# DESIGN AND OPERATION SCHEMES FOR BATTERY ENERGY STORAGE SYSTEMS IN LOW-VOLTAGE DC DISTRIBUTION SYSTEMS CONSIDERING VOLTAGE CONTROL AND ECONOMIC FEASIBILITY

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## *ABSTRACT*

*Low voltage DC (LVDC) distribution system is a promising candidate that can create an innovative solution for distribution networks that can serve electric power with high quality and efficiency. By the way, LVDC systems are intrinsically weak to voltage drop and energy losses in the lines. It is fairly difficult to maintain the voltages within a predefined region in LVDC systems. This paper discusses the advantages of the use of a battery energy storage system (BESS) in LVDC distribution systems to effectively control the voltages. The procedure to design BESSs in LVDC systems is presented. This paper also presents methods of power flow and economic analysis for LVDC systems.*

## INTRODUCTION

DC distribution systems have strengths especially when they are integrated to power electronic loads and distributed energy resources such as photovoltaics or energy storage systems. In addition, DC systems are a promising candidate for small-scale power networks for homes, buildings, and internet data centres [1].

On the other hand, there have been pioneering researches to apply DC distribution systems to long-distance distribution systems. References [2] and [3] demonstrates economic potential and viability of low-voltage DC (LVDC) distribution systems. Their first pilot plant was implemented in Finland. The references enumerated the benefits and incentives acquired while using LVDC distribution systems. In [3], a set of methodology and formulation for evaluating economic benefits of LVDC systems was addressed against medium-voltage AC (MVAC) systems. The authors showed how to improve the reliability and quality of service to customers with LVDC distribution systems.

Recently, the Korea Electric Power Corporation (KEPCO) plans to renovate some application of 22.9kV MVAC network with LVDC distribution technology. References [4] and [5] presents the results of previous studies that proves economic feasibility of $1500V_{DC}$ distribution system for rural distribution systems.

However, despite its advantages, LVDC distribution systems are intrinsicallyy vulnerable to voltage variations compared to MV systems. To deal with the shortcomings, the paper propose to use a battery energy storage system (BESS) that can help to improve the voltage profile and reduce line losses in LVDC distribution systems. BESSs can also bring economic benefits through peak-loads shaving. This paper discusses design strategies of a BESS for a LVDC system considering voltage control and economic benefits.

## LVDC DISTRIBUTION SYSTEM

Fig. 1 shows the configuration of the bipolar LVDC distribution system with three connections – positive, negative and neutral nodes. This configuration has three distribution lines whose voltages are rated as $750V_{DC}$, $0V_{DC}$, and $-750V_{DC}$, respectively. The loads are connected between the positive and negative poles so that the rated distribution voltage is $1,500V_{DC}$. The neutral line provides natural point for earthing.

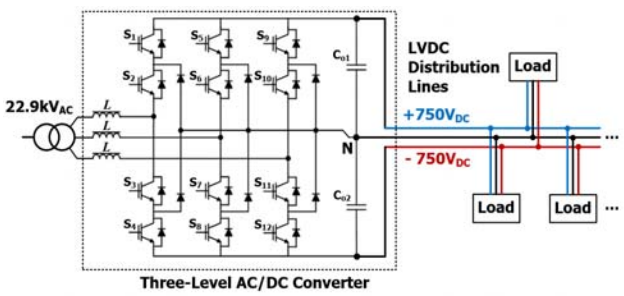


Fig. 1. Configuration of a bipolar LVDC distribution system with a three-level converter

The rated voltage $1500V_{DC}$ is chosen according the European Standard in [2]. The bipolar networks can improve system reliability efficiently because the power converters of loads can be energized by both $750V_{DC}$ and $1500V_{DC}$. This means that when a fault occurs at one pole, load power can be supplied by the other pole. Therefore, bipolar systems have natural redundancy, which is technically classified into N-1 contingency.

