Extended Battery to Cope with ELAP for APR1400

Hamdy Samier Hamdy Abdelbadea and Chang Choong-Koo

KEPCO International Nuclear Graduate School-KINGS, 658-91 Haemaji-ro, Seosaeing-myeon., Ulju-gun, Ulsan 689-882, Koera

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Abstract: Since the Fukushima nuclear accident, the interest in securing a reliable emergency power has increased, and as follow-up measures, each country is conducting various studies for enhancement of safety such as re-examination of EDG (emergency diesel generator) capacity, securement of additional emergency power, etc. This study was performed to find the way to implement a reliable DC system in coping with 72 hours extended station blackout for APR1400 within the battery room size. By using the largest capacity battery in the market which satisfies the requirements for Class 1E to perform a duty cycle for 24 hours, after the decay of the qualified class-1E lead acid battery a Non-Class 1E Lithium ion based battery system can be used as a backup system for 48 hours.

Key words: Station blackout, ELAP (extended loss of AC power), FLEXES equipment, Non-Class-1E Lithium ion based system.

Acronyms

AAC	Alternating AC source
AFW-ISO valve	Auxiliary feed water isolation valve
BOP	Balance of plant
DC	Direct current
EDG	Emergency diesel generator
ELAP	Extended loss of alternating power source
IP	Instrumentation power
IWS	In-containment water storage
LCP	Local control panel
LRC	Locked rotor current
MDG	Mobile diesel generator
MOV	Motor operated valve
NSSS	Nuclear steam supply system
POSRV	Pilot operated safety relief valve
RCS Valve 2	Reactor coolant system valve 2
SWGR& LC	Switchgear and load centers
SIS	Safety injection system
TD-AFW	Turbine driven auxiliary feed water

1. Introduction

1.1 Background

A SBO (station blackout) is defined as the loss of all AC power at an NPP (nuclear power plant). This is a loss of off-site power together with a failure of the

on-site emergency backup generators to operate. Per NRC Regulations Title 10, CFR (code of federal regulations) 50.63 “Loss of all alternating current power”, all nuclear power plants have a coping capability for SBO conditions for a limited time period ranging from approximately two to sixteen hours. An ELAP (extended loss of AC power) event is defined as a loss of all off-site and on-site AC power sources for an indeterminate period of time, which will challenge the long-term cooling of the reactor core and the SFP (spent fuel pool) unless mitigating actions are taken. This extended requirement is the result of the events at Fukushima.

Fukushima accident is the event which shows how the natural accident can lead the plant to a complete loss all of alternating current (LOOP (loss of offsite power)) which initiates a complete and extended SBO. The operators lost the ability to cool the fuel in the Unit 1 reactor after several hours. As Unit 2 & 3 DC battery system was still supplying power to Controlled Steam-Driven RCIC (reactor core isolation cooling), the RCIC was operated and got the ability to cool the reactor for more time in both units. The operator lost the ability to cool the fuel in Unit 3 reactor after about 30 hours, and in the Unit 2 reactor after about 70

Corresponding author: Chang Choong-Koo, Ph.D., professor, research field: nuclear power plant engineering.

hours, resulting in damage to the nuclear fuel shortly after the loss of cooling capabilities [1].

APR1400 is equipped with AFWS (auxiliary feed-water system) in order to provide an independent safety-related means of supplying secondary-side with quality feed-water to the steam generator(s) for removal of heat and prevention of reactor core uncover during emergency phases of plant operation. This system is designed to be automatically or manually initiated, supplying feed-water to the steam generators for any event that results in the loss of normal feed-water and requires heat removal through the steam generators, including the loss of normal onsite and normal offsite AC power. Following the event, the AFWS is the only way to maintain adequate feed-water inventory in the steam generator(s) for residual heat removal and it is capable of maintaining hot standby and bringing the plant to cool shutdown condition. All controls, instrumentation, and valves, which are essential to the emergency operation of the turbine-driven pumps subdivisions, are powered by battery-backed Class 1E power. The batteries are capable of powering the auxiliary feed-water turbine-driven pump and subdivisions for a station blackout (station loss of all AC power) up to eight hours with appropriate load shedding and the cooling capability will remain up to the depletion of the Class 1E battery system [2].

Extended station blackout coping capabilities of APR1400 which is a research done on the APR1400 by other researchers by applying an ELAP analyses using the MAAP severe accident computer code concludes that in case of failure of both EDG and AAC-DG, the extension of I&C loads associated with the TD-AFW may be necessary to assure the coping integrity for safe shutdown and more efficient core cooling capability [3].

