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

Daesik Kim *, and Hanju Cha **

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].

* Dept. of I&C and Electricity, Korea Institute of Nuclear Safety, Korea (dskim@kins.re.kr)
** Department of Electrical Engineering, Chungnam National University, Korea (hjcha@cnu.ac.kr)

Received 16 October 2013; Accepted 28 October 2013
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Voltage</td>
<td>2 V</td>
</tr>
<tr>
<td>Final Voltage</td>
<td>1.81 V</td>
</tr>
<tr>
<td>Discharge Rate</td>
<td>10 hour</td>
</tr>
<tr>
<td>Capacity</td>
<td>1400 Ah</td>
</tr>
</tbody>
</table>

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).

\[ F_s = \sum_{p=1}^{N} \frac{A_p - A_{p-1}}{C_t} \]  

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

\[ F = \max_{s=1}^{s=N} F_s \]  

\[ F = \max_{s=1}^{s=N} \left( \sum_{p=1}^{P_s} [A_p - A_{p-1}] \right) K_t \]  

4. Peukert’s Equation

4.1 Capacity Rating Factor (Kt)

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:

\[ K_t = C / I \]  

Where Kt is capacity rating factor, C is rated capacity, I is discharge current. Discharge current of battery is expressed as:
Batteries are never specified this way so the extra term \((/n-1)\) corrects the given capacity specification to match that at 1 amp current draw.

Since \(l=C/R\) and \(l=p\) then \(l=p(C/R)^n\) and \(C_p=I R\) therefore,

\[C_p = (C/R)^n R = C^n R^{n-1} = C(C/R)^{n-1}\]  

(7)

Note the final term here: \((C/R)n-1\) 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 \(T=C/I\)

We also know that the Peukert's Capacity \(C_p1\) and \(C_p2\) must be equal because this never changes for any one particular battery.

\[C_p1 = C_p2\]

And therefore

\[C_p1(C_p1/R_1)^{n-1} = C_p2(C_p2/R_2)^{n-1}\]  

(8-1)

Thus we may also write

\[\log [C_p1(C_p1/R_1)^{n-1}] = \log [C_p2(C_p2/R_2)^{n-1}]\]  

(8-2)

This can be simplified to:

\[\log C1 + (n-1) \log (C1/R1) = \log C2 + (n-1)\]  

(8-3)

Rearranging

\[\log (n-1) \log (C_p1/R_1) - (n-1) \log (C_p2/R_2) = \log C2\]  

(8-4)

This simplifies to

\[\log (n-1) \log (C_p1/R_1/C_p2/R_2) = \log (C_p2/C_p1)\]  

(8-5)

Therefore

\[n = 1 + [\log (C_p2/C_p1)] / [\log (C_p1/R_1/C_p2/R_2)]\]  

(8-6)

Which simplifies again to

\[n = [\log (R_2/R_1)] / [\log (C_p1/R_1) - \log (C_p2/R_2)]\]  

(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:

\[[\log (1/10)] / [\log (1400/10) – \log (560/1)] = 1.661 (9-1)\]
[Log (4/10)] / [Log (1400/10) – Log (1036/4)] = 1.489 (9-2)
[Log (5/10)] / [Log (1400/10) – Log (1094/5)] = 1.552 (9-3)

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

Table 1. Kt Factor and Peukert’s Exponent

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>560</td>
<td>560</td>
<td>2.5</td>
<td>1.661</td>
</tr>
<tr>
<td>3</td>
<td>304</td>
<td>912</td>
<td>4.6</td>
<td>1.553</td>
</tr>
<tr>
<td>5</td>
<td>219</td>
<td>1094</td>
<td>6.4</td>
<td>1.552</td>
</tr>
<tr>
<td>7</td>
<td>179</td>
<td>1253</td>
<td>7.8</td>
<td>1.451</td>
</tr>
<tr>
<td>10</td>
<td>140</td>
<td>1400</td>
<td>10</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 7. PS-1400’s Kt factor curve

Fig. 8. Kt 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 Fukuushima 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


Daesik Kim received his B.S. degree in Nuclear Engineering from Chosun University and M.S degree in Electrical Engineering from Chungnam National University, Korea in 1995 and 2011, respectively. He is in the course of PhD in Electrical Engineering from Chungnam National University, Daegoeon, Korea. His research interests are lead-acid battery; lithium-ion battery; BMS(Battery Management System); transfer switch.
Hanju Cha received his B.S. degree in Electrical Engineering from Seoul National University, Korea, and M.S degree in the same field from Pohang Institute of Science and Technology, Korea in 1988 and 1990, respectively. He obtained his PhD in Electrical Engineering from Texas A&M University, College Station, Texas in 2004. From 1990 to 2001, he was with LG Industrial Systems in Anyang, Korea where he was engaged in the development of power electronics and adjustable speed drives. In 2005, he joined the Department of Electrical Engineering, Chungnam National University, Daejeon, Korea. He worked as a visiting professor in the United Technology Research Center, Hartford CT, USA in 2009. His research interests are advanced ac/dc, dc/ac, and ac/ac converters; renewable energy system; power quality; energy storage system and micro-grids.