## VOLTAGE REGULATION IN LVDC SYSTEM

Although LVDC systems can bring many advantages to rural distribution systems, they can suffer signficant voltage drop and line losses compared to MV distribution. According to the regulation of distribution systems, KEPCO must maintain the bus voltage within 5% variation from the rated voltage. This restricts the extension of LVDC distribution systems.

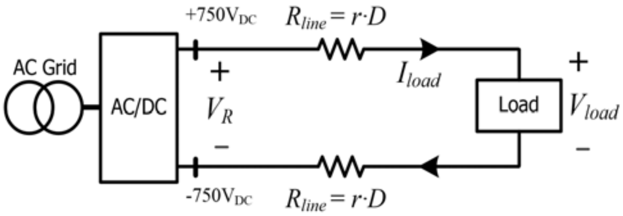


Fig. 2. Simplified distribution line model to calculate the maximum length of distribution lines

Fig. 2 illustrates a simplified model to calculate the maximum line length of the LVDC system. Then, the load voltage ($V_{load}$) must meet the following condition as

$$V_{load} = V_R - 2r \cdot D \cdot I_{load} \geq (1-T) \cdot V_{rated} \qquad (1)$$

where $T$ is the voltage tolerance (=0.05); $r$ is the line resistance per length; $D$ is the line length; $I_{load}$ is the line current ; and $V_{rated}$ is the rated line-to-line voltage. It must be noted that because the current flows through both positive and negative lines in bipolar LVDC systems, the equivalent line resistance is doubled from single line resistance. Then, the maximum line length can be formulated from (1) as

$$D \leq \frac{T \cdot (1-T) \cdot V_{rated}^2}{2r \cdot P_{load}} \qquad (2)$$

where, $P_{load}$ is the power consumed by the load.

Table 1 shows the maximum line lengths of LVDC distribution system calculated from (2). The maximum line lengths are determined with respect to the types of distribution lines and the sizes of load power. It can be noted that the lengths of the LVDC distribution system is limited within just a few kilometers. If we can compensate the voltage of the line, the line length of the LVDC system can be extended. To this end, the voltage compensation using battery energy storage system is the main idea of this paper.

TABLE 1. THE MAXIMUM LINE LENGTHS OF LVDC DISTRIBUTION LINE THAT MEETS THE VOLTAGE REGULATION (5% TOLERANCE)

| Load [kW] / Line Type | 50 | 100 | 150 | 200 | 250 | 300 |
|---|---|---|---|---|---|---|
| OW 38 mm$^2$ | 2.12 | 1.06 | 0.71 | 0.53 | 0.42 | 0.35 |
| OW 60 mm$^2$ | 3.40 | 1.70 | 1.13 | 0.85 | 0.68 | 0.57 |
| OW 150 mm$^2$ | 8.76 | 4.38 | 2.92 | 2.19 | 1.75 | 1.46 |

## LVDC SYSTEM MODELING

Fig. 3 illustrates the single line diagram of the LVDC distribution system planned to be installed in Geoje Island, by KEPCO. The original MVAC system has served six communication repeaters on top of the mountain named as Oknyeobong Peak in the island [5]. The total length of the distribution lines is about 1.6km from the main AC/DC converter at the foot of the mountain to the end of the line. According to the KEPCO's plan, OW 60mm$^2$ will be used for overhead lines.

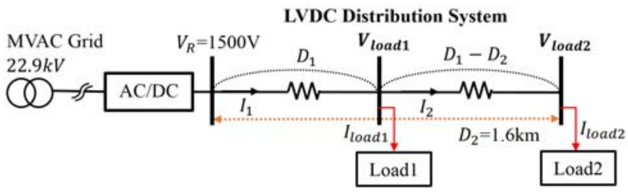


Fig. 3. Single line circuit diagram of LVDC distribution system

In the original system, communication loads are scattered on the mountain. However, in this paper, we simplified the load models into two identical equivalent loads as shown in Fig. 3 for simplicity in computation. It is also assumed that one of the loads is located in the middle of the system and the other is connected to the very end of the line. The typical daily load pattern as shown in Fig. 4 is applied to the simulation studies. Fig. 5 shows the load voltages when the load pattern is applied to the system. The simulation was obtained via power flow algorithms explained in the next section. As a result, it is noted that the voltages drop under the lower limits during peak-loading conditions.

