전력저장전지시스템의 경제성 평가

論 文
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Economic Evaluations of Secondary Battery Energy Storage Systems in Power Distribution Systems

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Abstract - This paper presents an efficient evaluation method on the role of new energy storage systems, especially the secondary Battery Energy Storage (BES) systems, in the case where they are interconnected with the power distribution systems. It is important to perform the economic evaluation for the new energy storage systems in a synthetical and quantitative manner, because they are very costly in the early stage of their development and commercialization. In this paper, the multiple functions of BES systems, which are operated at distribution systems, such as load levelling, effective utilization of power distribution systems and uninterruptible power supply at the emergency conditions are classified and analyzed. And then the quantitative evaluation methods of the multiple functions for BES systems are proposed using the mathematical modelling.

Key Words : Battery Energy Storage Systems, Distribution Systems, Economic Evaluation Method

1. Introduction

Recently, the operation of electric power systems has become more difficult because the peak load demand is increasing continuously and also the daily and annual load factors are worsening. Furthermore, the global environmental issues are required in the electric power systems. One countermeasure to overcome these problems is a study on the operation method of the electric power systems including new energy storage systems such as superconducting magnets (SMES), secondary batteries and flywheels[1]-[9]. They have made remarkable advances lately and will be applied practically to a great advantage in the near future.

It is thus necessary to establish a mathematical method on the multiple functions of BES systems. However, most of previous approaches are based on the load levelling of total power system and annual load duration curve[5]-[9]. This paper concentrates on the multiple functions such as load levelling in both power systems and distribution systems, effective utilization of power distribution facilities and uninterruptible power supply. They are evaluated by the quantitative methods, which are the successive approximation solution, the analysis of present worth and the concept for interruption cost.

This paper is mainly devided into four parts according to the evaluation methods for the multiple functions of BES systems. The first part (Chapter **II**) shows the definition of multiple functions for BES systems which are dispersed in the distribution substations. At the second part (Chapter **III**), the successive approximation solution considering both the optimal generation mix and optimal operation of BES systems is proposed to evaluate the benefit of the load levelling for BES systems. Since the operating mode of BES systems is dependent to the storage capacity (kWh) unlike conventional generators, they cannot operate the desired power continuously. Therefore, the appropriate load model which reflects the operating strategies of BES systems should be used to determine the optimal generation mix. The third part (Chapter **IV**) presents the evaluation method using the present worth analysis to model the function of the effective utilization for the distribution facilities in the case where BES systems are operated at the distribution substation during the peak hours. And the last part (Chapter **V**) proposes the concepts of expected interruption cost to evaluate the function of uninterruptible power supply for BES systems at the emergency conditions.

Numerical examples are shown in order to indicate the efficiency of the proposed methods. From the simulation

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results, it is verified that BES systems interconnected with the power distribution systems can be introduced and commercialized in the near future.

2. Multiple Functions of BES Systems

Two major cases of the allocation sites for BES systems can be generally considered. One is a power system bus consisting of generator units and power transmission systems and the other is a distribution system bus including the customers. However, the latter is considered more effective as the allocation sites of BES systems, because the multiple functions of BES systems can be demonstrated effectively even if BES systems have a small ratings. By allocating the BES systems to the distribution system bus (distribution substation) as shownin Fig. 1, the direct benefit of the load levelling for both the total power system and distribution system can be expected, and the indirect benefits appendent to the direct benefit can also be expected, such as reduction of the investment cost by the effective utilization of the distribution facilities and reliability improvement by the uninterruptible power supply at the emergency.

3. Load levelling of distribution systems

With the allocation of BES systems to distribution systems, the simultaneous load levelling of both the total power system and power distribution systems increases the utilization rates of less expensive generator units, and the benefit for the reduction of the total power operation cost is expected. In other words, the fundermental problem of the load levelling is to decide the most appropriate type and number of generators, called an optimal generation mix, in the case where BES systems are operated in the distribution systems.

