Abstract

After the Fukushima Daiichi accident (Loss of all AC and DC power sources and the distribution panels), several design enhancements have been incorporated or are under consideration to Japanese BWRs.

Especially, there are several important enhancements in the area of the electrical system design.

In this paper, the design enhancements related to the following systems will be introduced.

Supplemental AC power supply system
Enhancement on DC Battery system

In addition, this paper will show our practice of the solid state equipment in Japanese BWRs which have some special specifications, considering the special condition in the NPP’s auxiliary electrical power system.

1. SBO & DC power blackout in Fukushima Daiichi NPP

At the Fukushima Daiichi NPP, Units 1 to 3 were in rated power operation before the earthquake which had occurred on March 11th, 2011. Units 4 to 6 had been shut down and had been in the outage for the periodic inspection. Of these three units, at Unit 4, all fuel was removed from the RPV and being stored and cooled in the SFP for the shroud replacement work. The outage for Unit 5 was nearly complete, fuel was loaded into the RPV and the water pressure leak tests were underway to verify its integrity. Unit 6 was also near completing outage, and fuel was already loaded into the RPV.

On March 11, 2011 at 14:46, the earthquake caused an automatic reactor scram at Unit 1 to 3, and all control rods were inserted at 14:47. Due to the loss of off-site power, two D/Gs started up automatically at 14:47.

Off-site power for the Fukushima Daiichi NPP consists of a total of 7 lines with six transmission lines from the Shin-Fukushima Substation (275kV Okuma Line 1L to 4L and 66kV Yonomori Line 1L and 2L) and one 66kV transmission line for the standby off-site power to the Unit 1 from the Tohoku Electric Power Company (66kV TEPCO Genshiryoku Line). Of the transmission lines from the Shin Fukushima Substation, the Okuma Line 1L and 2L connect to the Unit 1 and Unit 2 and Okuma Line 3L and 4L connect to the Unit 3 and Unit 4.
The Yonomori Line 1L and 2L connect to the Unit 5 and Unit 6. The TEPCO Genshiryoku Line was connected to the Unit 1 normal M/C (Metal-Clad Switchgear) via the standby switchyard.

On the day of the earthquake, the Okuma Line 3L was under repairs and out of service.

The Remaining all transmission lines were lost their power by the earthquake and caused loss of the off-site power.

The causes were as follows,

Okuma Line 1L and 2L; The electrical equipments in the switchyard, the CBs and the DSs were damaged by the earthquake. They were an air–blast type.
Okuma Line 4L ; The switchyard was flooded by the Tsunami.
The CBs have replaced to the GCBs already. They were not damaged by the earthquake.
Yonomori Line 1L and 2L: The transmission tower collapsed due to the landslide of the embankment near it. The switchyard was flooded by Tsunami.

After loss of the off-site power, the D/Gs started up and provided their power. However, at 15:35, the second tsunami hit, shortly after which all of the D/Gs were lost except Unit 6, D/G 6B which was added in 1996 and had an air-cooling heat sink.

As the result of the Tsunami flooding the entire area around major buildings, water flowed into the buildings, and most of the electrical equipment inside them lost their functions. The water-cooled D/Gs themselves at Unit 5 and Unit 6 were not damaged by water, but became inoperable due to the loss of their sea water cooling pumps. All of the water-cooled D/Gs at Unit 1 to Unit 4 were shut down due to the flooding by the Tsunami. On the other hand, Unit 2, D/G 2B, Unit 4, D/G 4B and Unit 6, 6B are air-cooled D/Gs and did not have sea water cooling pumps, thus there was no impact on their cooling systems caused by the Tsunami. D/Gs 2B and 4B were installed in the Common SFP building to the southwest of Unit 4 R/B, although there was no water to the D/Gs themselves, however the electrical equipment room in the basement of the building was flooded, submerging D/Gs excitation system panels and M/Cs causing them to lose their functions. As the result, all of the D/Gs for Unit 1 to Unit 5 were shut down, causing their station blackout. Only Unit 6 air-cooled D/G, 6B continued its operation and maintained its power.

At Units 1 to 5, all middle voltage switchgears (M/Cs) were damaged by sea water due to the Tsunami.

