Techno-Economical Analysis of Energy Storage Systems in Conventional Distribution Networks

Amin Foroughi Nematollahi, Abolfazl Rahiminejad, and Behrooz Vahidi

Abstract Growing trend of integrating renewable energy resources in conventional Distribution Networks and their intermittent output increase the need for Energy Storage Systems. In this chapter, a closed form equation is proposed for optimal management of multi Energy Storage System in a conventional Distribution Network, analytically. Using the proposed approach, Energy Storage System can be embedded and utilized optimally in today's Distribution Network using the existing facilities. In order to find optimal performance of the storage system, the objective function is solved analytically and a closed form equation is achieved for storage system performance. The Energy Storage System management is performed in order to minimize total cost of daily energy loss and energy supply of the system. In addition, technical assessment of Energy Storage System is also taken into account to obtain a situation in which utilization of Energy Storage System is economical. In the Optimization problem, energy price, storage utilization duration, amount of load demand, power loss of the system, costs, limits and characteristics of storage system are integrated in the objective function. The proposed approach is applied to two test systems with different load levels. Obtained results indicate that the proposed approach can be successfully applied to practical networks and enhance efficiency of the distribution systems.

Keywords Energy storage systems (ESS) · Technical and economic model · Energy storage management · Power distribution network

---

A. Foroughi Nematollahi · B. Vahidi (✉)
Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran
e-mail: vahidi@aut.ac.ir

A. Foroughi Nematollahi
e-mail: amin.foroughi@aut.ac.ir

A. Rahiminejad
Department of Electrical and Computer Science, Esfarayen University of Technology, Esfarayen, North Khorasan, Iran
e-mail: abolfazl.rahiminezhad@gmail.com

N. Mahdavi Tabatabaei and N. Bizon (eds.), *Numerical Methods for Energy Applications*, Power Systems,
https://doi.org/10.1007/978-3-030-62191-9_16

Nomenclature

A. Acronyms

ESS	Energy storage system
DN	Distribution network
PV	Photovoltaic
WTG	Wind turbine generators
TN	Transmission networks
SLDs	Storage-like devices
FC	Fuel cell
PEVs	Plug-in electric vehicles
HESS	Hybrid energy storage system
DGs	Distributed generations
DR	Demand response
BES	Battery energy storage
ST	Smart transformer
HEMS	Home energy management system
MILP	Mixed-integer linear programing
ADN	Active distribution network
MILP	Mixed-integer linear programing
OF	Objective function
SOC	State of charge
MaxCap	Maximum capacity of ESS
MinCap,	Minimum capacity of ESS
$P_{storage}$	The charge or discharge power of ESS
AvailableCap	The ESS capacity which can be used
LF	Load factor
Ch	Charging
D.CH	Discharging
ESSE	Energy storage system efficiency

B. Symbols/parameters

Cost	Network energy cost
C and D	Denote charging and discharging period
T_C	Duration of ESS charging
T_D	Duration of ESS discharging
Pr	Power price
PL	Active power loss
T	Time duration
P^{Ch} and P^{DCh}	Charging and discharging power of ESS, respectively
$V_i \angle \delta_i$	Voltage of ith Bus,
$r_{ij} + jx_{ij} = z_{ij}$,	The element (i,j) of impedance matrix
P_i and Pj	Net injected power at ith and jth buses
Es	The energy stored in the ESS

P_{Lch}	The active power loss of the system during charge period of ESS
η_s	The discharging efficiency
P_{LD}	Active power loss of the system during discharging period
$V^i_{\min} \leq V_i \leq V^i_{\max}$	The bus voltage and indices max and min denote the upper and lower bounds. k
Limitk	The thermal limit of line k, and
Sk	The power flow through line

1 Introduction

Today, ESSs are one of the fundamental devices that ensure durability of energy supply and improve the reliability of the power system. ESSs can be utilized in different forms and sizes. The characteristics of an ESS highly depend on the form of the stored energy. Energy can be stored as potential, kinetic, chemical, electromagnetic, thermal, etc. [1–3].

1.1 Motivation

Integration of renewable energy resources in DNs has attracted attentions, significantly. However, the most challenging issue related to these kinds of resources is their variable outputs which highly depend on weather conditions. Utilization of ESS is one the most appropriate ways to deal with this issue.