The optimal generation mix with BES systems is a static problem against the time period and in which the objective is to dertermine the process in such a manner as to minimize the total cost for load demands provided for a target year. It must be optimized for both the generation mix (nonlinear integer programming problem) and the operating mode of BES systems (nonlinear programming problem). The problem can be thus formulated and solved as a nonlinear mixed integer programming problem. However, the nonlinear mixed integer programming problem will become rapidly impracticable when the size of the problem increases. In this paper, the successive approximation solution, in which the screening method and the gradient method are

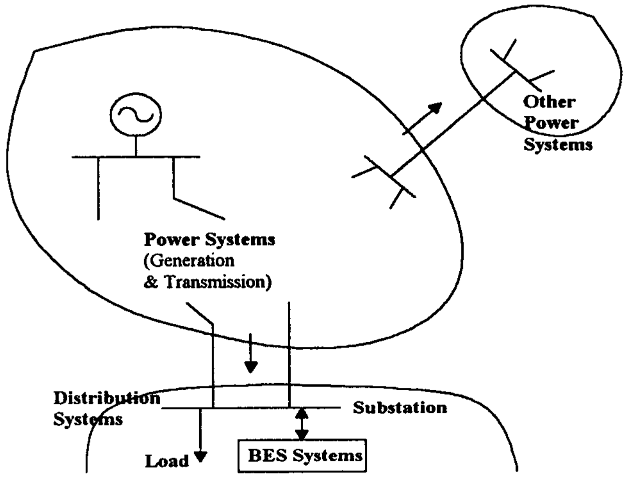

Fig. 1 New power system with BES systems

combined, is developed to overcome this difficulty. The optimization problem stated above is devided into two subproblems which must be optimized successively as described in the following section.

Problem Formulation

The optimal generation mix problem considering BES systems, whose objective is to determine the generation mix that minimizes the total cost at the target year, can be formulated as a nonlinear mixed integer programming problem as follows :

$$Min\ F_n(x, v) = \sum_{i=1}^{n} [\ a_i x_i + b_i Q_i(X_{i-1}, X_{i-1} + x_i, v)\ ] + a_s x_s \tag{1}$$

$$\text{Subj. to}\ \ \sum_{i=1}^{n} x_i + x_s \geq P_D + P_R \tag{2}$$

$$x_{imin} \leq x_i \leq x_{imax},\ \ i=1,\cdots,n \tag{3}$$

$$v_{imin} \leq v_{ik} \leq v_{imax},\ i=1,\cdots,n,\ \ k=1,\cdots,T \tag{4}$$

where, $Q_i(X_{i-1}, X_{i-1}+x_i, v) =$

$$\sum_{k=1}^{K} [z_k \int_{X_{i-1}}^{X_{i-1}+x_i} L_k(u, v) du],\ i=1,\cdots,n \tag{5}$$

$$X_i = \sum_{k=1}^{i} x_k,\ i=1,\cdots,n,\ \ X_0=0 \tag{6}$$

The symbols used in the above equations are shown in Table 1 and the index s denotes the BES systems.

The problem formulated as indicated above, which is composed of two kinds of variables such as generation

Table 1 List of symbols

F_n : total cost at target year
n : number of generation types
a_i, b_i : fixed and variable cost of generation type i
x_i, x_s : capacity of generation type i and BES systems
a_s : fixed cost of BES systems
v_{ik} : output power of BES systems at daily load curve i and time period k
Q_i : annual energy production for generation type i
X_i : cumulative capacity up to generation type i
$L_k(u)$: fraction of time that demand equals or exceeds load level u at duration curve k
z_k : number of days that provides $L_k(u)$
P_D, P_R : peak demand and spinning reserve
K : number of patterns of daily load duration curve
T : number of time periods for daily load duration curve

mix (**x**) and operating mode of BES systems (**v**), is a nonlinear mixed integer programming problem. From a theoretical viewpoint, the problem can be solved by evaluating the objective function for all combinations of generation mix (**x**) which satisfy equations (2)~(4). However, this method will become rapidly complicated with the increase of system size.

In this paper, the optimal generation mix considering BES systems is decided under the following assumptions.

