# OPTIMAL ENERGY STORAGE SYSTEM DESIGN FOR ENERGY MANAGEMENT OF PEA DISTRIBUTION SYSTEMS

Areewan KAJORNDECH
Provincial Electricity Authority (PEA) – Thailand
areewan_kik@hotmail.com

Dulpichet RERKPREEDAPONG
Kasetsart University – Thailand
dulpichet.r@ku.ac.th

## *ABSTRACT*

*This paper proposes the methodology of ESS design for PEA power distribution systems. It consists of the sequential steps to select the optimal size and technology for ESS, and the development of ESS control strategy for effective energy management. The objectives of the proposed methodology are not only reliability enhancement but also maximizing economic benefits from cost saving on energy trading as well as loss reduction in power distribution systems. The proposed method is applied to design an ESS for a real power distribution system in Mae Sariang, Mae Hong Son province, Thailand to verify its practicality and effectiveness. The results show that the designed ESS directed by the developed control strategy gives the highest economic return in terms of benefit cost ratio (BCR) while the system reliability is raised up to a desired level.*

## INTRODUCTION

Presently, Energy Storage Systems (ESSs) have been widely used in electrical industry, especially in electric power systems due to their characteristics, which are able to store and discharge energy at any time as desired. As a result, more flexibility for energy management of power distribution systems can be achieved. One of attractive ESS applications is reliability enhancement. ESS is used as a backup supply when the main grid cannot supply electrical energy to its loads. This can be a perfect solution for PEA power distribution systems whose load centers are distant from the substation. However, an optimal ESS design with the appropriate technology must be sought, together with an effective control strategy for energy management.

In this paper, the ESS design problem is focused on reliability and economy aspects. On the reliability, [1] describes an analytical approach to evaluate reliability improvement by using ESS as a backup storage and determines the size including the energy capacity and power rate to meet an increased reliability target. On the economy, [2] presents a residential hybrid ESS design based on the energy buffering strategy to maximize the annual profits on residential electric bills. Besides, [3] proposes a modified multi-objective particle swarm optimization approach to solve the energy storage design problem which considers the energy capacity and power rate as well as the operation strategy. However, [1], [2] and [3] do not cost-effectively select the appropriate ESS technology.

This paper presents an optimal ESS design methodology for energy management of electric power distribution systems by using the benefit cost ratio (BCR) to select alternatives. The returns on investment are considered, including the interruption cost reduction, cost saving on energy trading and loss reduction. The proposed ESS design variables consist of the conventionally considered ESS capacity and power rate, and also the ESS technology and operation strategy. The technique presented in this paper calculates the cost added to each unit of energy (COE) for the optimal selection of ESS technologies for each possible size. The selected ESS technology is the one resulting in the minimum COE. In addition, an effective control strategy for ESSs is required to be developed to achieve attractive energy management. In this paper, such an ESS control strategy is applied to an electric power distribution system [4] equipped with a limited size of ESS by determining an optimal dispatching schedule of the ESS. Finally, the results show that not only the higher reliability is achieved, but also the better economic benefits resulted from cost saving on energy trading as well as loss reduction in power distribution systems are realized.

## METHODOLOGY

At the first step, the appropriate technology for each size of ESS is determined from the cost added to each unit of energy (COE), which is derived from life-cycle cost analysis. The best ESS technology will presents the minimum COE. At the second step, the effective control strategy of ESS for energy management is developed. The proposed concept is described as follows. For each period of time, a portion of state of charge (SOC) must be sufficiently preserved as backup energy to be discharged to the critical loads for reliable microgrid operation while the main grid is not energized. The remaining SOC is then used for optimal energy management through energy trading directed by the control strategy. This leads to a maximum benefit of each ESS size, including reliability worth, gains from energy trading and cost saving from loss reduction. Finally, the optimal ESS size can be selected for the case study according to the highest benefit cost ratio (BCR).

### Calculation of cost added to each unit of energy

This section presents the development of a technique [5] to convert the installed and annual costs of energy storage to the cost added to each unit of energy (COE) in kilowatt hour (kWh).