ESS refers to the apparatuses which shift generation and consumption of energy over time. These apparatuses save energy (charge) when there is excess energy so that it can be consumed (discharged) when required. It should be mentioned that the charging and discharging are asynchronous and there is a transform coefficient ($\eta < 1$) for both charging and discharging of the ESS [2, 4, 5].

In recent years, utilization of storage systems has increased dramatically due to growth of electric load, environmental issues, financial problems and development of technologies [6–12]. One of the most important advantages of ESS is reducing generation investment. To meet the load demands, 20% higher than estimated load should be generated and only 55% of total capacity is used annually [13]. However, by optimal management and employment of ESS, more power plants can operate close to their maximum capacity [14].

These systems which can be installed in both DN and TN, can enhance efficiency of utilizing both renewable resources and conventional fossil fuel generators [9–12, 15]. Lots of efforts have been performed for optimal utilization of ESS using different objective functions [16–19]. The most well-known targets that can be achieved using

ESSs are load leveling, stability, reliability, power quality, frequency control, loss reduction and source intermittency reduction.

ESS can be located near renewable energy-based generators such as PV and WTG in order to improve their unpredictable behavior. In fact, ESS with controllable behavior can be employed besides renewable energy resources to tackle output power fluctuations. Lots of efforts have been performed on optimal design of hybrid systems which mainly consist of renewable energy resources (PV and WTG) and ESSs (battery/hydrogen tank) [20].

The concept of smart grids and micro-grids are introduced as the future networks in which controllability and monitoring of the power system can be enhanced through employing communication infrastructure [21]. In such systems, distributed renewable energy generators are easily embedded into network and utilized effectively. Moreover, these systems provide an appropriate platform for utilizing SLDs including energy storage systems such as batteries and devices with similar properties such as PEVs. Optimal utilization of SLDs in smart grids can be performed easily due to existence of adequate infrastructure [15, 21, 22].

In addition to smoothing out renewable energy output and optimal utilization of ESS in smart grids, ESSs can also be integrated and utilized optimally in conventional DNs. They can be charged by the power drawn from the main grid and discharged to supply DN loads so that performance of the conventional network is enhanced economically and technically. Many researches have been conducted in this context [12, 16–19]. In this chapter, a new closed form equation is proposed for optimal utilization of ESS in conventional DNs in order to enhance efficiency of the DNs using analytical methods.

1.2 Literature Survey

Nearly, all the attempts regarding ESS utilization can be considered in four different areas including hybrid systems, smart grids, HESS, and conventional networks.

1. Hybrid system- lots of efforts have been performed for optimal design of hybrid systems which mainly include renewable energy resources and ESSs. These systems which are known as micro-grids can operate in two modes including stand-alone and grid-connected modes. Micro-grids consist of a set of DGs and ESS. These systems can supply a building (residential, commercial, or office), a market, or even a village. The stand-alone hybrid systems are mainly designed to supply the load demands in remote areas. Since these areas are far from the main grid, the more economical method for supplying the load is to establish a micro-grid consisting of generators which are based on renewable energies such as solar and wind. Due to unpredictable output of PVs and WTGs, presence of ESS is almost obligatory. These systems must be designed so that the load is supplied all the time, while the system is low cost. Thus, ESS must be designed optimally so that it can store an amount of energy which is sufficient for supplying

the load demand when there is no generation. In this situation, the number or the capacity of ESS must be obtained optimally and technically. Thus, there is no optimal placement or utilization for ESS. In other words, ESS must be controlled so that excess energy of generators is stored in ESSs, then they are discharged to load whenever needed. ESS which is mainly used for these systems is battery or hydrogen tank which is used to supply a FC. Some efforts in this area can be found in [23–30].