The main goal of this study is to survey current practices and problems in NPP battery-based back-up power, and to find the way to improve the current DC system based on new technologies in accordance with

the new requirements raised by nuclear regulatory authority after Fukushima Daiichi accident. These provided information of current practices and potential interest in applying new energy storage technology solutions. Subsequently, calculated required battery capacity to cope with ELAP in APR1400 nuclear power plants to propose solutions for the safety related DC system in future power plant designs.

1.2 The DC Power System in APR1400

The APR1400 nuclear power plant is provided with DC (direct current) systems, which are classified into Class-1E system and Non-Class 1E system and designed to provide DC power for DC motor operated valves and for various NSSS and BOP control and instrumentation systems, as well as providing DC power for the turbine/generator emergency loads during normal and abnormal operating conditions [2]. The Class 1E DC system consists of four 125 V DC power systems per unit. The batteries are sized in accordance with the recommendations in KEPIC EEG 1,100 (IEEE 485). Each Class-1E battery rating is as follows:

Battery type	Lead acid
Number of cells (channel A & B)	58 Cell × 2 (parallel)
Number of cells (channel C & D)	58 Cell × 3 (parallel)
Total nominal voltage	125 V DC
Battery capacity (channel A & B)	(2,800 AH)
Battery capacity (channel C & D)	(4,200 AH)
Minimum operating voltage	1.81 V/cell
Voltage range	105-140 V DC

2. New Regulatory Guide Recommendations

2.1 US-NRC Recommendations

After Fukushima accident, the NTTF (near-term task force)—which consisted of a group of senior NRC staff-NTTF suggested enhanced station blackout mitigation strategies, within NTTF Recommendation 4.1, as follows: Initiate rulemaking to revise 10 CFR 50.63 to require each operating and new reactor licensee to [4-7]:

- Establish a minimum coping time of 8 hours for a loss of all ac power;
- Establish the equipment, procedures, and training necessary to implement an “extended loss of all ac” coping time of 72 hours for core and spent fuel pool cooling and for reactor coolant system and primary containment integrity as needed;
- Preplan and pre-stage offsite resources to support uninterrupted core and spent fuel pool cooling, and reactor coolant system and containment integrity as needed, including the ability to deliver the equipment to the site in the time period allowed for extended coping, under conditions involving significant degradation of offsite transportation infrastructure associated with significant natural disasters.

2.2 Nuclear Energy Institute Recommendations

The underlying strategies for NEI (Nuclear Energy Institute) Diverse and Flexible Coping Strategies (FLEX) Implementation Guide (NEI 12-06, Aug. 2012) recommended a three-phase approach:

- (1) Initially cope by relying on plant equipment.
- (2) Augment plant equipment with sufficient on-site FLEX equipment and consumables should be provided for 24 h from the event initiation to maintain or restore key functions.
- (3) Obtain additional capability and redundancy from off-site equipment until power, water, and coolant injection systems are restored or commissioned.

On-site resources will be used to cope with the first two phases of the casualty for a minimum of the first 24 hours of the event. The site-specific ELAP analysis will dictate the deployment schedule for off-site equipment. The delivery schedule for the off-site equipment must allow for sufficient margin to meet the deployment times of the off-site equipment. The schedule for initial delivery of off-site equipment (equipment needed to back up on-site equipment and extend the coping duration) needs to be contractually arranged with the off-site facility. This

strategy means with the failure of EDG and AAC-DG, the 125 V DC Class 1E batteries to last for 24 hours [8].

These requirements can be achieved by the following:

- Load-shedding scheme;
- Sizing channel C & D with large capacity battery;
- Cross-tying batteries between divisions;
- Delayed battery operation.

3. Current APR1400 Coping Capabilities

3.1 Coping with SBO

As shown in Fig. 1 each division of the 4.16 kV AC Class 1E auxiliary power system is supplied with emergency standby power from an independent EDG. The EDG is designed in accordance with the USNRC regulatory guide RG1.32 and international Standard IEEE 308 and sized with sufficient capacity to enable all the needed ESF and emergency shutdown loads powered from its respective Class 1E buses. Each EDG is designed to attain rated voltage and frequency within 17 s after receipt of start signal, supply power to 4.16 kV AC Class 1E bus within 19 s, and begin to accept sequenced loads to meet the response times. After LOOP, operation and loads sequencing of EDG is operated automatically [9].