The total capital cost (*TCC*) for ESS consists of three components: the total (power) cost for power conversion system (*PCS*), the total (energy) cost for storage units

(*SUC*) and the extensive costs associated with the balance of plant (*BOP*), all in US$ which can be written as (1)-(4).

$$TCC = PCS + SUC + BOP \tag{1}$$

$$PCS = PCSU \cdot P \tag{2}$$

$$SUC = SUCU \cdot E \tag{3}$$

$$BOP = BOPU \cdot E \cdot \sqrt{eff} \tag{4}$$

Where *PCSU* is unit cost for power conversion system (US$/kW), *SUCU* is unit cost for storage unit (US$/kWh) and *BOPU* is unit cost for balance of plant (US$/kWh). *P* is the power rating (kW), *E* is the stored energy capacity (kWh) and *eff* is round-trip efficiency.

The annual capital cost (*ACC*) in US$/year is given by (5), and the capital recovery factor (*CRF*) is given by (6).

$$ACC = TCC \cdot CRF \tag{5}$$

$$CRF = \frac{i_r \cdot (1+i_r)^y}{(1+i_r)^y - 1} \tag{6}$$

Where $i_r$ is annual interest rate (%) and $y$ is lifetime of energy storage (year).

When batteries are used as the storage element, they may be replaced one or more times during the life of the plant. The annual storage unit replacement cost (*ARC*) in US$/year can be written as (7).

$$ARC = E \cdot F \cdot \left[(1+i_r)^{-r} + (1+i_r)^{-2r} + \ldots\right] \cdot CRF \tag{7}$$

Where *F* is future value of replacement cost (US$/kWh). The number of terms in the blanket of (7) is equal to the number of times batteries are replaced during the life of the system. The battery life is specified by the fixed number of charge/discharge cycles. The replacement period (*r*) in year can be calculated by (8).

$$r = \frac{C}{n \cdot D} \tag{8}$$

Where *C* is number of charge/discharge cycles during the life of storage, *D* is annual operating days for storage unit (day/year) and *n* is number of charge/discharge cycles per day.

The annual operation and maintenance cost (*OMC*) in US$/year is given by (9).

$$OMC = OM_f \cdot P \tag{9}$$

Where $OM_f$ is unit cost for operation and maintenance (US$/kW-year).

The total annual cost (*TAC*) in US$/year, which is the sum of *ACC*, *ARC* and *OMC*, is described by (10).

$$TAC = ACC + ARC + OMC \tag{10}$$

The total energy discharged annually by ESS is referred as annual energy production (*AEP*), which can be found by (11).

$$AEP = n \cdot \left(E \cdot \sqrt{eff}\right) \cdot D \tag{11}$$

Finally, the cost added to each unit of energy (*COE*) is described by (12) and (13) respectively.

$$COE = TAC / AEP \tag{12}$$

$$COE = \left[\frac{PCSU \cdot CRF + OM_f}{\sqrt{eff} \cdot D}\right] \cdot \frac{P}{E} + \left\{SUCU + \sqrt{eff} \cdot BOPU + F \cdot \left[(1+i_r)^{-r} + (1+i_r)^{-2r} + \ldots\right]\right\} \cdot \frac{CRF}{\sqrt{eff} \cdot D} \tag{13}$$

This paper proposes the method to choose the appropriate ESS technology for each size, which is determined from the cost added to each unit of energy which is derived from life-cycle cost analysis. The best ESS technology presents the minimum COE.

## Power distribution system integrated with ESS

The utility participates in the wholesale power markets to purchase electric energy to serve its customers in the power distribution system. The objective is to serve its customers reliably and economically. ESSs integrated in the power distribution system could be utilized to improve system reliability and economy. The topology is simplified as shown in Fig. 1.