2. Smart grids—smart environment of distribution networks, micro-grids and even homes, facilitates optimal utilization of renewable energy resources, conventional resources, and ESS. In such networks, in addition to conventional ESS, SLD such as PEVs can also be operated as ESS [31–33]. In [34], Demand Response (DR), Smart management of PEVs, and smart management of thermal energy storage are performed to reduce the cost of energy consumption for residential sector. Game theory is used for optimal control of ESS and demand-side management in a smart power system in [35]. A stochastic energy management of PVs, PEV and as ESS has been performed in a smart home in [36]. The authors have tried to charge the PEVs in low tariff electricity time and supply the load with the lowest possible cost. Authors of [37] have implemented optimal sizing of BESS in a smart grid equipped with ST to reduce the rate of ST converters. The paper showed that the BESS incorporating with ST can operate more efficiently. A review on HEMS including management of generators especially renewable ones, ESS, and SLD such PEVs can be found in [38]. Mixed-integer linear programing (MILP) has been used for sizing of a hybrid system consisting of renewable DGs and ESS for a smart home in [39]. They have used MILP for long term tech-economical HEMS. Real-time optimal management of charge/discharge of ESS has been performed in [40] for a smart grid. The authors have predicted load and scheduled an optimal ESS management, then, they have proposed an on-line algorithm for real time energy management. Establishing a balance between energy saving and a comfortable lifestyle aiming for low cost energy consumption, user convenience rates and thermal comfort level in a smart home has been done in [41]. Lots of other efforts conducted on ESS and energy management in smart grids and smart homes, which are equipped with smart metering devices and communication infrastructure, can be found in the literature. It is completely obvious that in such systems, optimal management of ESS can be performed in real-time manner easily. Thus, high efficient operation of ESS is quite expected.
3. HESS—different storage devices have different features which determine their application and location of use. However, in some cases, a hybrid energy storage system is an efficient way for storing excess energy and supplying the load in a different situation. For instance, due to high energy density of batteries and high power density of ultra-capacitors, an HESS consisting of batteries and ultra-capacitors is an adequate ESS for a PEV. However, it is very important to manage such systems to have an optimal operation of HESS. In a majority of works performed in this area, the main objective is to reduce the current stress of batteries and increase their life time. Some of the attempts done in HESS management can be found in [42–46].

4. Conventional network- the three important concerns of today's societies are energy, environmental and financial concerns [47]. Researchers and experts have tried a lot to deal with these crises especially in the field of electricity energy production and management. Loss reduction methods, distributed generation incorporation, power market, micro-grids and smart grids are some of the proposed methods to reduce the cost, fuel consumption, and the environmental threats. Some of these methods such as DG integration and loss reduction methods are now applied to the power systems and some of them are not. ESS management is a novel method for increasing efficiency of today's distribution systems. As mentioned before, ESS can be easily managed in smart grids which actually refer to the future networks. However, in conventional networks (i.e., nowadays networks), there is no direct communication between producers and consumers. Thus, ESS management in conventional networks with existing facilities is very important for enhancing efficiency of the networks and fossil fuel producers. ESS management means managing charge and discharge of these devices to move the generation and consumption over time aiming to enhance network performance. Using ESSs, large and even small power plants can operate in their exact optimal operation points; while, the load variation can be smooth out by means of ESSs.

A real-time BES management has been done in [48]. In that paper, the load is forecasted, BES scheduling is performed, and the errors are met in real-time. Shen et al. have discussed the ADN expansion in the presence of ESS [49]. The charging and discharging of ESS has been performed aiming to shift peak and enhance reliability. Optimal control of ESS in a micro-grid integrated with renewable energy resources has been discussed in [50]. In that paper, an optimal power flow by which the optimal control of ESS is obtained has been introduced. Optimal power flow considering ESS has also been discussed in [51]. They have integrated ESS in their proposed OPF by adding simple charge/discharge dynamics of ESS. BES also have proposed an AC optimal power flow for optimal placing of large ESS in a power system in the presence of wind turbine generators [52]. In that paper, changes in storage allocation in the network are studied as a function of total storage budget and transmission line-flow constraints. Nik et al. have used a mixed integer second-order cone programming to solve optimal power flow of ADN for optimal sitting and sizing of distributed ESS [53]. The problem is solved as a multi-objective optimization problem in which the network voltage deviations; line congestion; power loss, ESS cost, load supplying cost; etc., are considered as the objectives. Tang et al. have performed the optimal placement and capacity of ESS in distribution networks aiming to minimize energy loss [54]. They have simulated the distribution network as a tree and have shown that the best place for ESS is near the leaves far from the substation.

As can be seen, lots of efforts have been done in the field of optimal allocation and management of ESS in conventional networks, smart grids and stand-alone micro-grids. This subject is one of the most interesting fields of research which motivated the authors to perform the current study.