① Total cost of generators is composed of the sum of the variable cost and fixed cost. And the total cost of BES systems is composed of the fixed cost only.

② Generator maintenance is ignored.

③ Unit sizes for the existing generators are previously provided and unit sizes for new generators are not fixed.

④ Two types of BES systems are treated. One is the lead-acid battery (developed) with the round trip efficiency of 70% and the other is new type battery (developing) of 80%.

Algorithm for Evaluation Method

In this paper, an efficient method based on the successive approximation technique is developed to overcome the above difficulty. the optimal generation mix problem considering BES systems is divided into following two subproblems :

(1) Optimal generation mix problem for generators only, where the operating mode of BES systems is fixed (nonlinear integer programming problem).

(2) Optimal operation problem of BES systems, where the generation mix is fixed (nonlinear programming problem).

These are optimized successively fixing the small unit size of BES systems. As the optimization technique for solving above subproblem **(1)**, this paper adopts the extended screening method, which can handle the existing generators in approximate manner as shown in References [7]~[9]. And the optimization technique for solving above subproblem **(2)** is described in the next section. The optimization procedure is summarized as follows :

<step1> Provide system parameters. Put K_0 = 0 (initial fixed cost of BES systems) and X_0 = 0 (initial capacity of BES systems).

<step2> Decide the optimal generation mix for generators only (**x**) fixing the output power of BES systems to zero (**v** = 0). Use F_0 for the total cost of this solution.

<step3> Decide the optimal operating mode of BES systems (**v**) fixing the generation mix (**x**). And calculate the optimal generation mix considering BES systems Fs.

<step4> If Fs ≤ F_0, add the unit size of BES systems △X and go to **<step3>**. Otherwise, go to next step.

<step5> If the introduction capacity of BES systems is zero (X = 0), the algorithm terminates. the generation mix (**x**) and the capacity and fixed cost of BES systems are the optimal solution. Otherwise, increase the unit fixed cost of BES systems △K and go to **<step3>**.

The detailed flowchart of the above algorithm is shown in Fig. 2. In this figure, BESS represents BES systems and △ denotes a small unit size of the capaciy and fixed cost for BES systems.

Optimal Operation of BES Systems

In this section, the algorithm, which decides the optimal operation of BES systems fixing the generation mix, is described. The gradient method which has already been developed in Reference [10] is used for dertermining the optimal operation mode of BES systems.

The economic operating condition of BES systems is provided as follows :

$$\eta > \frac{\lambda_{charge}}{\lambda_{discharge}} \tag{7}$$

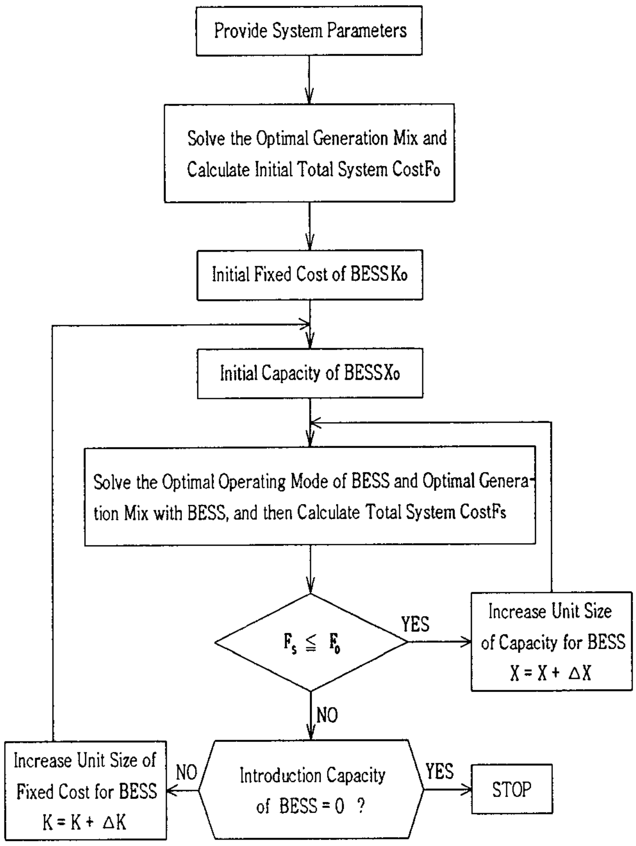

Fig. 2 Determination of the optimal generation mix considering BES systems

where, η : round trip efficiency of BES systems, λ_{charge} : incremental cost in charging period, $\lambda_{discharge}$: incremental cost in discharging period.

