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Kt Factor Analysis of Lead-Acid Battery for Nuclear Power Plant

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Abstract – Electrical equipments of nuclear power plant are divided into class 1E and non-class 1E. Electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, are classified as class 1E. Class 1E batteries of nuclear power plant are divided into four channels, which are physically and electrically separate and independent. The battery bank of class 1E DC power system of the nuclear power plant uses lead-acid batteries in present. The lead acid battery, which has a high energy density, is the most popular form of energy storage. Kt factor of lead-acid battery is used to determine battery size and it is one of calculating coefficient for capacity. This paper analyzes Kt factor of lead-acid battery for the DC power system of nuclear power plant. In addition, correlation between Kt parameter and Peukert's exponent of lead-acid battery for nuclear power plant are discussed. The analytical results contribute to optimize of determining size for Lead-acid battery bank.

Keywords: Kt factor, Lead-acid battery, Peukert's Law

1. Introduction

The lead acid battery, which has a high energy density, is the most popular form of energy storage utilized. And it is generally the most popular energy storage device, because of its low cost and wide availability. The lead acid battery is complex, nonlinear device exhibiting memory effect. The modeling of the battery is a complex process because many phenomenon are occurred inside the battery during its life cycle for example self discharging, gassing effect, diffusion process, acid stratification etc. This effect is caused by the internal resistance of the batteries, and also by what is called "polarization" of the electrolyte in the battery, which causes the voltage to be dragged down when the load current is higher [1]. Kt parameters are used to determine battery size and Peukert's coefficient is utilized to measure battery state of charge (SOC).

2. DC Power for Nuclear Power Plant

Lead-acid batteries are installed across nuclear power plants and have been used DC power system of nuclear power plant. The onsite power system of nuclear power plant is divided into Class 1E and non-Class 1E. Electrical equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, are classified as Class 1E. They are essential in preventing significant release of radioactive material to the environment. Four Class 1E dc power subsystems are provided for each unit. These subsystems are identified as Class 1E on Fig. 1. The dc subsystems A and B provide control power for ac load groups A and B respectively. These subsystems also provide dc power to the inverters for channels A and B respectively. Power for solenoid valves and diesel generator field flashing is also supplied by dc subsystems A and B. The dc subsystems C and D provide dc power to the inverters for channels C and D respectively, as well as to the inverters for the two redundant residual heat removal isolation valves. Subsystem C also provides dc power to the turbine driven auxiliary feedwater pump controls. Each Class 1E dc power subsystem consists of one 125V battery, one battery charger, and one dc control center [2]. 480V bus supplies class 1E 120V I&C (Instrument and Control) load through charger, and regulator transformer.

Class 1E batteries of nuclear power plant are divided into four channels, which are physically and electrically separate and independent and each channel consists of 58 cells or 116 cells. Capacities of all batteries are based on a 10-hour discharge rate. PS-1400 is one type of class 1E 125V DC battery [3].

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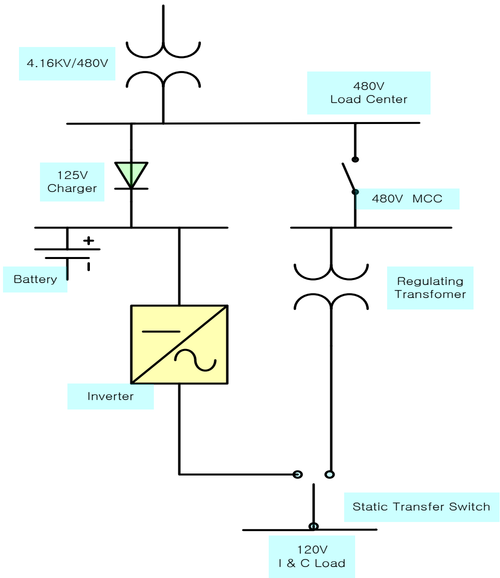

Fig. 1. Single diagram of Class 1E UPS in nuclear power plant

3. Battery of Nuclear Power Plant

3.1 Battery Parameter of Sebang PS-1400

Fig. 2 shows the Sebang PS-1400 type battery that is used in nuclear power plants. It shows the names of each component. Fig. 3 shows states of battery installation of the Class 1E DC power system for the Shinwolsong Nuclear Power Plant. PS-1400 battery is a valve regulated lead acid rechargeable battery, 2V, 1400Ah.