1.3 Research Gap

Role of ESSs on performance enhancement of power systems cannot be denied. They reduce power losses by leveling out the load profile, increase reliability by storing the power in energy excess time and supplying the load in time of low generation, enhance the power quality by smoothing out the load variation and provide a better platform for renewable DG penetration by tackling their intermittent output. As mentioned before, lots of efforts have been done in the field of ESS management or allocation. Numerical and evolutionary methods are used for optimal management or ESS setting; however, there is no guarantee for optimal performance of ESS using these methods [55–57]. Moreover, the simulation for finding the optimal management of ESSs must be performed once again as the load varies. Since a series of optimization problems must be solved in each iteration and according to complexity of the problem, solving these problems would be time consuming and unreasonable. Furthermore, in the previous studies on optimal management of ESS, the energy price and duration of each level are considered to be constant.

Besides all appropriate efforts done in ESS management of conventional network, and to overcome the aforementioned shortcomings, an analytical approach for ESS management is proposed in this chapter. A novel OF which is a closed form equation is proposed. Using this closed form equation for optimal management of ESS, the exact optimal operation point can be achieved easily using analytical methods. The novelties of this chapter can be addressed as follows:

1. A new formulation is introduced for operation cost of the system in the presence of ESS.
2. A closed form equation is proposed for charging and discharging ESS with the aim of cost minimization.
3. Analytical solution is employed to solve the optimization problem.
4. The global optimal operation point of the system is reached mathematically.
5. Optimal management of ESS is achieved in real-time.
6. The energy cost based on consumption time is taken into account.
7. Using the proposed approach, effects of ESS parameters such as efficiency and charging rate on optimal performance of the ESS can be investigated easily.
8. A critical efficiency is calculated for each ESS by means of the proposed closed form equation. This critical efficiency illustrates whether utilization of ESS is beneficial for the system or not.

1.4 Chapter Organization

In Sect. 2, problem formulation is illustrated and the proposed objective function which is a closed form equation for ESS management is extracted. In this section, the algorithm for optimal allocation and management of ESS is presented. In Sect. 3, the simulation and results are presented for two test cases and the optimal management of ESS is discussed. Finally, the chapter is concluded in Sect. 4.

2 Problem Formulation

In both conventional and smart distribution grids, the power price varies in different load levels and periods. In other words, in a deregulated environment, power price is determined by the market participants based on network conditions. The system operator tries to minimize the overall cost of the system. In passive DNs, the overall cost consists of power consumption cost and active power loss. However, for the active DNs, the total costs include not only the cost of power consumption and active power loss, but also the cost of energy produced by different resources. Moreover, in such a network, revenue is obtained from selling output power of resources. For a network equipped with ESS, cost of charging and revenue of discharging are also added to system cost. Thus, the total cost of a system equipped with ESS can be formulated as follows (Eq. 1):

$$Cost = T_C \times \Pr_C \times P_{LC} + T_D \times \Pr_D \times P_{LD} + T_C \times \Pr_C \times P^{Ch} - T_D \times \Pr_D \times P^{DCh} \tag{1}$$

In this equation, indices C and D denote charging and discharging period, P_r, P_L, and T are power price, active power loss and time duration, and P^{Ch} and P^{DCh} are charging and discharging power of ESS, respectively. The first and second parts of the equation are costs of active power loss of the system in both charging and discharging periods, respectively. The third part is the cost of purchasing power for charging ESS, and the fourth part is the revenue of selling power by discharging the ESS.

The active power loss can be formulated as follows (Eq. 2) [58–60]:

$$P_l = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_i P_j + Q_i Q_j\right) + \beta_{ij}\left(Q_i P_j - P_i Q_j\right)\right] \tag{2}$$

where

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j}\cos\left(\delta_i - \delta_j\right) \tag{3}$$

$$\beta_{ij} = \frac{r_{ij}}{V_i V_j}\sin(\delta_i - \delta_j) \tag{4}$$

And $V_i\angle\delta_i$ is the Voltage of *i*th Bus, $r_{ij}+jx_{ij}=z_{ij}$, is the element (*i,j*) of impedance matrix, and P_i and P_j are net injected power at *i*th and *j*th buses, respectively,