Therefore, it would not have been possible to supply power to the necessary equipment even-if D/Gs had been operable. Most of the low voltage switchgears (P/Cs) were also damaged by sea water.

In regard to the DC systems, they were damaged by sea water at Unit 1,2 and 4, but not at Unit 3,5 and 6. Flooding sea water most appeared on the lowest basement levels and at the main entrance area of the T/B where was just behind the T/B main entrance shutter, because the Tsunami had broken into the T/B main entrance shutter and flooding sea water, ingressed from the T/B main entrance and the intake air louvers for D/Gs. There were some penetrations such as ducts or trenches in the building, which were both water ingress pathways, therefore most of the underground level floors were flooded by the Tsunami.

For Unit 6, there was no damage to not only the air-cooled D/G 6B but also the M/Cs and the DC systems, thus the emergency on-site power for Unit 6 was available.
For Unit 5, there was the bus-tie connection between Unit 5 and Unit 6 low voltage MCCs as an one of the accident management countermeasures, thus Unit 5 on-site power could be restored.

2. Restoration of on-site power in Fukushima Daiichi NPP

In order to restore the onsite power of Unit 1 and Unit 2, TEPCO dispatched a power truck and tried to connect it to the low voltage switchgear P/C 2C of Unit 2 which was the only usable switchgear in Unit 1 and Unit 2 and was located in Unit 2 T/B B1. However immediately after the connection, around 15:30 on March 12, the Hydrogen explosion of Unit 1 disturbed the connection.

Meanwhile, in order to restore on site power of Unit 3 and Unit 4, a power truck connected to the low voltage switchgear of P/C 4D at 14:00 on March 13, 2011, but the Unit 3 hydrogen explosion occurred on March 14 interrupted its operation.

On March 12, the TEPCO power recovery team initially determined that it would be difficult to quickly restore the 275kV Okuma Lines because of the damage and flooding of the switchyards at Fukushima Daiichi NPP and decided to use the 66kV Yonomori Line 1L and 2L as 6.9kV lines to restore power using of mobile 66kV/6.9kV step down transformer truck at the Shin-Fukushima Substation. 66kV Yonomori Lines are originally connected to Unit 5 & 6, in order to place power as close as possible to Units 1 to 4, which needed off-site power the most, it was decided to connect the Yonomori 1L to Okuma Line 3L, which was the transmission line to supply power from Shin-Fukushika Substation to the Unit 3 and 4. 66kV Yonomori Line 2L to supply power to Unit 5 & 6. On March 15, the 66kV TEPCO Genshiryoku Line was charged up until the disconnecter on the standby switchyard, and facility integrity was verified. Due to the damage on the secondary cable to the Unit 1 and the damage of M/Cs in Unit 1, temporary M/C which was on the truck arrived at the Fukushima Daiichi NPP and stopped at the street north side of the Unit 1 T/B was laid on March 17th, and the cable from temporarily M/C to the low voltage switchgear P/C 2C was laid on March 17 and 18, and about 1.5km cable from the standby switchyard to temporarily M/C was laid on March 19th. After that, Unit 2 off-site power was restored on March 20. The former cabling work was done by the TEPCO power distribution division by using the cable laying car. The latter cabling work was done by about 100 Hitachi managers by the manual cable laying work under Hitachi supervisors because of the high level radiation after hydrogen explosions. On March 15, the Okuma Line 3L was connected to the Yonomori Line 1L on the transmission tower then connected to the mobile mini-clad switchgear (installed by the TEPCO Transmission Division), and charged up on March 18. On March 19, Multi-circuit breakers and the cable between the mobile mini-clad switchgear and the Multi-circuit breakers were installed by the TEPCO Distribution Division.

On March 21, about 100 Hitachi managers also laid the cable from the mini-clad switchgear to P/C 4D in the Unit 4 T/B by the manual cable laying work. On March 22, P/C 4D, which was the on-site power of Unit 3 and Unit 4, was restored.