Table 1. Parameter of Battery

Normal Voltage	2 V
Final Voltage	1.81 V
Discharge Rate	10 hour
Capacity	1400 Ah

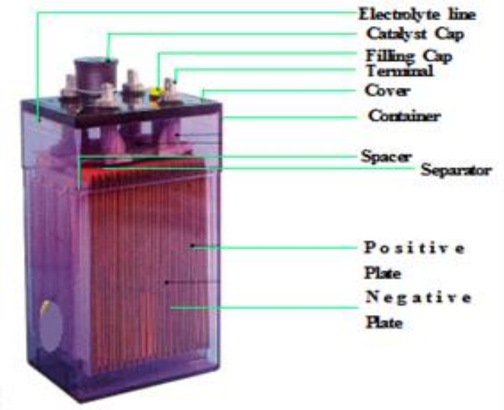

Fig. 2. The Sebang PS-1400 type battery

Fig. 3. Battery room in nuclear power plant

3.2 Manufacture's Data

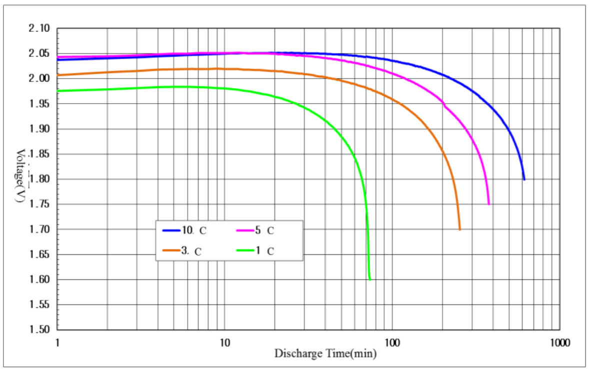

Fig. 4. Discharge Characteristics Curve

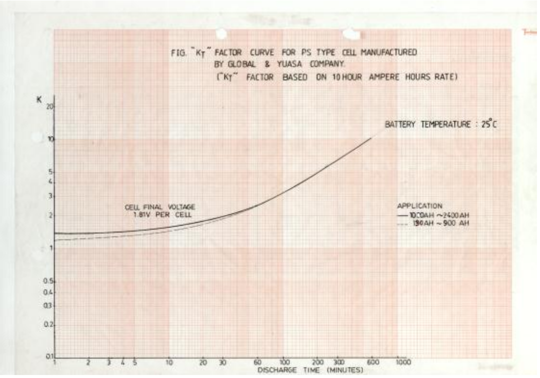

Fig. 5. K_t factor curve

The Fig. 4 shows discharge characteristics curve by cell manufacture. The Fig. 5 is Kt factor curve of the battery manufacture. These are obtained by battery manufacture, and these curves are used to Kt Factor of worksheet when calculating the cell size.

3.3 Battery Capacity

Battery capacity in Amp-hour is defined as the stored charge that can be delivered to a constant current load, up to a pre-defined cut-off voltage. Battery capacity is dependent on several factors including, but not limited to the following: cell construction, shelf life, charge and discharge cycles, temperature, and aging. The Amp-hour capacity of any group of cells may vary by ± 20% to ± 500% when shelf time, number of recharge cycles, manufacturing variances and possibly other factors are taken into account[4].