The minimization for the objective function F_n, where the generation mix is fixed, can be obtained by the load levelling so as to satisfy the economic operating condition. In this procedure, the output power (kW) and storage capacity (kWh) constraints for BES systems must be also satisfied. The optimal operation mode of BES systems over the target year is decided when the following algorithm is applied to all daily duration curves. The procedure is as follows :

<step1> Select the lowest and highest demand periods out of the daily load duration curve. And calculate the incremental costs λ_{charge} and $\lambda_{discharge}$.

<step2> If the equation (7) is satisfied, the algorithm terminates. Otherwise, let charge a small amount of power $\triangle P_s$ in the lowest period, and discharge the power $\eta \triangle P_s$ in the highest period.

<step3> If the maximum storage capacity (kWh) constraint for BES systems is reached, the algorithm terminates.

<step4> If the maximum output (kW) constraint for BES systems is reached, eleminate the period from the consideration. Go to **<step1>**.

Numerical Examples

To test validity of the proposed method, we carried out simulations using the model systems and parameters as shown in Fig. 3 and Table 2. The table shows the data of the statistical materials of Korea Electric Power Coperation in the fiscal year of 1997. In this table, the coal and LNG plants are considered as the existing generators and the nuclear and oil plants are new generators. The four load patterns for the distribution substations (A, B, C, D) and the peak demand of 10million kW in Fig. 4 are considered. This figure is the typical load pattern in summer and the load patterns of

Table 2 Parameters of generation units

Type	Variable Cost (Won /kWh)	Fixed Cost (Won /kW)	Rating (MW)	Failure Rate (%)	Maintenance Rate (%)
Nuclear	3.24	202,109	-	6.5	16.4
Coal	12.10	144,037	1,000	7.0	12.3
LNG	25.94	71,700	1,000	6.0	11.2
Oil	20.36	103,216	-	6.0	12.3
BESS	-	**Ca**	20(8Hr)	-	-

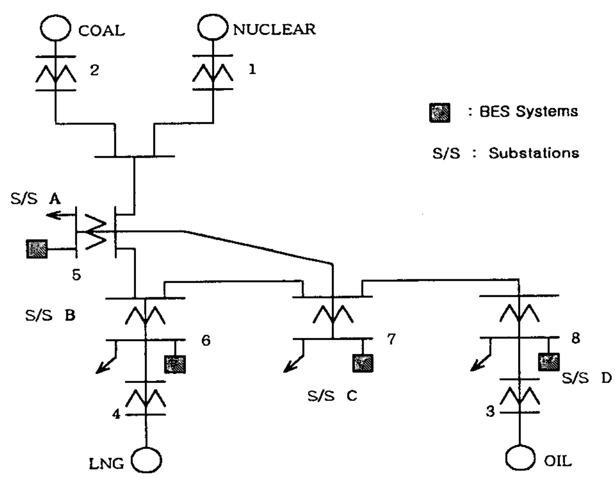

Fig. 3 Model power systems [1, 9]

