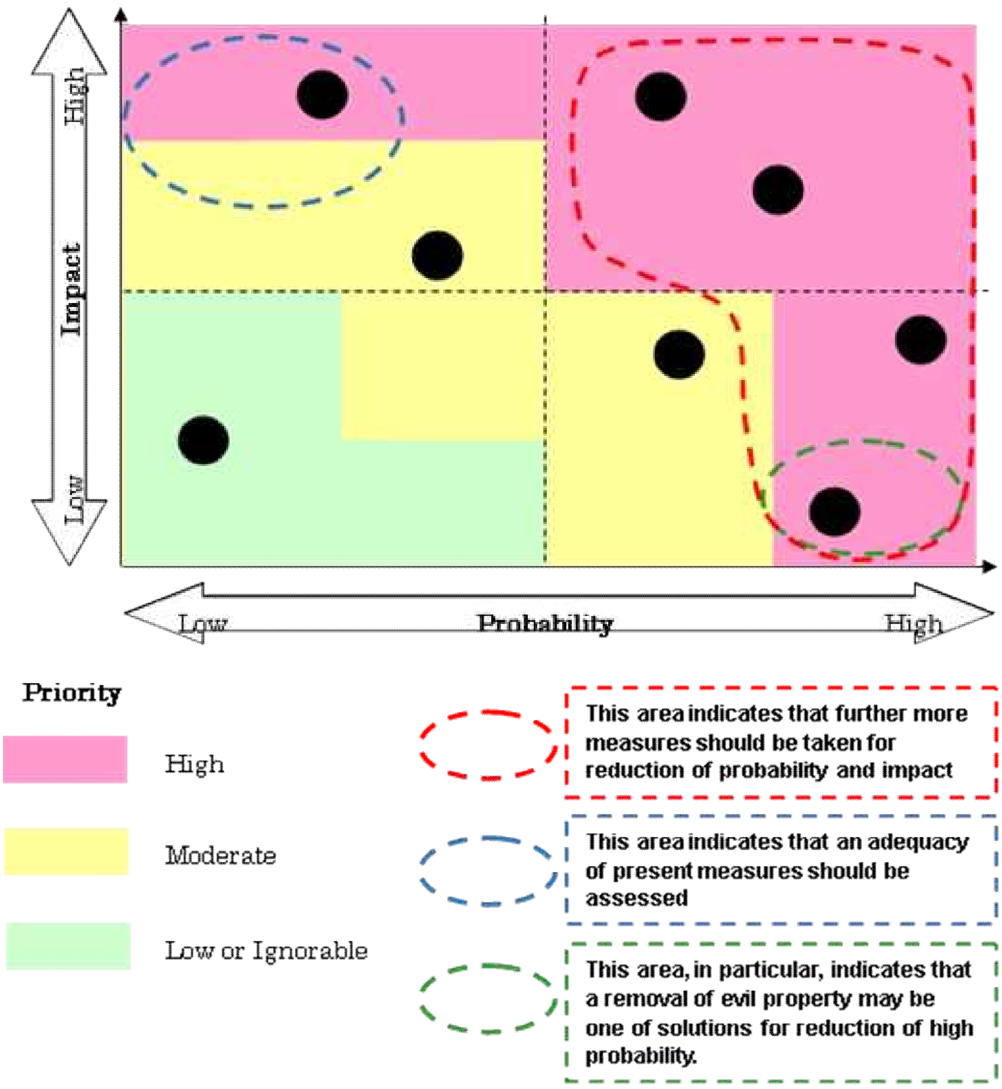


Figure 5-1 Probability/Impact Chart for Risk Assessment

5.2.3 Future Works

As summarized in the section 4.6.3, measures for volcanic eruption, geomagnetic storm, inaccuracy of demand forecast or deficiency of power source, reserves seem not to be adequately established. Vigorous efforts to overcome these issues are desired.

In particular, exponential connection of renewable energy, in particular, photovoltaic and wind power, will have greater influence on stable supply-demand and frequency control in the near future. Therefore, development for:

- Accurate demand forecasting technology
- Output prediction technology for PV and wind power

are eagerly desired.

6. Biographies

[1] Mathaios Panteli and Pierluigi Mancarella, “The Grid: Stronger, Bigger, Smarter?”, IEEE power & energy magazine, May/June 2015.

[2] C.S. Holling, “Resilience and Stability of Ecological Systems”, Annual Review of Ecology and Systematics, Vol. 4, pp. 1-23. 1973.