In case that EDG fails to start, each two NPP units in the plant were equipped with AAC Diesel Generator designed in accordance with the regulatory guide RG 1.155 in early preparation for the case of simultaneously unserviceable off-site power and on-site power (main generator, emergency generator) [3].

AAC D/G has a sufficient amount of capacity to supply power to the auxiliaries of safety shutdown load and alternating current power will be connected to the 4.16 KV Class-1E bus during the SBO event. It should be designed in the way that it can supply power again within 10 min after on-site power outage. Every operation related to alternating current power is

Fig. 1 APR1400 auxiliary power system configuration.

performed manually. AAC D/G supplied with sufficient fuel enough to maintain continuous operation for 24 h, 8,700 kW is rated power on continuous operation (22 h) and 9,750 kW on short-time operation (2 h) [9].

3.2 Coping with ELAP

In Korea, in response to the severe accident and long-term station blackout, each plant site is equipped with a mobile generator and a storage battery (including charger and cable), to supply power to the safety related loads within 2 h after any accidents by securing temporary power connection points. The mobile DG is rated at 1,500 kW and connected to the 4.16 kV Class-1E buses to cope with a complete station blackout SBO scenario [9].

4. The Proposed Strategy for Coping 72 h SBO

According to NEI recommendation, the plant shall rely on the onsite equipment to cope with ELAP situation for 24 h until the access route is recovered, but with the concurrent failure of EDG and AAC supply, 125 V DC Class 1E systems should remain able to supply the safety related loads for 24 h. As EnerSys Gn-45 with nominal capacity 3,600 Ah is the

Table 1 WB-LYP10000AH general specifications.

Nominal voltage	2.8 V
Operating temperature	-45 ~ 85 °C
Maximum continuous discharge current	≤ 1 CA
Maximum impulse discharge current	≤ 20 CA (impulse current)
Standard charge/discharge current	0.5CA
Battery dimensions	(L (687), W (367), and H (756) mm)
Weight	335 kg

largest qualified Class 1E battery in the market, it recommended to be used as a stationary class 1E DC source to supply the critical loads for channel C & D up to 24 h, after the decay of the battery the WB-LYP lithium ion battery will be used as a Non-Class 1E backup source for the class 1E 125 V DC source for 48 h. WB-LYP10000AH general specifications will be as Table 1 [12].

Energy's Power safe GN-45 general specifications are listed in Table 2 [10].

5. The Loads Considered to Cope with ELAP

A typical nuclear power plant will include both AC and DC loads. The DC loads, with battery backup, are designed to carry out all critical plant operations even

Table 2 Enersys Gn-45 general specification.

Battery type	NOM Ah Cap	Nominal dimensions													
		Length		Width		Height		Unpacked		Domestic packed				Electrolyte only/1215SG	
		In	mm	In	mm	In	mm	lbs	Kg	lbs	kg	lbs	kg	gal	ltr
GN-45	3,600	16.6	422	15.1	384	27.2	691	705	320	727	330	140	63	14	53

Table 3 Channel C load profile for 24 h.

125 V DC load name	Continuous 24 h		Non-continuous	Momentary	Random
	2 h	22 h	24 h		
MOV Inverter SI no-load current	40	40			
IWS valve 1					229.6
IWS valve 2					229.6
RCS valve					58.8
RCS valve 2_LRC					581.2
AFP turbine LCP	8.8	8.8		68.8 (note 1)	
AFW ISO-valves			180 (note 2)		
Reactor trip switchgear system				3 (note 1)	
EDG A-control panel	7.3	7.3			
Lamp and relay, trip of medium & low voltage SWGR & LC	4.3	4.3		34.3 (note 1)	
IP inverter	247.4	73.8			

Note (1): A momentary load which occurs at the 1st minute of the battery duty cycle (0 ~ 1 min).

Note (2): A random load of (180 A) is loaded 5 min every hour.

if the normal AC power is lost. Loads that are not likely to be on the DC system are space conditioning, non-critical lighting, and convenience receptacles. Otherwise all equipment necessary for the plant to function and provide required circuit control and protection would operate from the DC bus or via IP system providing AC power with DC battery backup.

The loads are classified into continuous, non-continuous, momentary and random loads in accordance with IEEE 485 and based on the battery duty cycle as listed in Table 3 [11].

