Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2015

Verification of Safety Margins of Battery Banks Capacity of Class 1E DC System in a Nuclear Power Plant

Abdulrauf Lukman [a*], Oon-Pyo Zhu [b],
[a] *Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
author:lukman@kaist.ac.kr
[b] *Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon, 305-338, Republic of Korea*
Corresponding author:zhu@kins.re.kr

1. Introduction

The Fukushima Daiichi accident in 2011 resulted in common cause failure of electrical power systems due to earthquake and tsunamis which subsequently caused the melting of the core of three reactors and difficulty in heat removal at the spent fuel pools for long period. This event illustrated how the restoration of AC power can be significantly affected by external events and can take a longer time to recover than was previously postulated [1].

According to Ref[1] “Station blackout (SBO) is generally a plant condition with complete loss of all alternating current (AC) power from off-site sources, from the main generator and from standby AC power sources important to safety to the essential and nonessential switchgear buses. Direct current (DC) power supplies and uninterruptible AC power supplies may be available as long as batteries can supply the loads, alternate AC power supplies are available”. The above IAEA document indicated the importance of batteries during SBO. Prior to the Fukushima accident, most batteries might be designed with coping capability of four hours. However, the accident showed the need for the coping capability to be increased to at least eight hours.

The purpose of this research is to verify the safety capacity margin of the nuclear qualified battery banks of class 1E DC system and test the response to SBO using the load profile of a Korean design nuclear power plant (NPP).

2. DC power supply systems

2.1 DC power supply systems in a NPP

DC Power system in nuclear power plant comprises of batteries and charger. The DC power system is categorized into Class 1E and non-Class 1E. The Class 1E categories are electrical equipment and systems essential for emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal in order to prevent significant release of radioactive material to the environment. To ensure continuing DC power, generally nuclear power plant use Lead-acid batteries [2]. In addition, Class 1E batteries of nuclear power plant are divided into four channels with 116 cells for each channel. To satisfy single failure criteria, these batteries are physically and electrically separated and independent. These channels provide supply to 40KVA inverter, safety system control panels for reactor trip, and engineering safety feature load (ESF). The one line diagram of DC power is presented in figure 1

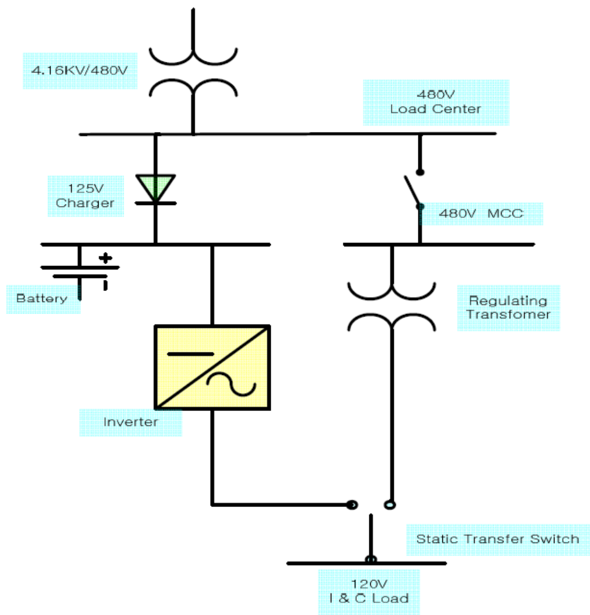

Fig.1. One of the trains of DC system of a nuclear power plant Source: Kim and Cha (2013).

2.2 Lead-acid battery characteristics

The DC power systems of NPPs utilize Lead-acid battery for energy storage, use during SBO. Lead-acid batteries are widely used rechargeable energy storage technology [3]. In addition lead acid batteries are low cost, mature, fast response, and low self-discharge rate, easy to install, and require relatively low level of maintenance [4]. However, Lead-acid batteries are faced with heavy metals pollution problem, and the performance is dependent on the environmental operation conditions. Thus, a change of temperature has a significant impact on the battery lifetime and electrical performance.