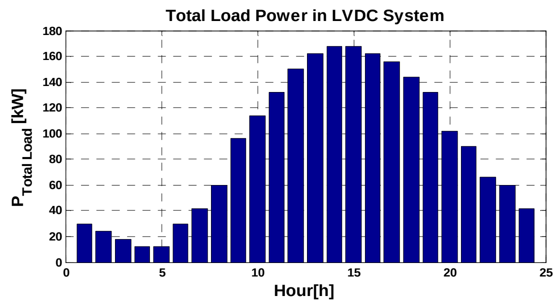


Fig. 4. Daily load pattern of the total load in the LVDC distribution system

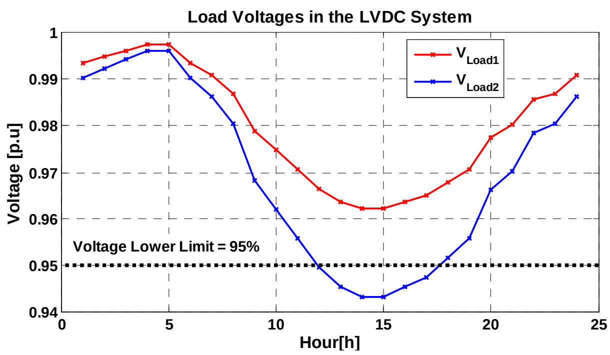


Fig. 5. Power flow simulation results – load voltages

## POWER FLOW ANALYSIS ALGORITHM FOR DC DISTRIBUTION SYSTEM

To analyse the effect of BESSs in LVDC systems, this paper formulates power flow equations for DC distribution systems. Among various power flow algorithms, this paper modifies Forward Sweeping Method proposed by [6] fit for DC distribution systems. This method is efficient especially for radial distribution systems because it is not needed to calculate the inverse of Jacobian matrix. On top of it, convergence of the algorithm is guaranteed for practical radial distribution systems with realistic R/X ratios [5].

Fig. 6 shows the equivalent circuit model of radial DC distribution system. The circuit equations of Fig. 6 can be expressed as

$$P(i) = V(i)\cdot I(i) = \sum_{j=i}^{N} P_{load}(j) + \sum_{j=i}^{N-1} P_{loss}(j) \tag{3}$$

$$V(i+1) = V(i) - R(i)I(i) \tag{4}$$

$$P_{loss}(i) = \frac{[V(i) - V(i+1)]^2}{R(i)} \tag{5}$$

where, $i$ is the bus index; $N$ is the total number of buses; $V(i)$ is the voltage at bus $i$; $I(i)$ and $R(i)$ is the line current and the equivalent line resistance between buses $i$ and $i+1$, respectively; $P(i)$ is the real power injected to bus $i$; $P_{load}(i)$ is the load power at bus $i$, which is a given value in the power flow analysis; and $P_{loss}(i)$ is the power loss caused by the line resistance $R(i)$.

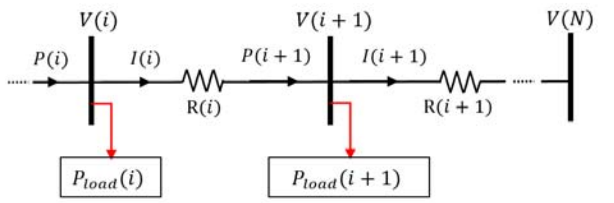


Fig. 6. Equivalent circuit diagram of a radial DC distribution system to formulate power flow equations