6. Battery Sizing Calculation Procedures and Results

6.1 Sizing Criteria

The DC battery sizing calculation will follow the following criteria:

- The battery sized to supply the loads for 2 h without load shedding, and 22 h with applying load shedding;

- The minimum allowable cell voltage at any time in the duty cycle is considered to be 1.81 V PC;

- A minimum electrolyte temperature of 65 °F (18.3 °C) shall be used in derating battery capacities;

- To account for future DC loads, a design margin of 15% shall be added, it can be reduced to 10% in order to avoid excessive margin;

- An aging factor of 25% will be considered for Lead acid battery;

- A temperature correction factor will be considered for Lead Acid batteries as 8%;

- An aging factor of 15% will be considered for L-Ion batteries;

- 20% will be considered for temperature correction.

6.2 Calculation Procedure

The Battery sizing calculations were calculated in accordance with IEEE 485 and IEEE 946 using the following procedure.

- Constant-power-load currents had been

calculated based on minimum allowable battery voltage of 105 V DC. For conservatism, 100 V DC at load terminal was used in the calculation to account for voltage drop;

- Random load assignment is accomplished by first sizing the battery without the random load to determine the most limiting period of the duty cycle. The random load is then assigned to the end of the most limiting period and the battery size recalculated;

- Calculated battery size is corrected for a minimum temperature of 65 °F (18.3 °C) with 15% margin and 25% added for aging;

- The K-factor curve of vented lead acid GN-45 was used for battery sizing calculation.

6.3 Results and Discussion

By applying EnerSys Gn-45 battery, channel C & D battery shall be sized to 7,200 Ah to cope with 24 h SBO. As the current dimension of the battery room for

Shin Kori 5, 6 L (11.76 m) × D (8.534 m) is one of the factors that should be considered, the room can allow to implement the proposed strategy by limiting the installation and the spacing between each two tires to 600 mm as shown in Fig. 2, enough space will be saved to implement a supplementary backup source to cope with the last 48 h.

Table 4 Load profile for DC backup system.

Load name	Estimated load (A)	
	55 min × 48 cycles	5 min × 48 cycles
MV & LV switchgear control	4.3	4.3
Safety depressurization valve	40	40
Inverter no-load current		180
Aux. feed-water isolation valve		
Instrument power inverter channel C	73.8	73.8
Miscellaneous valves	7.2	7.2
Reactor trip SWGR		
AFW turbine local control panel	8.8	8.8
Total	134.1	314.1

Fig. 2 Battery room proposed configuration.

Table 5 Class 1E and Non Class 1E combined battery system.

Type	Vented lead acid
Battery model	EnerSys GN-45, 3,600Ah
Number of cells (channel C & D)	58 Cell × 2 (parallel)
Qualification	10CFR50 Appendix B, and ASME NQA-11994
Industrial standard	IEEE-323-1974, IEEE-344-1987, IEEE-450-2002, IEEE-535-2006
Total nominal voltage	125 V DC
Battery capacity (channel C & D)	7,200 Ah
Minimum operating voltage	1.81 V/cell
Voltage range	105-140 V DC
Non-class 1E	125 V DC source
Battery type	lithium-ion
Number of cell per string	45 cell/string
Number of string	1 string
Voltage range	105-140 V DC
Total battery model & capacity	WB-LYP 10,000AH

Required capacity for backup system using lithium ion battery (WB-LYP type) was calculated based on the load profile shown in Table 4.

The capacity required for DC-backup source =

$$134.1 \text{ A} \times 55/60 \text{ H} \times 48 \text{ Cycles} + 314.1 \text{ A} \times 5/60 \text{ H} \times 48 \text{ Cycles} = 7,156.8 \text{ Ah}$$

$$7,156.8 \text{ Ah} \times 1.35 = 9661.68 \text{ Ah}$$

where 1.35 is safety margin and consists of the following factors;

Design margin: 10%;

Aging margin: 25%;

K factor (assumed): 1.

The calculation results for the lithium ion battery show that a 9,661 Ah is required to be a backup source after the depletion of the lead acid battery. This amount of capacity can be achieved by using WB-LYP 10,000 AH. The system's proposed specifications and ratings will be as in Table 5.

7. Conclusions

Throughout this work, Class 1E 125 V DC system

for both channels C & D can be sized to cope with 72 h Extended station blackout by utilizing the largest qualified vented lead acid battery (EnerSys Gn-45) type for 24 h and applying lithium ion (WB-LYP 10000Ah) battery for both channels as supplementary source for 48 hours. As the proposed system will exist at the class 1E battery room, so the system shall pass the seismic qualification test to be applied for APR1400 NPP.

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