3.4 Battery Sizing Methodology

The cell selected for a specific duty cycle must have enough capacity to carry the combined loads during the duty cycle. To determine the required cell size, it is necessary to calculate, from an analysis of each section of the duty cycle (see Figure 6), the maximum capacity required by the combined load demands (current versus time) of the various sections. The first section analyzed is the first period of the duty cycle. Using the capacity rating factor for the given cell type, a cell size is calculated that will supply the required current for the duration of the first period. For the second section, the capacity is calculated assuming that the current A1, required for the first period, continued through the second period; this capacity is then adjusted for the change in current (A2–A1) during the second period. In the same manner, the capacity is calculated for each subsequent section of the duty cycle. This iterative process is continued until all sections of the duty cycle have been considered. The calculation of the capacity FS required by each section S, where S can be any integer from 1 to N, is expressed mathematically in Equation (1). FS will be expressed as watt-hours, ampere-hours, or number of positive plates, depending upon which Ct is used capacity rating factor [5].

$$F_S = \sum_{p=1}^{p=s} \frac{A_P - A_{(P-1)}}{C_t} \qquad (1)$$

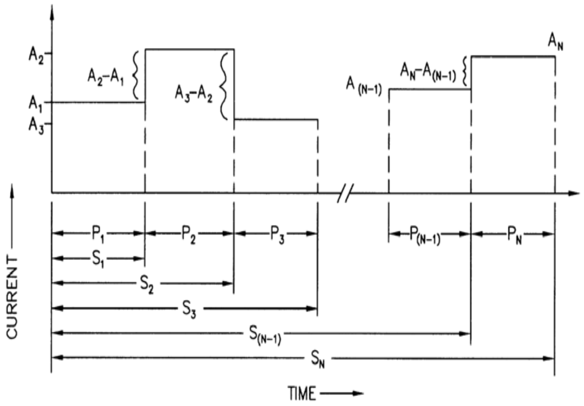

Fig. 6. Generalized Duty Cycle

The maximum capacity (max FS) calculated determines the uncorrected cell size that can be expressed by the following general equation.

$$F = \max \overset{s=N}{\underset{s=1}{F_S}} \qquad (2)$$

F is the cell size (uncorrected for temperature, aging, and design margin). S is the section of the duty cycle being analyzed. Section S contains the first S periods of the duty cycle (e.g., section S5 contains periods S1 through S5). See Figure 6 for a graphical representation of "section." N is the number of periods in the duty cycle; P is the period being analyzed. AP are the amperes required for period P. t is the time in minutes from the beginning of period P through the end of Section S. Ct is the capacity rating factor for a given cell type, at the t minute discharge rate, at 25° C (77 ℉), to a definite minimum cell voltage. FS is the capacity required by each section.

There are expressing the capacity rating factor Ct of a given cell type in cell sizing calculations. The other term Kt is the ratio of rated ampere-hour capacity [at a standard time rate, at 25 ℃ (77 ℉) and to a standard minimum cell voltage] of a cell, to the amperes that can be supplied by that cell for t minutes at 25 ℃ (77 ℉) and to a given minimum cell voltage. Therefore, Ct = 1/Kt can be written [5].

As follows:

$$F = \max \overset{s=N}{\underset{S=1}{F_S}} = \max_{S=1}^{S=N} \sum_{P=1}^{P=S} [A_P - A_{(P-1)}]K_t \qquad (3)$$

4. Peukert's Equation

4.1 Capacity Rating Factor (K_t)

Battery has discharge rate by battery type and change capacity according to discharge current. The capacity rating factor is used in order to reflect discharge efficiency by hours of battery use. This is expressed Kt factor. Kt factors are obtained battery manufactures. Kt of battery is expressed as:

$$K_t = C / I \qquad (4\text{-}1)$$

Where Kt is capacity rating factor, C is rated capacity, I is discharge current. Discharge current of battery is expressed as:

$$I = C / K_t \tag{4-2}$$

$$I = 1400\text{Ah}/2.5 = 560\text{A} \tag{4-3}$$

This is calculated when Kt is 2.5 at 1 hour and rated capacity is 1400Ah. It is calculated as the following Kt of the table 2.