In addition, 66V Yonomori Line 2L was restored with a new transmission route using 500kV Futaba Line No.2 tower instead of the collapsed No.27 tower of 66kV Yonomori Line. At the same time, integrity of the equipment (Start up transformers, circuit breakers, etc.) was verified and cables were installed on March 20. It was charged up to the Unit 5 and 6 Start up transformers, then off-site power of Unit 5 and Unit 6 was restored on March 21.

To enhance the supply reliability of the off-site power, the following actions have been done. The Okuma lines voltage changed from 6.9kV to 66kV in April, 2011. New switchyard with 66kV/6.9kV 30MVA transformer constructed for Unit 1 to Unit 4, and new 66/6.9kV transformer was installed at the standby switchyard and in the both of new and the stand-by switchyard, new M/Cs were installed. Air cooled D/Gs 2B and 4B in the Common spent fuel pool building have been restored by the replacement of
their excitation panels and M/Cs in June(4B), 2011 and Jan. 2012(2B). The endeavour to enhance the reliability of the on-site and off-site power of the Fukushima Daiichi is still on the way now.

3. New Safety Guide for Electrical System in Japan

The Nuclear Regulation Authority in Japan submitted a new safety standards for nuclear power stations based on the lessons learned from the Fukushima Daiichi Accident. The Standards consists of three parts; Design basis Safety Standards, Severe Accident Measures and Safety Standards relative to Earthquake and Tsunami.

3.1 Off-site power;

The off-site power shall be connected to the electrical power system with two or more transmission lines, which are connected to two or more independent substations or switchyards in which at least one line out of these lines is physically separated from the other lines. Also, in the case of that multiple reactors are sitting at a nuclear power station, it shall be designed so that loss of any two lines of the power transmission lines may not cause the loss of its off-site power at the same time in these nuclear power facilities.

3.2 Sever Accident Measures;

Prepare equipment and procedures for securing electricity required to prevent a severe core damage, prevent a containment vessel failure, etc., against loss of power beyond the design base accidents.

AC power;
   a) Alternative system shall be independent and dispersed at different locations to the equipment for the design basis requirements.
   b) Mobile alternative power sources (for example, power trucks) shall be made available and ready to use.
   c) Install permanent alternative power sources (for example, gas turbine generators).

DC power
   a) On site permanent DC power source shall have the capacity to keep supplying electricity 8 hours without load shedding. In addition, the electricity supply shall be assured for 24 hours in total, to cover 16 hours by load shedding.
   b) The mobile DC power equipment shall be prepared for a capable for 24 hours in total including 8 hours without load shedding.
   c) For further improvement of reliability, one more system (namely 3rd system) of permanent onsite DC power supply shall be prepared.
   d) Connection of mobile power supply and start of power supply shall be feasible with sufficient time allowance within the time where onsite permanent DC system can continue to provide DC power.

Power Sharing;
   Power sharing among the units shall be feasible.
   a) Prepare cables in advanced and facilitate the manual connection.
   b) Prepare a stand-by electrical cable in order to cope with the situation where installed electrical cable may not be usable

Alternative on-site power supply;
   Install alternative onsite power supply (MCC, P/C, M/C etc.)
a) Alternative on-site power supply as well as design basis facilities shall not lose its function caused by the common cause, maintain its function provided by at least one line, and allow personnel access.

4. Example of Assessment against New Safety Guide

Shimane Unit 2 is a 2436MWt BWR5 owned by the Chugoku electric power company and started its commercial operation in 1989. Unit 2 had 2(two) 220kV transmission lines which were connected to Kita-Matsue Substation.

According to the New Safety Guide, they built 66kV back-up switchyard which is fed from the 66kV transmission line which is connected to the other substation named Tsuda Substation.

They also built an emergency electrical panel building which has a back-up switchgear in it. Through the back-up switchgear, Unit 2 can be fed from 500kV transmission lines via Unit 3.

As for the on-site power, they prepared the gas-turbine generator power trucks as alternative, independent and diver seed AC power source which are located at high elevation area against Tsunami. In addition, they prepared the mobile power trucks and the terminal boxes for their cables connection.