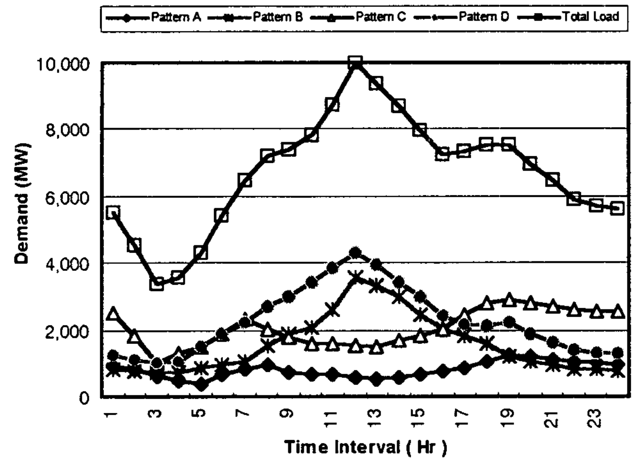

Fig. 4 Load patterns of distribution substations

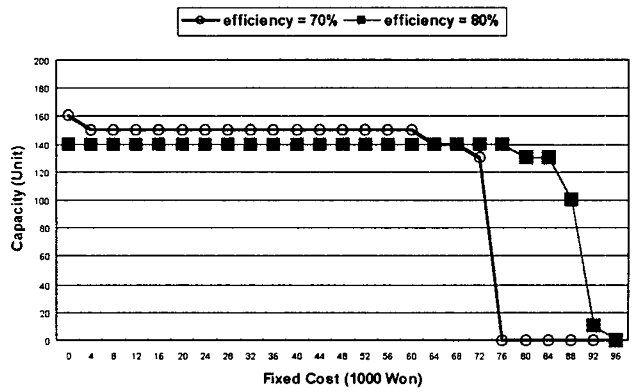

Fig. 5 Optimal capacity and fixed cost of BES systems (1unit : 20MW, 180MWh)

Table 3 Composition ratio of generation units at the peak load demand (10,000MW)

Type	Output power without BES systems (MW)	Output power with BES systems (MW)
Nuclear	2,899.3	3,766.3
Coal	1,000.0	1,000.0
LNG	1,000.0	1,000.0
Oil	5,100.0	2,399.1
BESS	0.0	**2,600.0**

other seasons are assumed by the same pattern with the magnitudes of 70%, 80% and 90% based on the summer load pattern, respectively. Furthermore, the round trip efficiencies of 70% and 80% for BES systems are also asummed.

With the successive increase of a small unit size of the capacity and fixed cost for BES systems, the optimal capacity and fixed cost of BES systems are obtained as shown in Fig. 5, by comparing the total operation cost $F_n(x)$ and $F_0(x)$ for the two cases where BES systems are operated and not operated. Because of the computation time for the parameter analysis, a small unit size of the capacity for BES systems is considered as 20MW(160MWh, 8Hr) and one of the fixed cost for BES systems is considered as 1000Won, respectively.

Figure 5 shows that the benefit of the load levelling for BES systems in the distribution substations, which is the fixed cost (C_a), becomes 75 ~ 94 thousand Won per kW. From the configuration of Fig. 5, the marginal and saturated fixed costs can also be defined. The marginal cost, in which the composition ratio of BES systems is zero, represents the economical point for BES systems. And the saturated fixed cost, in which the complete load levelling is accomplished at each fixed cost, keeps a costant value although the fixed costs change.

In additions, Table 3 is the comparison results for the composition ratio of generation units at the peak load demand (10,000MW) for the two cases where BES systems are operated and not operated. The results are obtained under the condition of the fixed cost of 75 thousand Won per kW for BES systems. The table shows that the output power of oil plant (high variable cost) is replaced by the output powers of the BES systems and the nuclear plant (low variable cost).

4. Effective Utilization of Distribution Facilities

The expansion planning of the electrical facilities in distribution systems is usually performed considering the utilization rate related to the increase of the peak load demand in distribution systems. If BES systems allocated to distribution substations are used as the power source during the peak hours, the economic benefit can be expected. In other words, the investment cost of the distribution facilities can be reduced because the starting year of the expansion construction for the distribution facilities is delayed for some years. In order to evaluate the benefit quantitatively, this paper adopts the present worth analysis[11],[12].