4.2 Peukert's Law

Peukert's law is known that increasing the average level of current extracted from the battery decreases the discharge capacity. Peukert's law expresses the capacity of a battery in terms of the rate at which it is discharged. It is described as the following equation [6].

$$CN = Ik \cdot t \qquad (k>1) \tag{5}$$

Where C_N is the nominal capacity of the battery, I is the discharge current, k is the Peukert's exponent which is determined by the characteristics of batteries and more than one, and t is the time of discharge. Because C_N is given, this equation indicates that the time of discharge decreases exponentially as the discharge current increases. In addition, discharge capacity C_D is described as follows using the same notation as:

$$C_D = I \cdot t = I\ 1-K \cdot C_N \qquad (k>1) \tag{6}$$

This equation also means that excessive I decreases the discharge capacity[5].

This electrochemical phenomenon is explained as follows. The discharge capacity of a battery is determined by the availability and accessibility of active reaction sites, which are parts of the electrode where electro-chemical reactions occur. When the discharge current is low, the inactive sites, where there are inactive compounds formed by previous reactions, are distributed uniformly throughout the electrode. On the other hand, when the discharge current is high, reactions occur only at the surface of the electrode and the surface is coated with inactive compounds. This makes inner active sites inaccessible. Consequently, the battery is declared fully discharged even though many active sites remain unutilized[6]

4.3 Peukert's Exponent

The original Peukert's equation operates from the starting point that the battery capacity is the total amp hours that can be drawn from the battery at a discharge rate of 1 amp. Batteries are never specified this way so the extra term (C/R)n-1 corrects the given capacity specification to match that at 1 amp current draw.

Since I=C/R and $I_p=I^n$ then $I_p=(C/R)^n$
and C_p=RI therefore,

$$C_p = (C/R)^n R = C^n/R^{n-1} = C(C/R)^{n-1} \tag{7}$$

Note the final term here: C(C/R)n-1 which is how the capacity was defined in the modified equation.

This is now a capacity that can be used with the normal Peukert's equation of T=C/In

We also know that the Peukert's Capacity Cp1 and Cp2 must be equal because this never changes for any one particular battery.

$$Cp_1 = Cp_2$$

And therefore

$$C_1(C_1/R_1)^{n-1} = C_2(C_2/R_2)^{n-1} \tag{8-1}$$

Thus we may also write

$$\text{Log}\ [C_1(C_1/R_1)^{n-1}] = \text{Log}\ [C_2(C_2/R_2)^{n-1}] \tag{8-2}$$

This can be simplified to:

$$\text{Log C1} + (n-1)\ \text{Log (C1/R1)} = \text{Log C2} + (n-1) \tag{8-3}$$

Rearranging

$$(n-1)\ \text{Log}\ (C_1/R_1) - (n-1)\ \text{Log}\ (C_2/R_2) = \text{Log}\ C_2 \tag{8-4}$$

This simplifies to

$$(n-1)\ [\text{Log}\ (C_1R_2/C_2R_1)] = \text{Log}\ (C_2/C_1) \tag{8-5}$$

Therefore

$$n = 1 + [\text{Log}\ (C_2/C_1)] / [\text{Log}\ (C_1R_2/C_2R_1)] \tag{8-6}$$

Which simplifies again to

$$n = [\text{Log}\ (R_2/R_1)] / [\text{Log}\ (C_1/R_1) - \text{Log}\ (C_2/R_2)] \tag{8-7}$$