2.3 Standard requirements for lead acid battery used in Nuclear Power Plants

In nuclear power plant battery design, installation, maintenance, testing procedures, and qualification are based on the following IEEE Standards. The IEEE Std. 485[5] is recommendation practice used in defining the load and ensuring adequate battery capacity. This showed recommendation on design practice and procedure for storage, location, mounting, ventilation, instrumentation and charging of lead-acid batteries. Details of testing procedure of the DC power system are described in IEEE Std. 450[6]. Design and Installation of large lead-acid batteries is in accordance with IEEE Std. 484[7].

3. Methodology for verification

In general, battery capacity in Ampere-hour (AH) is defined as the stored energy that can be delivered to a constant current load, up to a pre-defined cut-off voltage. Cut-off voltage, also called end voltage of battery discharge, is the voltage designated at the end of the discharge and is defined as a 'safety' voltage above which most of the capacity of the cell has been delivered [8].These capacity determinations depend on the following factors: cell construction, shelf life, charge and discharge cycles, temperature, and aging [2].

The load profile or duty used for this study is of a Korean design NPP. For accuracy the duty cycle of the load was analyzed based on each section as shown in figure 2. This analysis is used to calculate the maximum capacity required by the combined load demands of the various sections with respect to current and time of the duty cycle in an iterative manner. This iterative process is continued until all sections of the duty cycle have been considered. The calculation of the capacity F_S required by each section *s*, is expressed in equation (1). Where *s* can be any integer from 1 to *N*. F_S is expressed as Ampere-hour (AH) [5].

$$F = \max_{s=1}^{N} F_S = \max_{s=1}^{N} \sum_{p=1}^{N} [A_p - A_{(p-1)}] K_t \qquad (1)$$

Where;
F is the cell size uncorrected
s is the section of the duty cycle analyzed
F_s *is the capacity required by each section*
N is the number of periods in the duty cycle
A_p *are amperes required for the period P.*
t is the time in minute from the beginning of the p through end of s
K_t *is the capacity rating factor of a given cell type at t minute and a given temperature*

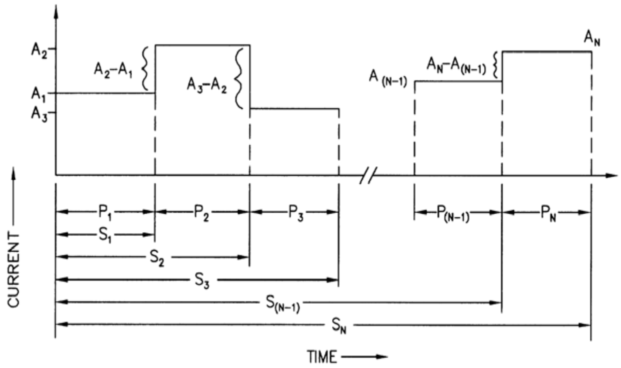

Fig.2. Generalized form of duty cycle.

3.1 Capacity Rating Factor (K_t)

In capacity analysis of batteries the K_t value is very critical due to it variance for different cell voltage, temperature, and duration of time. The capacity rating factor is used in order to reflect discharge efficiency by hours of battery use. K_t factors are obtained from the battery manufacturer [2, 5].

In order to determine the required battery capacity, it is necessary to use the appropriate capacity factor K_t value for the battery. The battery manufacturer and K_t data for the nuclear power plant under consideration was not available. However, for the purpose of this study the K_t value was generated by interpolation for battery range of PS 900 – 2400 ampere hour (AH) and PS 2800 – 4400 AH.

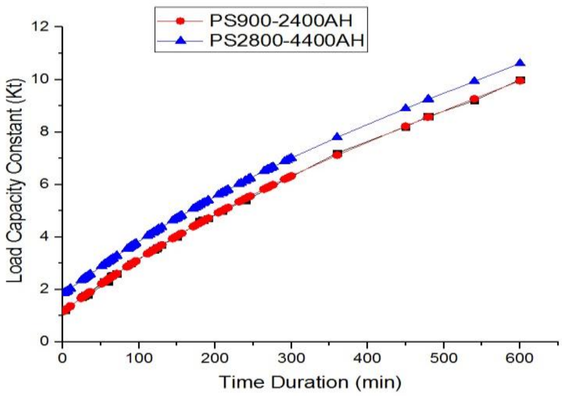

Fig.3. Discharge rate linear curve to generate the K_t value based on eight hour.