Now, imagine that ESS is installed at bus m. Thus, the active power loss of the system during charge period of ESS can be written as follows (Eq. 5):

$$P_{LCh} = \sum_{j=1, j\neq m}^{N}\ \sum_{i=1, i\neq m}^{N}\left[\alpha_{Cij}\left(P_{Ci}P_{Cj} + Q_{Ci}Q_{Cj}\right) + \beta_{Cij}\left(Q_{Ci}P_{Cj} - P_{Ci}Q_{Cj}\right)\right]$$

$$+\alpha_{Cmm}\Big((P_{Cm}+P^{Ch})^2+Q_{Cm}^2\Big)$$
$$+\sum_{j=1,j\neq m}^{N}\Big[\alpha_{Cmj}\Big((P_{Cm}+P^{Ch})P_{Cj}+Q_{Ci}Q_{Cj}\Big)+\beta_{Cij}\Big(Q_{Ci}P_{Cj}-(P_{Cm}+P^{Ch})Q_{Cj}\Big)\Big] \tag{5}$$

The load level during charging period is different from the one in discharging period. Index 1 denotes charging period. The charging period lasts for T^1 and the energy stored in the ESS in this period is $Es = T_C \times P^{Ch}$. The stored energy is injected to the network in discharging period with time duration of T_D. It should be mentioned that T_D does not have to be continuous. In other words, the charged energy can be discharged whenever required. Considering the discharging efficiency of η_s the discharged power can be formulated as follows (Eq. 6):

$$P^{DCh}=\frac{\eta_s\times E_s}{T_D}=\frac{\eta_s\times T_C\times P^{Ch}}{T_D} \tag{6}$$

Based on aforementioned phrases, active power loss of the system during discharging period would be calculated based on the following equation (Eq. 7):

$$\begin{aligned}P_{LD}=&\sum_{\substack{j=1\\j\neq m}}^{N}\sum_{\substack{i=1\\i\neq m}}^{N}\big[\alpha_{Dij}\big(P_{Di}P_{Dj}+Q_{Di}Q_{Dj}\big)+\beta_{Dij}\big(Q_{Di}P_{Dj}-P_{Di}Q_{Dj}\big)\big]\\&+\sum_{\substack{j=1\\j\neq m}}^{N}\left[\begin{array}{l}\alpha_{Dmj}\left(\left(P_{Dm}+\dfrac{\eta_s\times T_C\times P^{Ch}}{T_D}\right)P_{Dj}+Q_{Di}Q_{Dj}\right)\\+\beta_{Dij}\left(Q_{Di}P_{Dj}-\left(P_{Dm}+\dfrac{\eta_s\times T_C\times P^{Ch}}{T_D}\right)Q_{Dj}\right)\end{array}\right]\\&+\alpha_{Dmm}\left(\left(P_{Dm}+\frac{\eta_s\times T_C\times P^{Ch}}{T_D}\right)^2+Q_{Dm}^2\right)\end{aligned} \tag{7}$$

Now, by substituting Eqs. (5) and (7) in Eq. (1), the cost function can be rewritten as follows (Eq. 8):

$$Cost=T_C\times\Pr_C\times\left\{\begin{array}{r}\displaystyle\sum_{\substack{j=1\\j\neq m}}^{N}\sum_{\substack{i=1\\i\neq m}}^{N}\big[\alpha_{Cij}\big(P_{Ci}P_{Cj}+Q_{Ci}Q_{Cj}\big)+\beta_{Cij}\big(Q_{Ci}P_{Cj}-P_{Ci}Q_{Cj}\big)\big]\\ \displaystyle+\sum_{\substack{j=1\\j\neq m}}^{N}\left[\begin{array}{l}\alpha_{Cmj}\Big((P_{Cm}+P^{Ch})P_{Cj}+Q_{Ci}Q_{Cj}\Big)\\+\beta_{Cij}\Big(Q_{Ci}P_{Cj}-(P_{Cm}+P^{Ch})Q_{Cj}\Big)\end{array}\right]\\+\alpha_{Cmm}\Big((P_{Cm}+P^{Ch})^2+Q_{Cm}^2\Big)\end{array}\right\}$$