R_1 and R_2 are discharge time of the battery, C_1 and C_2 are capacity at different discharge rate. Peukert's exponents are derived as:

$$[\text{Log}\ (1/10)] / [\text{Log}\ (1400/10) - \text{Log}\ (560/1)] = 1.661 \tag{9-1}$$

$$[\text{Log}(4/10)] / [\text{Log}(1400/10) - \text{Log}(1036/4)] = 1.489 \quad (9\text{-}2)$$

$$[\text{Log}(5/10)] / [\text{Log}(1400/10) - \text{Log}(1094/5)] = 1.552 \quad (9\text{-}3)$$

The calculation results of Peukert's exponent under different discharge time and capacity are shown in table Ⅱ. These are used to obtain Peukert's exponent. This paper is obtained discharge capacity using the manufacturers' data sheet K_t parameters. It is calculated as the following Peukert's exponent of the table Ⅱ.

The figure 7 shows the relation between K_t factor and discharge time. It changes K_t factor during 600 minute. The figure 8 shows the change Peukert's exponent and discharge time at 1hr, 3hr, 5hr, and 7hr. The K_t factor curve is drawn as linear curve. The values can utilize to optimize of determining size for Lead-acid battery bank. The analytical results contribute to optimize of determining size for Lead-acid battery bank. Also K_t factor and Peukert's exponent of lithium battery will use to evaluate Lithium battery capacity.

Table 1. Kt Factor and Peukert's Exponent

Discharge Time [Hour]	Discharge Current [A]	Capacity [Ah]	K_t factor	Peukert's Exponent
1	560	560	2.5	1.661
3	304	912	4.6	1.553
5	219	1094	6.4	1.552
7	179	1253	7.8	1.451
10	140	1400	10	-

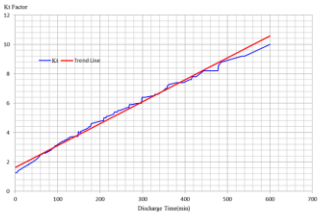

Fig. 7. PS-1400's K_t factor curve

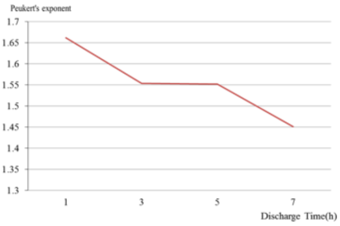

Fig. 8. K_t factor and Peukert's exponent curve

5. Conclusion

Kt factor of lead-acid battery is used to determine battery size and it is one of calculating coefficient for capacity. This paper analyzes Kt factor of lead-acid battery for the DC power system of nuclear power plant. In addition, correlation between Kt parameter and Peukert's constant of lead-acid battery for nuclear power plant are discussed. The analytical results contribute to optimize of determining size for Lead-acid battery bank. If we get Kt factor and Peukert's exponent of variety secondary batteries, it will use to evaluate battery determining size and battery state of charge (SOC).

Safety improvements implemented or planned of the Fukushima accident has been considered a variety of mobile devices such as mobile generators, mobile battery chargers or mobile DC power sources in nuclear power plants. A variety mobile DC power sources are more likely to use in nuclear power plants. We need to evaluate capacity of mobile DC power sources that is optimized to use Kt and Peukert's exponent.

References

[1] Ralph Hiesey, "Some comments on Peukert's compensation", Bogart Engineering, April 2011.

[2] Daesik Kim and Hanju Cha, "Analysis on Lead-Acid Battery Bank for Nuclear Power Plants in Korea", IEEE 7th International Power Electronics and Motion Control Conference - ECCE Asia, pp.2118-2122, May 2012

[3] Nosh K. Medora and Alexander Kusko, "An Enhanced Dynamic Battery Model of Lead-Acid Batteries Using Manufacturers' Data", IEEE, pp.21-1, 2006

[4] "IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications", ANSI/IEEE Standard 485-2010

[5] Takeshi KITAHARA and Hajime NAKAMURA, "A Data Transmission Control to Maximize Discharge Capacity of Battery" IEEE Communications Society, pp. 2951-2956, WCNC 2008.

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