Present Worth Analysis

The present worth analysis is one of the simple method for the economical assessment. It deals with the comparison process of the investment costs for some alternative plans. It is evaluated by converging the investment costs occurring at different years to present values of basis year. It can be expressed by the present worth factor for a single payment.

$$V^n = \frac{1}{(1+i)^n} \tag{8}$$

where, V^n : present worth factor, i : interest rate, n : target year.

The relationship between the present worth factor and the cumulative present worth factor A_n can be denoted as follows :

$$A_n = V^1 + V^2 + V^3 + \cdots + V^n$$
$$= \frac{(1-V^n)}{i} = \frac{(1-\frac{1}{(1+i)^n})}{i} \tag{9}$$

Thus, the cumulative present worth (B_n) of investment cost corresponding to the expansion construction beginning at the year '**n**' during the total target year, can be obtained as follows :

$$B_n = A_n - A_{n-1} \tag{10}$$

Evaluation Algorithm for BES Systems

For the cases where BES systems dispersed in distribution systems are operated as the function of load levelling, the economic operating condition can be expressed by equation (11). The most economical point is where the expansion investment cost without BES system is equal to the sum of the expansion investment cost with BES systems and the investment (capital) cost of BES systems.

$$C_{without} \leq C_{with} - C_{bess} \tag{11}$$

where, $C_{without}$: investment cost without BES systems, C_{with} : investment cost with BES systems, C_{bess} : capital cost of BES systems.

Each alternative plan may have several investment costs of expansion construction during the total target year. Therefore, the present worth of each alternative plan can be expressed by equation (12), by considering the carrying charge rate which includes the return, depreciation and taxes.

$$C_{alter} = \sum_{m} \sum_{n=1}^{N} K_m \alpha_m B_n \tag{12}$$

where, C_{alter} : cumulative present worth of each alternative plan, K_m : construction cost, α_m : carrying charge rate, n : target year starting expansion construction, N : total target year, m : the number of facility related to expansion construction, alter : the number of alternative plan.

By substituting equation (12) into equation (11), the total present worth cost, called the capital (investment) cost of BES systems, can be obtained. This is the economical benefit caused by the effective utilization of the distribution facilities according to the operation of BES systems in distribution substations. It may be called the credit of distribution system.

Numerical Examples

We carry out the simulation using the system parameters of Table 4 and some following assumptions.

① Model distribution system has two distribution substations with 6 Main Transformers (Banks) of 60MVA rating. Typical type of distribution substation (S/S) has 2 banks and one more bank can be added.

② The peak load demand in the basis year of 270MVA (243MW) is assumed, which is 75% of the capacity of total banks and the power factor of distribution systems is 90%.

③ The annual load increase of 5% and the interest rate (i) of 10% are also assumed.

④ Whenever the utilization factor reaches at 75% with the increase of annual peak load demand, the distribution facilities such as S/S or bank should be expanded.

The expansion schedule for the two cases where BES systems are operated and not operated in distribution substations is obtained as shown in Table 5. The table indicates that the total utilization rate of the case where BES systems is operated can be improved by 4% compared to the case where BES systems are not operated. The table also shows that the starting year of the expansion construction of distribution facilities for the case where BES systems is operated can be delayed for 6 years. By using the present worth analysis above mentioned, the benefit for the effective utilization of distribution facilities, C_b, becomes about 90 thousand Won per kW for the 10 years expansion planning. In addition, the benefit may be increased by the expansion construction cost of the underground cable (or overhead transmission line, 154kV), by which the distribution substations are connected to the transmission network.

Table 4 *System parameters*

	Unit Size	Cost (Thousand Won)	Carrying Charge Rate (%)
Distribution Substation(S/S)	45/60MVA x 2	5,911,800	9.2
Bank (M.Tr)	45/60MVA	773,540	9.2
BESS	7MW	C_b	12.0

(*) M.Tr stands for Main Transformer.