$$
+T_D \times Pr_D \times \left\{ \begin{array}{r} \left(\sum_{\substack{j=1 \\ j \neq m}}^{N} \sum_{\substack{i=1 \\ i \neq m}}^{N} \left[\begin{array}{c} \alpha_{Dij}\left(P_{Di}P_{Dj} + Q_{Di}Q_{Dj}\right) \\ +\beta_{Dij}\left(Q_{Di}P_{Dj} - P_{Di}Q_{Dj}\right) \end{array} \right] \right. \\ + \sum_{\substack{j=1 \\ j \neq m}}^{N} \left[\begin{array}{l} \alpha_{Dmj}\left(\left(P_{Dm} - \frac{\eta_s \times T_C \times P^{Ch}}{T_D}\right)P_{Dj} + Q_{Di}Q_{Dj}\right) \\ +\beta_{Dij}\left(Q_{Di}P_{Dj} - \left(P_{Dm} - \frac{\eta_s \times T_C \times P_{ch}}{T_D}\right)Q_{Dj}\right) \end{array} \right] \\ \left. +\alpha_{Dmm}\left(\left(P_{Dm} - \frac{\eta_s \times T_C \times P^{Ch}}{T_D}\right)^2 + Q_{Dm}^2\right) \right) \end{array} \right\}
$$

$$
+T_C \times \Pr_C \times P^{Ch} - T_C \times \Pr_D \times \frac{\eta_s \times T_C \times P^{Ch}}{T_D} \tag{8}
$$

As can be seen, cost is a function of charging power, and the other parameters are constant. It should be noticed that cost is a function of coefficients α and β which depend on voltage magnitude and angle. Updating values of α and β requires calculating load flow. However, numerical results show that variation of α and β by different sizes of ESS is small and negligible [59]. With this assumption, optimum size of ESS for each bus, given by the aforementioned relations can be calculated from the base case load flow (i.e., without ESS). Thus, by setting derivative of the Cost function with respect to charging power equal to zero, the optimal amount of power charging can be achieved (Eqs. 9–11).

$$
\begin{aligned} \frac{\partial Cost(P^{Ch})}{\partial P^{Ch}} = & T_C \times \Pr_C \times \frac{\partial P_{LC}}{\partial P^{Ch}} + T_D \times \Pr_D \times \frac{P_{LD}}{\partial P^{Ch}} \\ & + T_C \times \Pr_C - T_D \times \Pr_D \times \frac{\eta_s \times T_C}{T_D} = 0 \end{aligned} \tag{9}
$$

$$
\frac{\partial P_{LC}}{\partial P^{Ch}} = \underbrace{\sum_{\substack{j=1 \\ j \neq m}}^{N} \left[\alpha_{Cmj} \times P_{Cj} - \beta_{Cmj} \times Q_{Cj}\right]}_{A_1} + 2 \times \alpha_{Cmm} \times (P_{Cm} + P^{Ch}) \tag{10}
$$

$$
\begin{aligned} \frac{\partial P_{LD}}{\partial P_{ch}} = & \underbrace{\sum_{\substack{j=1 \\ j \neq m}}^{N} \left[\alpha_{Dmj} \times \left(-\eta_s \times \frac{T_C}{T_D}\right) \times P_{Dj} - \beta_{Dmj} \times \left(-\eta_s \times \frac{T_C}{T_D}\right) \times Q_{Dj}\right]}_{A_2} \\ & + 2 \times \alpha_{Dmm} \times \left(-\eta_s \times \frac{T_C}{T_D}\right) \times \left(P_{Dm} + \left(-\eta_s \times \frac{T_C}{T_D}\right) \times P^{Ch}\right) \end{aligned} \tag{11}
$$

Finally, by substituting both derivatives of loss functions ($\frac{\partial P_{LC}}{\partial P^{Ch}}$ and $\frac{\partial P_{LD}}{\partial P^{Ch}}$) in cost function derivate ($\frac{\partial Cost(P^{Ch})}{\partial P^{Ch}}$), the optimal amount of charging power is achieved as follows (Eq. 12):

$$P^{Ch} = \frac{\begin{bmatrix} -T_C \times \Pr_C \times (1 + A_C + 2 \times \alpha_{Cmm} \times P_{Cm}) \\ -T_D \times \Pr_D \times \left(-\eta_s \times \frac{T_C}{T_D} + A_D - \alpha_{Dmm} \times P_{Dm} \times \left(\frac{2 \times \eta_s \times T_C}{T_D} \right) \right) \end{bmatrix}}{T_C \times \Pr_C \times 2 \times \alpha_{Cmm} + 2 \times T_D \times \Pr_D \times \left(\frac{\eta_s \times T_C}{T_D} \right)^2 \times \alpha_{Dmm}} \quad (12)$$

Based on the obtained closed form equation, determining time duration of both charging and discharging periods, power price at both periods, ESS efficiency, and information of load flow, the exact optimal power charging of the ESS can be obtained.