The approach that was taken was to use the available K_t data to develop a mathematical curve fitting technique relationship that could be used to estimate the missing data as shown in figure 3 and 4 or denoted 'x' in Column 1 and 3 of Table1. Figure 3 represent the linear curve and figure 4 is the log-log curve for two set of battery K_t values respectively.

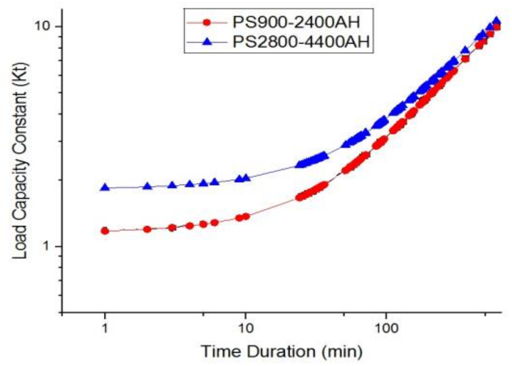

Fig.4. Log-Log curve to generate the K_t value based on eight hour.

The curves was to normalize each of the K_t data that were available for batteries range of PS 900 – 2400 AH and PS 2800 – 4400 AH for a minimum period of eight hours. The procedure use is plotting available data in 'Origin Pro 2015' software, and select appropriate curve that fit data. Examination of the trend of the data suggested that a curve fit to the collective data from the battery would be best represented by a polynomial function. The third order polynomial best fit the curve and equation (2) was generated. Where, T is the time measured in minutes. This resulted in a set of normalized K_t vs. time of Column 2 and 3 of Table 1.

$$K_t = 1.15433 + 0.02181T - \left(1.8458\times10^{-5}\right)T^2 + \left(1.09623\times10^{-8}\right)T^3 \qquad (2)$$

Table I: Capacity factor for a given duration

Time (minute)	Column 1	Column 2	Column 3	Column 4
1	1.25	1.24	1.80	1.84
54	2.3	2.28	3.14	3.12
59	2.45	2.46	3.23	3.19
60	2.5	2.49	3.25	3.20
114	3.4	3.42	X	4.09
119	3.5	3.51	X	4.19
120	3.5	3.52	X	4.20
180	4.6	4.54	5.2	5.23
184	4.65	4.61	X	5.29
234	5.4	5.36	X	6.07
239	5.4	5.46	6	6.14
240	5.4	5.47	6.1	6.16
294	6	6.29	X	6.97
300	6.4	6.34	X	7.01
354	X	7.12	X	7.70
360	X	7.2	X	7.80
384	X	7.51	X	8.31
389	X	7.52	X	8.35
390	X	7.53	X	8.36
474	8.53	8.52	X	9.16
479	8.6	8.57	X	9.24
480	8.6	8.58	X	9.25

Note: X- Not available
(1) Capacity factor K_t (PS 900 – 2400 AH): Available data
(2) Generated value of K_t (PS 900 – 2400 AH)
(3) Capacity factor K_t (PS 2800 – 4400 AH): Available data
(4) Generated value of K_t (PS 2800 – 4400 AH)

3.2 Batteries capacity with duty cycle to be verified

The load profile of the nuclear power plant under consideration is for two and eight hours for the duty cycle for four set of batteries. The batteries are divided into four channels A, B, C, and D. The load profile on channel A and B, channel C, and channel D are illustrated in figures 5, 6 and 7 respectively.

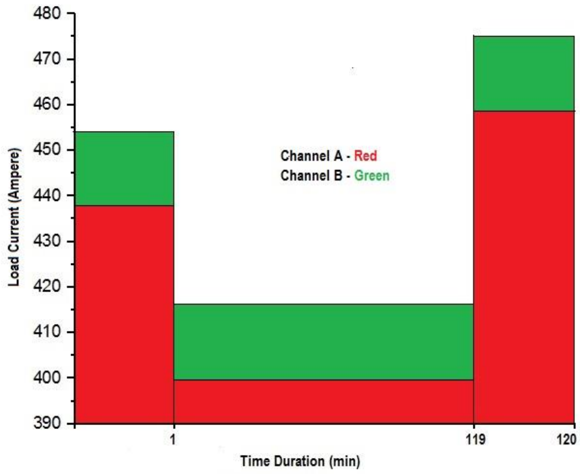

Fig.5. Duty cycle of load profile of channel A and B

Each battery of A and B is sized to supply channel loads of two hours. However battery C and D have load profiles to provide a SBO coping capability which, assumes manual load shedding or the use of load management programs, exceeds 2 hours and, as a minimum, permits operating the instrumentation and control of loads associated with the turbine-driven auxiliary feed-water pumps for 8 hours.