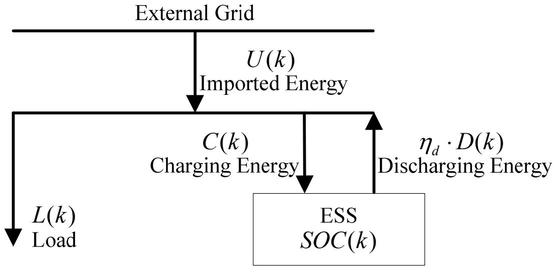

**Fig. 1.** A simple topology of ESS integrated in a power distribution system.

The distributed loads are modeled into one lumped load. Load in each period, *L(k)* is price inelastic. ESS is operated by determining the charging, *C(k)* and discharging, *D(k)* operations. The imported energy, *U(k)* from the external grid is the summation of the load and the ESS operations, which can be written as (14).

$$U(k) = L(k) + C(k) - \eta_d \cdot D(k) \tag{14}$$

Assume utility can only purchase energy and does not exceed the limit of transmission line, $U_{max}$ as (15).

$$0 \le U(k) \le U_{\max} \tag{15}$$

In this paper, the power market is simplified as a real-time power market model. The energy purchasing cost is the product of the amount of energy purchased in power market, *U(k)* and the market clearing price, *P(k)*.

The ESS is modeled as a set of parameters and operation limits. The State of Charge, SOC at the end of each period is determined by the previous period SOC and the charging/discharge operation during this period is described by (16).

$$SOC(k) = SOC(k-1) + \eta_c \cdot C(k) - D(k) \tag{16}$$

Where $\eta_c$ and $\eta_d$ are charging and discharging efficiency respectively.

Those variables need to be within the SOC upper and lower limits ($SOC_{\max}$, $SOC_{\min}$) and charging/ discharging power limits ($C_{\max}$, $D_{\max}$) as given by (17)-(19).

$$SOC_{\min} \le SOC(k) \le SOC_{\max} \tag{17}$$

$$0 \le C(k) \le C_{\max} \tag{18}$$

$$0 \le D(k) \le D_{\max} \tag{19}$$

### Energy storage system control strategy

The ESS operation strategy concept in [4] explains that at each time, while a portion of the ESS capacity is utilized as a backup power source, the other portion can be utilized to manage energy cost. The backup portion is always reserved for the failure events in order to prevent a loss of load or reduce an amount of energy not served. Meanwhile, the other portion is employed to take advantage of the ESS control flexibility to reduce energy cost. With a certain size of ESS capacity, if the standby backup portion increases, the portion for energy cost management will decrease. Accordingly, the reliability of the system is improved, but the energy cost saving is reduced. There is a tradeoff between reliability and energy cost saving. In order to better utilize a limited ESS capacity, the portion for standby backup power source is adjusted as needed in each period. During peak load periods, the system is less reliable; hence a larger portion of ESS is assigned for the purpose of backup power source. On the other hand, during non-peak load periods, the system becomes more reliable, and the loss of load probability is very small. Therefore, a smaller portion of ESS is assigned for the backup power source; a larger portion of ESS can be used for energy management.

## PROBLEM FORMULATION

The objective of the ESS design is to simultaneously achieve both objectives including reliability enhancement and maximizing economic benefits from cost saving on energy trading as well as loss reduction in power distribution systems by choosing the optimal ESS parameters subject to the constraints for a specific distribution system. In this paper, the design variables of ESS include the conventionally considered ESS capacity and power rate, and also the ESS technology and operation strategy. The proposed methodology to optimally select them is the major contribution of this paper.

### Reliability enhancement

The SOC level of ESS must be dedicated to the backup power source to serve the critical loads during a power outage. In this paper, Failure Mode and Effect Analysis (FMEA) method could be used to calculate the reliability indices of the system before and after the ESS is installed in a specific distribution system. The selected reliability index is Energy Not Supplied (ENS) which gives the total amount of energy that would have been supplied to the interrupted customers if there would not have been any interruption. The reliability benefits is assessed from a reduction in damage costs caused by power failures including the loss of revenues from electricity sales of utility, and the customer outage cost or Expected interruption COST (ECOST).

### Maximizing economic benefits

Higher technical benefits can be gained from a larger ESS size and/or better ESS technology. However, it normally comes with a higher cost. Therefore, the optimal ESS design should maximize economic benefits while keeping the total cost as low as possible. This paper uses Benefit Cost Ratio (BCR) as an index to assess the alternatives. The benefit includes a decrease in interruption cost, cost saving on energy trading and loss reduction. The cost is considered as the ESS cost, which is the sum of the capital cost, the replacement cost, the operation & maintenance cost, and the energy purchasing cost during the lifetime of project.