The parameters of (3), (4) and (5) can be obtained recursively by adopting Gauss-Seidel method. The parameters of ($k$+1)-th iteration can be obtained from the values of $k$-th iteration as

$$P(i)^{(k+1)} = \sum_{j=i}^{N} P_{load}(j) + \sum_{j=i}^{N-1} P_{loss}(j)^{(k)} \tag{6}$$

$$V(i+1)^{(k+1)} = \frac{V(i)^{(k+1)} + \sqrt{\left[V(i)^{(k+1)}\right]^2 - 4R(i)P(i+1)^{(k+1)}}}{2} \tag{7}$$

$$P_{loss}(i)^{(k+1)} = \frac{\left[V(i)^{(k+1)} - V(i+1)^{(k+1)}\right]^2}{R(i)} \tag{8}$$

where, $V(1)$ is the voltage at the main AC/DC converter, which is given as 1.0 p.u because it is controlled by the AC/DC converter.

The voltages at the neighboring buses can be calcuated sequentially by using (7). All the initial values for $P_{loss}$ are set to zero. The iteration continues until the the obtained power values converge within a predifined tolerance. According to our experience, all the values converge to the solutions rapidly within 5 iteraions.

## SIZE AND LOCATION OF BESS

### Location of BESS in LVDC system

It is possible to choose several objectives to determine the optimal location of a BESS in a LVDC system. For instance, loss minimization can be a good example. In this paper, voltage regulation is the most important objective. Because the voltage of load 2 is the lowest in the LVDC system, the location of the BESS can be determined as the end of the line where the load 2 is connected. Fig. 7 illustrates the location of the BESS according to the above discussion.

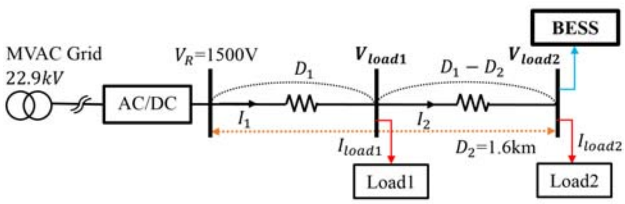


Fig. 7. Single line circuit diagram of LVDC distribution system with BESS installation

### Size of BESS for voltage control

The voltage control of the LVDC system is the prominent interest in this paper. To this end, the size of BESS must be selected to maintain the load voltage in normal regions regardless of loading conditions. From Fig. 7, the voltages of the loads ($V_{load1}$ and $V_{load2}$) can be expressed as

$$V_{load1} = V_{rated} - 2rD_1\left(\frac{P_{load1}}{V_{load1}} + \frac{P_{load2}}{V_{load2}}\right) \tag{9}$$

$$V_{load2} = V_{load1} - 2r(D_2 - D_1)\frac{P_{load2}}{V_{load2}} \tag{10}$$

where $P_{load1}$ and $P_{load2}$ are the power absorbed by load 1 and load 2, respectively; $r$ is the line resistance per unit length; and $D_1$ and $D_2$ are the distances of load 1 and 2 from the main AC/DC converter, respectively. Equations (9) and (10) can be rewritten with respect to $P_{load2}$ as

$$P_{load2} = \left(V_{rated} - 2rD_1\frac{P_{load1}}{V_{load1}} - V_{load2}\right)\cdot\frac{V_{load2}}{2rD_2} \tag{11}$$

Because the voltage at the load 2 ($V_{load2}$) must be larger than the minimum voltage limit as $V_{load2} \geq V_{rated}(1\text{-}T)$, the maximum allowed power consumption at the load 2 can be obtained as

$$P_{load2}^{max} = \left( T \cdot V_{rated} - 2rD_1 \frac{P_{load1}}{V_{load1}} \right) \cdot \frac{V_{rated}(1-T)}{2rD_2} \qquad (12)$$

If $P_{load2}$ is larger than $P_{load2}^{max}$, the BESS discharges the same power as the difference between $P_{load2}^{max}$ and $P_{load2}$ to make $V_{load2}$ higher than the minimum voltage. The discharging power of the BESS can be determined as

$$P_{BESS}^{discharge} = P_{load2} - P_{load2}^{max} \quad \text{if} \quad P_{load2} > P_{load2}^{max} \qquad (13)$$

Then, we can decide the battery size ($S_{BESS}$) as

$$S_{BESS} = \left( \sum_{h=1}^{24} P_{BESS}^{discharge}(h) \right) / DOD \qquad (14)$$

where $DOD$ is the depth of discharge of the battery (DOD). Because the DOD is related to the lifespan of battery packs, it is one of the parameters for economic analysis for BESSs. In this paper, we set the value of DOD to 70%.