As for DC power, they updated the existing DC batteries to cope with the 24 hours operation and they added the DC system for Sever Accident Measure equipment. In addition, they have prepared the DC power trucks with incoming middle voltage cubicle, rectifier and batteries to cope with 24 hours operation of the DC loads including RCIC pumps and valves combined with using AC power trucks. These DC loads require an inrush current periodically about every 90minutes, so to keep the load terminal voltage properly, Hitachi has developed the new DC power truck with both rectifier and batteries to feed the inrush current properly and to keep the reasonable equipment’s sizes. They can be mounted on 11ton truck.

5. Hitachi Experience of Solid state power equipment in Japanese BWRs

Hitachi has supplied UPSs and ASDs (Adjustable Speed drives) for more than 30 years in Japanese BWRs. As for the ASD, the first one and the second one are both current source-type, PAM control Thyristor inverters for PLR pumps. The third one is a voltage-source type, PAM control GTO inverter for RIP and the fourth one is a voltage-source type, PWM control IGBT 2 level inverter for RIP. The fifth and the latest one is a voltage-source type, PWM control IGBT multi cell inverter for RIP.

We, Hitachi applies the proven Power device and the main circuit design in which is the industry standard to avoid the initial failure due to the new design. In addition, Hitachi applies the Power equipment which has its sufficient de-rating, to ride through the electrical variations in NPP, such as over voltage due to the load rejection of main generator, etc. and to get the long life time.

Our ASDs for nuclear power plant have a special characteristics of duplex controller and seismic proof design to improve the reliability.

References

1) Fukushima Nuclear Accident Analysis Report, June 20, 2012
   Tokyo Electric Power Company Inc.
2) Draft New Safety Standards of Electrical Systems for Nuclear Power Stations
   NRA, Japan
3) The Outline of the assignment against New Safety Standards in Shimane Unit 2
Robustness of Electrical Systems of NPPs in Light of the Fukushima Daiichi Accident
OECD/NEA CSNI Workshop

Electrical System Design on Japanese BWR plants in the Light of the Fukushima Daiichi Accident and Hitachi Experience of the Solid state power equipment in Japanese BWRs.

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Fukushima-Daiichi unit 1-unit4
1. The Off-site Power was lost due to the earthquake.
2. The On-site power, D/Gs and DC power supply were lost due to the Tsunami.
3. The Emergency switchgears were lost their function by flooding due to the Tsunami.
   >>> SBO & DC Blackout >>> Fuel Melt down

Fukushima-Daiichi unit 5 & 6
1. The Off-site Power was lost due to the earthquake.
2. One of 5 D/Gs which was cooled by Air Fin Cooler continued its operation successfully, the other D/Gs were lost due to the loss of their heat sinks by Tsunami.
   >>> Cool shutdown Successfully

1-2. AC power system

1) There are 4 (four) 275kV transmission lines on two physically independent 2 transmission raceways for unit 1-4.
2) There are 2 (two) 66kV transmission lines for unit 5&6.
3) They were connected to the same substation and all of them were lost.
4) 1 (one) 66kV transmission line which was connected to the other substation was available.
5) Only one D/G, 6B which was air-cooled could operate after the Tsunami.
1-3. DC power system

Fukushima-Daiichi unit 1-unit 4
1. DC Power systems were lost due to the Tsunami (Flooding) except unit 3.
2. Unit 3 DC was lost its power more than 1 day after the Tsunami due to SBO.

Fukushima-Daiichi unit 5 & 6
1. Both of unit 5 & 6 DC system were available after the earthquake and Tsunami.
2. D/G 6B was available and using the Accident management system (Connection between adjacent units), unit 5 AC system was restored.

1-4. Restoration of Fukushima Daiichi Offsite power

Off-site power has restored after 9-11 days from Tsunami

Off-site power of Fukushima Daiichi

55kV Yonomori line 2
2. New Safety Guide of ELS in Japan

2.1 Off-site power

The off-site power shall be connected to the electrical power system with two or more transmission lines, which are connected to two or more independent substations or switchyards in which at least one line out of these lines is physically separated from other lines. Also, in the case of that multiple reactors are sitting at a nuclear power station, it shall be designed so that loss of any two lines of the power transmission lines may not cause the loss of its off-site power at the same time in these nuclear power facilities.