## CASE STUDY

The proposed methodology is illustrated through a real power distribution system equipped with an ESS in Mae Sariang, Mae Hong Son province, Thailand as shown in Fig. 2. The system peak load is 5.1 MW. The power demand pattern is assumed to be the same for each day, and the growth rate of demand is 3.53% every year. The electric energy price is based on the TOU rates, and it increases 2% yearly. The characteristics of ESS technologies for cost analysis used in this paper are obtained from [6].

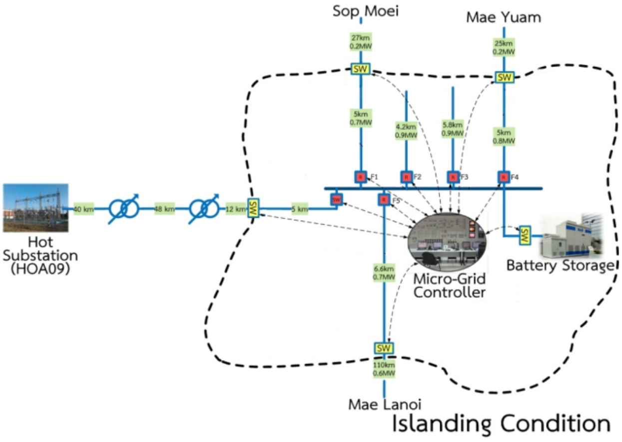

**Fig. 2.** The power distribution system in Mae Sariang, Mae Hong Son province, Thailand.

In order to meet the target of reliability enhancement, if the SOC level of ESS is sufficient to serve the critical loads, the portion of energy must be reserved as the backup power source for the critical loads in case of failure events. As such, the SOC in each period must not be less than the amount of energy required to be stored as backup power source ($SOC_{req}$), which is expressed as (20).

$$SOC(k) \ge SOC_{req}(k) \tag{20}$$

**Table 1** Benefit Cost Ratio (BCR) of each ESS size with the selected technology

| BCR | | RATED ENERGY (MWh) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| RATED POWER(MW) | 1 | 0.0978 | 0.1221 | 0.1818 | 0.2391 | 0.2850 | 0.3183 | 0.3379 | 0.3494 | 0.3567 | 0.3613 |
| | 2 | 0.0593 | 0.0783 | 0.1158 | 0.1661 | 0.2166 | 0.2559 | 0.2818 | 0.2986 | 0.3098 | 0.3178 |
| | 3 | 0.0487 | 0.0618 | 0.0839 | 0.0996 | 0.1368 | 0.1779 | 0.2125 | 0.2378 | 0.2557 | 0.2690 |
| | 4 | 0.0413 | 0.0532 | 0.0712 | 0.0891 | 0.1093 | 0.1372 | 0.1660 | 0.1910 | 0.2124 | 0.2300 |
| | 5 | 0.0359 | 0.0480 | 0.0602 | 0.0786 | 0.0981 | 0.1227 | 0.1494 | 0.1730 | 0.1936 | 0.2112 |
| | 6 | 0.0317 | 0.0437 | 0.0558 | 0.0704 | 0.0887 | 0.1118 | 0.1371 | 0.1597 | 0.1796 | 0.1969 |
| | 7 | 0.0284 | 0.0401 | 0.0520 | 0.0623 | 0.0809 | 0.1026 | 0.1266 | 0.1483 | 0.1675 | 0.1844 |
| | 8 | 0.0257 | 0.0371 | 0.0487 | 0.0589 | 0.0743 | 0.0949 | 0.1177 | 0.1384 | 0.1570 | 0.1734 |
| | 9 | 0.0235 | 0.0344 | 0.0458 | 0.0559 | 0.0693 | 0.0882 | 0.1099 | 0.1298 | 0.1477 | 0.1637 |
| | 10 | 0.0216 | 0.0322 | 0.0432 | 0.0532 | 0.0663 | 0.0828 | 0.1031 | 0.1222 | 0.1394 | 0.1549 |
| | | **Insufficient Backup** | **Sufficient Backup** | | | | | | | | |