The total amount of discharging power of the BESS must be the same as the total charging power of the BESS. Normally, the BESS can gain economic benefits by charging during off-peak period with cheaper price and discharging during peak-loading period. Therefore, the BESS normally shaves the peak loads and fills the low valley of the load curve. The size of the power converter of the BESS ($S_{PCS}$) can be determined as follows.

$$S_{PCS} = max\left( P_{BESS}^{discharge}, P_{BESS}^{charge} \right) \cdot (1+m) \qquad (15)$$

where $m$ is the design margin for power converters, which is set to 20% in this paper.

From (14) and (15), the sizes of the battery ($S_{BESS}$) and the power converter of the BESS ($S_{PCS}$) are determined to 77 kWh and 21 kW, respectivley in the LVDC model of this paper. Fig. 8 shows the charging and discharing powers of the BESS. Fig. 9 shows the load power before and after the BESS operation. It can be seen that the BESS can smoothe the load variation by peak load shaving. Fig. 10 shows the load voltages after BESS operation. When compared to the results of Fig. 5, the load voltages can be maintained above the 95% lower limit.

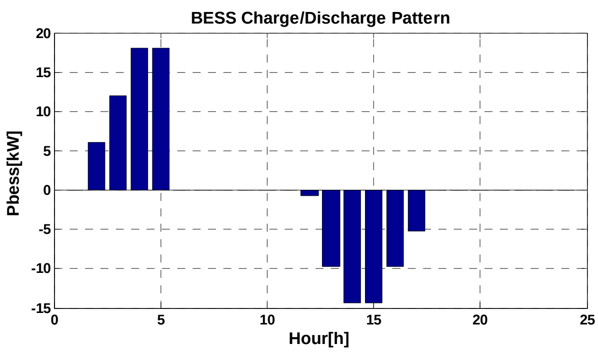


Fig. 8. Charging and discharging powers of the BESS (the positive values: charging, the negative value: discharging)

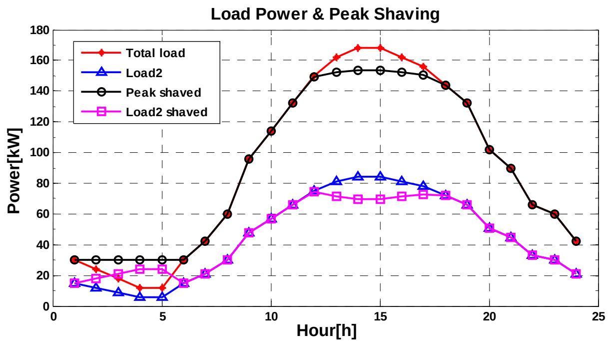


Fig. 9. Load powers before and after BESS operation

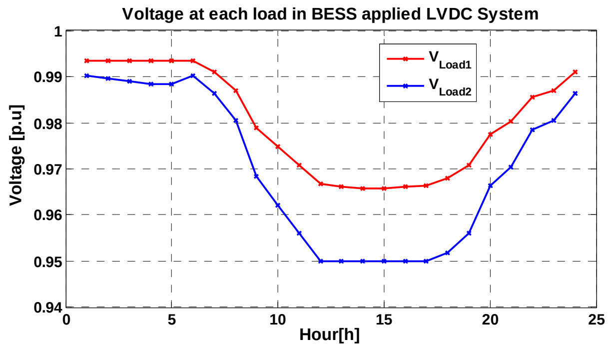


Fig. 10 Load voltages after BESS operation

## ECONOMIC ANALYSIS

This section provides the result of economic analysis of the LVDC distribution system based on net present values (NPVs). Table 2 lists the parameters for the economic analysis. The total period for the analysis is set to 30 years and the interest rate is roughly estimated to 7%. We assumed the lifespan of BESSs is 15 years in this study. Because the total period is 30 years, the BESS must be reinstalled after 15 years after the first installation.