2.2 Severe Accident Measures

Prepare equipment and procedures for securing electricity required to prevent a severe core damage, prevent a containment vessel failure, etc., against loss of power beyond the design base accidents.

2.2.1 AC Power

a) Alternative system shall be independent and dispersed at different locations to equipment for the design basis requirements.

b) Mobile alternative power sources (for example, power trucks) shall be made available and ready to use.

c) Install permanent alternative power sources (for example, gas turbine generators)
2. New Safety Guide

2.2 Severe Accident Measures

2.2.2 DC Power
   a) On site permanent DC power source shall have the capacity to keep supplying electricity 8 hours without load shedding. In addition, the electricity supply shall be assured for 24 hours in total, to cover 16 hours by load shedding.
   b) The mobile DC power equipment shall be prepared capable for 24 hours in total including 8 hours without load shedding.
   c) For further improvement of reliability, one more system (namely 3rd system) of permanent onsite DC power supply shall be prepared.
   d) Connection of mobile power supply and start of power supply shall be feasible with sufficient time allowance within the time where onsite permanent DC system can continue to provide DC power.

2.2.3 Power Sharing
   Power sharing among the units shall be feasible.
   a) Prepare cables in advanced and facilitate the manual connection.
   b) Prepare stand-by electrical cable in order to cope with the situation where installed electrical cable may not be usable.

2.2.4 Alternative onsite power supply
   Install alternative onsite power supply (MCC, PC, MC etc.)
   a) Alternative on-site power supply as well as design basis facilities shall not lose its function caused by the common cause, maintain its function provided by at least one line, and allow personnel access.
3. Example of assessment against New Safety Guide

3.1 Original
Unit 2 has 2 220kV Lines

3.2 Assessment against New Safety Guide
1) Unit 2 can be fed from 66kV line which is connected to the other S.S.
2) Unit 2 Class 1E buses can be fed from 2 500kV lines through Buck-up switchgear.
3) Unit 2 Class 1E buses can be fed from 66kV lines through Buck-up switchyard which is located at the high level area.

Off-site power

3.3 On-site Power

Permanent AC source
Gas turbine generator trucks

DC power

Up-rated 116V
Added 116V

DC Power trucks

%Terminal box for power truck connection
Power trucks
Dedexes for power sharing between Unit 2 and unit 3

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3. Example of assessment against New Safety Guide

3.3.1 DC Power Truck

a) RCIC loads require the periodic inrush current
b) Middle voltage AC power trucks are available
c) We improved DC power truck which has both Charger & Battery
d) DC power truck can feed the inrush current with proper voltage drop.

4. Hitachi Experience of Solid state power equipment in Japanese BWRs

4.1 Hitachi Experience

Hitachi has supplied UPSs and ASDs (Adjustable Speed drives) for more than 30 years in Japanese BWRs.

<table>
<thead>
<tr>
<th>Year</th>
<th>Plant Name</th>
<th>Inverter Type</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993.0</td>
<td>Shika-1</td>
<td>Current Source Type - PAM control Thyristor Inverter</td>
<td>3.3kV/3400kVA, 50%×2</td>
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<tr>
<td>1994.0</td>
<td>Kashiwazaki-Kariwa-4</td>
<td>Ditto Specification</td>
<td>6.7kV/7000kVA, 50%×2</td>
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<td>1997.0</td>
<td>Kashiwazaki-Kariwa-7</td>
<td>Voltage Source Type - PAM control GTO Inverter</td>
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<td>2006.0</td>
<td>Shika-2</td>
<td>Voltage Source Type - PWM control IGBT Inverter</td>
<td>9.9kV/1250kVA, 11.1%×10</td>
</tr>
</tbody>
</table>

History of the ASD for PLR & RIP in BWR
4.2 Our Concept

a) Hitachi applies the proven Power device and main circuit design in which is the industry standard to avoid the initial failure due to the new design.

b) Hitachi applies the Power equipment which has its sufficient de-rating, to ride through the electrical variations in NPP, such as over voltage due to the load rejection of main generator, etc. and to get the long life time.

c) Hitachi applies the ASD for RIP which has duplex controller and seismic proof panel to improve the reliability.