On the other hand, the remaining portion of energy can be used to take advantage of the ESS control flexibility to reduce energy cost from energy management. Next, the energy cost minimization problem as shown in (21) is solved to determine the optimal dispatching schedule of the ESS.

$$\min \sum_{k} \left[ U(k) \cdot P(k) \right] \qquad (21)$$

$$\text{s.t. } (14)-(20),\ (22)$$

However, the additional energy purchasing according to the ESS dispatching schedule needs to be verified the worthiness constraint because there is a loss of energy conversion while the energy is stored and then discharged to the grid. To comply with the constraint, the income from selling energy (discharging) must be greater than the cost of energy purchasing (charging), as described by (22).

$$\left( \eta_c \cdot \eta_d \right) \cdot P_D(k) > P_C(k) \qquad (22)$$

Where $P_D(k)$ and $P_C(k)$ are the electric energy price in discharging and charging periods respectively.

## RESULTS AND DISCUSSION

The relationship between COE and rated power per rated energy of ESS (P/E) of each ESS technology is shown in Fig. 3. It is found that the technology E (Tech-E) and the technology B (Tech-B) are the best technology in a range of P/E less than 1.6394 and higher than 1.6394 respectively.

The BCR of each ESS size with the best selected technology in Table 1 illustrates that the ESS sizes are divided into 2 groups: insufficient backup and sufficient backup for the critical loads. Only those ESS sizes in the sufficient backup group are considered for the optimal ESS design. Finally, the ESS size of 10 MWh and 2 MW is optimally selected for the studied power distribution system because it results in the highest BCR.

Fig. 4 and Fig. 5 illustrate the 10MWh and 3MW ESS operation dispatched by hybrid control strategy [4]. At the 15th year, the energy capacity and power rate of ESS will remain sufficient for handling both reliability enhancement and cost minimization on energy trading which can supply the 1st and 2nd priority loads as shown in Fig. 4. On the other hand, the energy capacity and power rate of ESS will no longer sufficient to supply the 1st and 2nd loads in the 16th year. Therefore, the ESS will be dispatched for cost minimization on energy trading only as shown in Fig. 5.

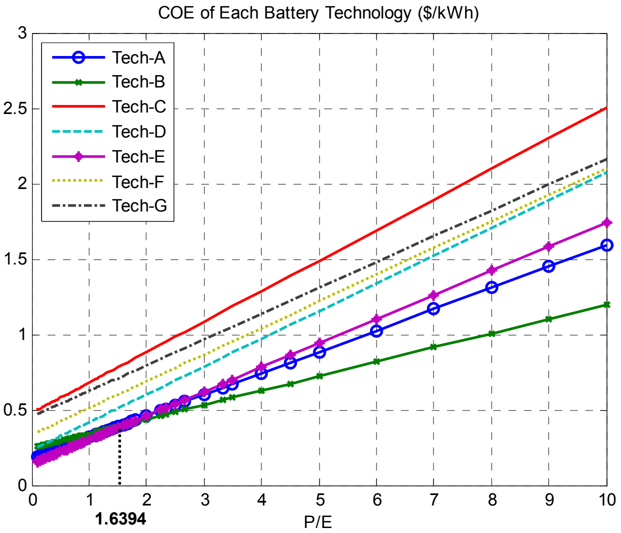

**Fig. 3.** The relationship between COE of each ESS technology and rated power per rated energy of ESS (P/E)

## CONCLUSIONS

This research proposes the method of ESS design for energy management of power distribution systems. While the control strategy of ESS is applied, the benefits including reliability improvement, gains from energy trading and loss reduction are considered to determine the BCR for each ESS size with the selected technology. The optimal size of ESS including the energy rating and power rating is then selected from the highest BCR. The results show that the proposed method is practical and effective for real power distribution systems.