Table 5 Expansion planning of distribution systems (annual load increase : 5%)

Year	Peak Load (MW)	Without BES Systems				With BES Systems				
		S/S (MW)	Bank (MW)	Total Bank (MW)	Utilization Rate (%)	BESS (MW)	S/S (MW)	Bank (MW)	Total Bank (MW)	Utilization Rate (%)
0	243			54×6	75.0				54×6	75.0
1	255	54×2		54×8	59.0	7×2			54×6	74.4
2	268			〃	62.0	〃			〃	74.1
3	281			〃	65.5	〃			〃	73.8
4	295			〃	68.3	〃			〃	73.8
5	310			〃	71.8	〃			〃	74.1
6	326		54×1	54×9	67.1	〃			〃	74.7
7	342			〃	70.4		54×2		54×8	59.7
8	359			〃	73.9				〃	63.7
9	377	54×2		54×11	63.5				〃	67.8
10	396			〃	66.7				〃	72.2
Total Cost (Million Won)		4522.5	459.3	4981.8	66.8	42Cb	1163.6	-	1163.6	70.8

(*) S/S denotes distribution sustations and the total cost is the sum of the present worth for the facilities.

5. Uninterruptible Power Supply at the Emergency

If BES systems are operated as the function of the load levelling in distribution systems at the normal conditions and as the uninterruptible power supply in fault areas at the emergency conditions, the reliability improvement of distribution systems can be expected. In other words, the benefit can be represented by the cost avoiding interruption according to the operation of BES systems when a fault is occured. In order to evaluate the benefit for the uninterruptible power supply in a quantitative manner, this paper adopts the concepts of expected interruption cost[13].

Expected Interruption Cost

An interruption cost can be expressed by several factors such as duration time of interruption, occuring time of fault and load characteristics of fault areas. It can be usually formulated by a quadratic equation of the duration time of interruption as follows :

$$F_{iju}(t) = (at^2_{ij} + bt_{ij} + c)\,L_{iju} \tag{13}$$

where, $F_{iju}(t)$: interruption cost (Won per kW), t_{ij} : duration time of interruption, L_{iju} : load amount of interruption, a, b, c : the coefficients of load characteristics (interruption cost), i, j : the number of substation and primary feeder, u : the number of time interval.

According to the allocation of BES systems to distribution systems and the operation of uninterruptible power supply at fault, the interruption cost of equation (13) can be reformed as follows :

$$F_{iju}(t, x_i, y_i) = \sum_{j\in L_0} F_{iju}\,[\,t_{ij}, L_{iju}(x_i, y_i)] + \sum F_{iju}\,[\,t_{ij}', L_{iju}(x_i, y_i)] \tag{14}$$

where, x_i, y_i : kW and kWh introduction capacity of BES systems, L_o : [j ‖ primary feeder unsupplied by BES systems at t = 0], t_{ij}' : t_{ij} - t_{sij}, t_{sij} : duration time supplied by BES systems after fault.

A restoration probability for the duration time interval of an interruption, t ~ t+△t, in the substation i and feeder j, is usually obtained as follows :

$$p_{ij}(t, t+\triangle t) = \mu_{ij}\,e^{-\mu_{ij}t}\,\triangle t \tag{15}$$

where, $p_{ij}(t)$: restoration probability, $1/\mu_{ij}$: average restoration probability.

Therefore, an expected interruption cost for the entire time interval can be expressed as follows :

$$F_{tot}=\sum_i\sum_j\int_{U_s}^{U_e}A_{iju}\int_0^{\infty}p_{ij}(t)F_{iju}\ (t,x_i,y_i)\ dt\ du \quad (16)$$

where, F_{tot} : total expected interruption cost, $U_s \sim U_e$: total time interval, A_{iju} : interruption probability at time interval U, $\int_{U_s}^{U_e}A_{iju}\,du = 1$, $\int_0^{\infty}p_{ij}(t)\ dt = 1$

Numerical Examples

To indicate the efficiency of proposed method, we carried out the simulations using the model systems and parameters as shown in Fig. 6 and Table 6. This paper considers three load types such as residential area, commercial area and industrial area in order to model the load characteristics.