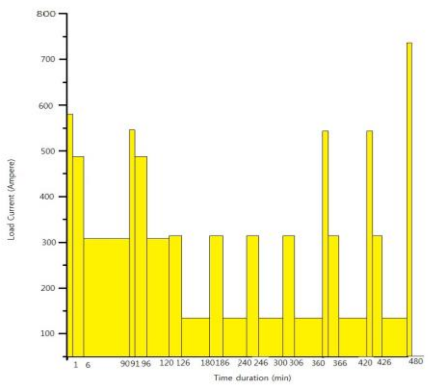

Fig.6. Duty cycle of the load profile on channel C battery of the NPP considered.

4. Result and Discussion

In order to calculate the capacity of the batteries and determine the safety margin of the capacity the aging factor, design margin and temperature correction factor of 1.25, 1.01 and 1.08 respectively are used. These values were selected as specified in IEEE Std 485. Most of the values use for the verification and calculation are chosen in a conservative manner. The corresponding nuclear power plant batteries installed capacity values were tabulated against the calculated value, standard cell size selected, safety margin and percentage of the margins in Table 2.

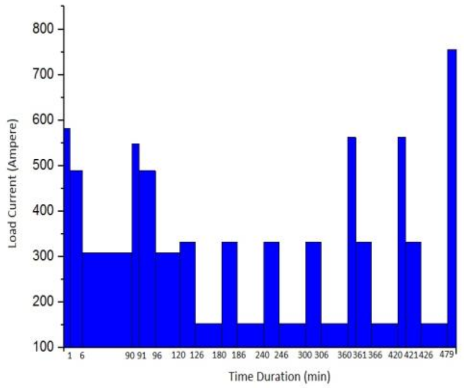

Fig.7. Duty cycle of the load profile on channel D battery of the NPP considered

Table 2: Comparison between calculated values to design value in FSAR of the plant

Batteries channels	Calculated value (AH)	Standard cell size selected (AH)	Plant designed value (AH)	Safety margin (AH)	% margin
Channel A	2206.59	2600	2800	200	7
Channel B	2272.35	2600	2800	200	7
Channel C	3975.91	4000	4400	400	9
Channel D	4015.75	4200	4400	200	5

The cell size is selected based on available standard battery size. When the cell calculated is greater than standard cell size, the next larger cell is required. Therefore 2600AH, 4000AH, and 4200AH are selected for channel A and B, channel C, and channel D respectively. From table 2, the capacity calculated indicated that the capacity margin between the calculated value and that installed for the DC power system of the nuclear power plant considered are 200 AH, 400 AH and 200AH for channels A and B, C and D respectively. The percentage of the capacity margin for channel A and B, C, and D are 7%, 9%, and 5% respectively. The evaluation of the verified capacity for the designed and installed batteries in the NPP of consideration shows that the safety margin for each battery is reasonable.

5. Conclusion

The capacity margins of class 1E batteries of DC power system batteries in a nuclear power plant were determined using the load profile of the plant. It was observed that if appropriate manufacturer K_t data are not available, the accuracy of the battery capacity might not be accurately calculated. However, this study estimate the missing data by mathematical curve fit method in a conservative manner. The result obtained shows that the batteries have the coping capability of two hours for channel A and B, and eight hours for channel C and D. Also capacity margin as show in figure show a reasonable margin for each batteries of the DC system.

6. Future work

The study covered load profile for the range of eight hour. Though, this study showed a reasonable safety margin for the battery considered. In future, it is intended to verify the response of the battery capacity in design extension condition beyond eight hour. Also to improve on the regulatory safety requirement for a robust DC power systems of NPPs.

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