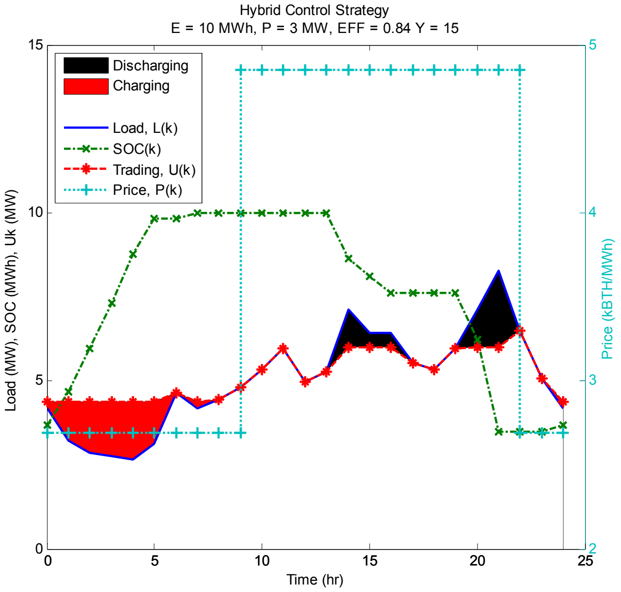

**Fig. 4.** The 10MWh and 3MW ESS operation dispatched by hybrid control strategy in 15th year.

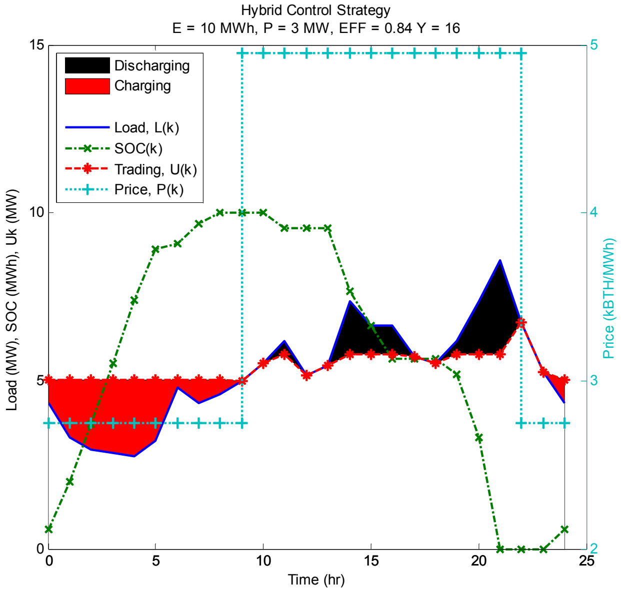

**Fig. 5.** The 10MWh and 3MW ESS operation dispatched by hybrid control strategy in 16th year.

## REFERENCES

[1] J. Mitra, 2010, "Reliability-Based Sizing of Backup Storage", *IEEE Transactions on Power Systems.* vol. 25 (2), 1198-1199.

[2] D. Zhu, S. Yue, Y. Wang, Y. Kim, N. Chang and M. Pedram, 2013, "Designing a Residential Hybrid Electrical Energy Storage System Based on the Energy Buffering Strategy", *The 11th ACM/IEEE international conference,* CODES+ ISSS, 1-9.

[3] Y. Xu and C. Singh, 2012, "Multi-Objective Design of Energy Storage in Distribution Systems Based on Modified Particle Swarm Optimization", *Power and Energy Society General Meeting (PES),* IEEE, 1-8.

[4] A. Kajorndech and D. Rerkpreedapong, 2014, "Energy Storage System Control Strategies for Power Distribution Systems", *KKU Engineering Journal.* vol. 42 (1), 1-11.

[5] P. Poonpun and W. Jewell, 2008, "Analysis of the Cost per Kilowatt Hour to Store Electricity", *IEEE Transactions on Energy Conversion.* vol. 23 (2), 529-534.

[6] S.M. Schoenung and W.V. Hassenahl, 2003, *Long- vs. Short-Term Energy Storage Technologies Analysis: A Life-Cycle Cost Study,* Sandia National Laboratories, Albuquerque, New Mexico, USA, 22-31.