The benefit for the avoided cost of the interruption according to the uninterruptible power supply of BES systems can be obtained as shown in Fig. 7, by the comparision of the total expected interruption costs for the two cases where BES systems are operated and not operated. This Figure shows that the benefit of BES systems becomes about 13 thousand Won per kW for one year in the case of the industrial area. The figure also indicates the benefit of BES systems according to the three load types. It is clear that the industrial area, which

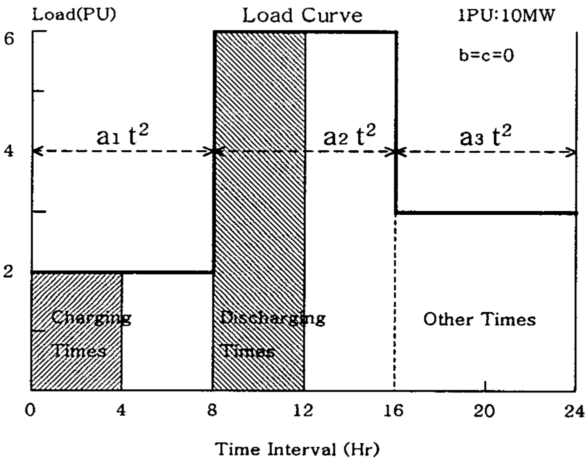

Fig. 6 Daily load curve and operation mode of BES systems

(charging period : 0~4, discharging period : 8~12)

Table 6 Coefficient values of interruption cost [13]

	a_1 (Peak Hours)	a_2 (Middle Hours)	a_3 (Off-peak Hours)
Residential Area	0.002	0.007	0.002
Commercial Area	0.002	0.025	0.01
Industrial Area	0.01	0.03	0.02

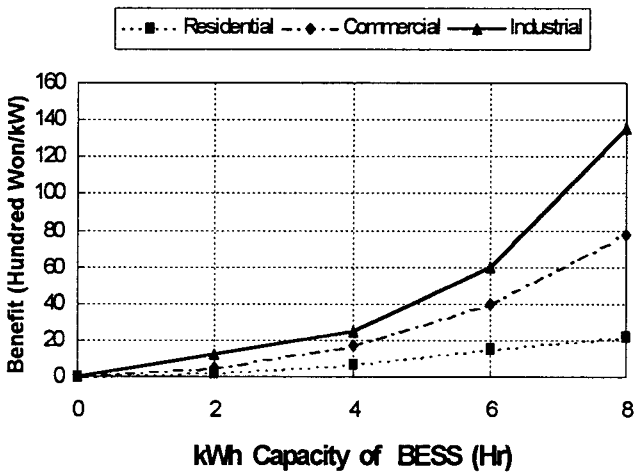

Fig. 7 Benefit of uninterruptible power supply (BESS : 6MW, μ_{ij} : 0.04)

has the largest coefficient value of interruption cost, can be selected as the most proper allocation site of BES systems.

6. Conclusions

This paper presents the efficient methods of the economic evaluation for BES systems interconnected with distribution systems. The economical benefits of BES systems are evaluated by the quantitative methods such as successive approximation solution, present worth analysis and interruption cost conception. The simulation results by using some model systems and parameters, are summarized as follows :

(1) The benefit of the load levelling by the operation of BES systems in the distribution substations, which is the fixed cost (C_a), is 75 ~ 94 thousand Won per kW for every year. By considering the carrying charge rate of 12%, this value becomes 625 ~ 783 thousand Won per kW. And the marginal and saturated fixed costs is also obtained. The marginal cost is the economical point for

the introduction of BES systems.

(2) The total utilization rate with BES systems is improved by 4% compared to without BES systems and the starting year of the expansion construction is delayed for 6 years. Therefore, the benefit of effective utilization of distribution facilities (C_b) becomes about 90 thousand Won per kW for the 10 years expansion planning.

(3) The benefit for the avoided cost of the interruption by the uninterruptible power supply of BES systems is about 13 thousand Won per kW for one year and the optimal allocation site of BES systems can be selected as the industrial area with the important load characteristics.

From the simulation results, it is verified that BES systems can be economically introduced and operated to distribution system in the near future.

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