Table 3 shows the result of NPV analysis of the BESS installation and operation in the LVDC distribution system. In this analysis, we used the parameters of NaS battery as an example. There are four categories such as installation cost, charging cost, loss reduction benefit, and discharging benefit in the analysis. Positive values mean expenses whereas negative values are profits in Table 3. Then, the NPV of the total expense for the BESS installation and operation is about 27 million Korean Won (KRW), which is similar to 27 thousand US dollars.

Table 4 shows the result of NPV analysis of installation of additional DC line to solve the voltage problem instead of using BESSs. Although additional DC line can easily deal with the line losses, its resultant NPV is higher than the BESS. Therefore, this economic analysis shows that BESSs can be economic solutions to deal with voltage problems for the LVDC system given in this paper.

TABLE 2. PARAMETERS FOR ECONOMIC ANALYSIS

| Parameters | | Value |
|---|---|---|
| Interest rate | | 7% |
| Distribution systems economic life time | | 30 years |
| Lifespan of the BESS | | 15 years |
| Battery size of the BESS | | 77 kWh |
| Power converter size of the BESS | | 21kW |
| Depth of Discharge of the BESS | | 70% |
| Unit Price of NaS Battery | | 300,000 KRW/kW ($C_P$)<br>300,000 KRW/kWh ($C_E$) |
| Total distribution line length | | 1.6km |
| Resistance of OW 60mm$^2$ per length | | 0.30049 Ohm/km |
| OW 60mm$^2$ installation cost including line cost (per Length) | | 35,895 KRW/m |
| Daily Electricity Price (General customers) | Time (hour) | Price |
| | 23:00~09:00 | 71.1 KRW/kW |
| | 09:00~10:00<br>12:00~13:00<br>17:00~23:00 | 98.4 KRW/kW |
| | 10:00~12:00<br>13:00~17:00 | 112.6 KRW/kW |

[KRW: KOREA MONETARY UNIT, 1,000 KRW ≈ 1 USD ]

TABLE 3. NPV ANALYSIS FOR BESS INSTALLATION

| Category | | Present Value [KRW] |
|---|---|---|
| Installation cost | Installation at present | 29,400,000 |
| | Second Installation at 15years later | 10,655,913 |
| | Present Value | **40,055,913 (A1)** |
| BESS charging cost | Annual charging cost | 1,404,962 |
| | Present Value | **17,434,235 (A2)** |
| Loss reduction benefit | Annual loss reduction benefit | -233,823 |
| | Present Value | **-2,901,515 (A3)** |
| BESS discharging benefit | Annual discharging benefit | -2,194,129 |
| | Present Value | **-27,227,040 (A4)** |
| **Net Present Value (A1+A2+A3+A4)** | | **27,361,593** |

TABLE 4. NPV ANALYSIS FOR ADDITIONAL LINE INSTALLATION

| Category | | Present Value [KRW] |
|---|---|---|
| Installation cost | Installation at present | 57,432,000 |
| | Present Value | **57,432,000 (B1)** |
| Loss reduction benefit | Annual loss reduction benefit | -1,560,155 |
| | Present Value | **-19,360,027 (B2)** |
| **Net Present Value (B1+B2)** | | **38,071,972** |

## CONCLUSION

This paper presents technical discussions for installation and operation of a BESS in LVDC distribution systems. The main objective to determine the optimal size and location of the BESS is voltage regulation of the distribution lines because, as discussed earlier, LVDC distribution systems can easily suffer significant voltage problems. This paper also provides useful formulas for optimization procedure of the BESS as well as power flow algorithms for DC distribution systems. Simulation studies and economic analysis can back up our discussion in the paper.

## MISCELLANEOUS

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