- Technical assessment (Effect of ESS efficiency)

One of the important parameters in ESS management is its efficiency. Regarding Eq. (12), when $P^{Ch} \geq 0$, charging ESS is economical. Thus, it can be said that there is a critical efficiency for which P^{Ch} is zero. Whenever, efficiency of ESS is greater than this critical value, charging and discharging of ESS is economical. To obtain the critical efficiency, let P^{Ch} to be positive. The critical efficiency is then obtained as follows (Eq. 13):

$$\eta_{critical} = \frac{\Pr_C \times (1 + A_1 + 2 \times \alpha_{Cmm} \times P_{Cm})}{\Pr_D \times \left\{ 1 + \sum_{\substack{j=1 \\ j \neq m}}^{N} \left[\alpha_{Dmj} \times P_{Dj} - \beta_{Dmj} \times Q_{Dj} \right] + 2 \times \alpha_{Dmm} \times P_{Dm} \right\}} \quad (13)$$

As can be seen, the critical efficiency is related to different parameters such as duration, power price, amount of load in each load level and the network characteristics. By calculating the critical value of ESS efficiency, an appropriate ESS can be selected to be installed in the studied system.

- Constraints

In solving the ESS management in this study, there are two kinds of constraints including those related to ESS and those related to DN.

The constraints related to the network are voltage limit and thermal limit of the line which can be mathematically presented as follows (Eqs. 14 and 15):

$$V_{\min}^{i} \leq V_i \leq V_{\max}^{i} \quad (14)$$

$$S_k \leq \lim it_k \quad (15)$$

where V is magnitude of the bus voltage and indices max and min denote the upper and lower bounds. $Limit_k$ is the thermal limit of line k, and S_k is the power flow through line k.

The constraints related to ESS include limited capacity, charging rate and discharging rate.

Capacity constraint: State of Charge (*SOC*) must lie in a predefined range as follows (Eq. 16):

$$Min_{\text{Cap.}} \leq SOC(t) \leq Max_{\text{Cap.}} \quad t = 1:24 \tag{16}$$

where

$$SOC(t) = SOC(t-1) + P_{storage}(t) \tag{17}$$

$$Min_{\text{Cap.}} = (1 - DOD) \times Max_{\text{Cap.}} \tag{18}$$

$$Availble_{Cap} = Max_{\text{Cap.}} - Min_{\text{Cap.}} \tag{19}$$

In these equations, t is time, *MaxCap* is maximum capacity of ESS, SOC is state of charge, DOD is depth of discharge, *MinCap* is the minimum capacity of ESS, *AvailableCap* is the ESS capacity which can be used, and $P_{storage}$ is the charge or discharge power of ESS.

Rate Constraint: the amount of power for charging or discharging (i.e. $P_{storage}$) cannot exceed limitation in an hour. In other words, charging or discharging rate must be lower than a maximum value as follows (Eq. 16.20):

$$\left|P_{storage}(t)\right| \leq Max_{Rate} \tag{20}$$

To satisfy this constraint, $P_{storage}$ in charging and discharging mode can be obtained as follows (Eqs. 21 and 22):

In charging mode:

$$P_{storage}(t) = min\left\{P_{ch}(t), Max_{cap} - SOC(t-1), Max_{Ch.Rate}\right\} \tag{21}$$

In discharging mode:

$$P_{storage}(t) = \max\left\{P_{Disch.}(t), Min_{cap} - SOC(t-1), -Max_{DisCh.\text{Rate}}\right\} \tag{22}$$

2.1 Optimal Placement and ESS Scheduling

According to the previous section, optimal management of ESS can be achieved analytically. However, the place of ESS installation might also influence performance of DN. Procedure of optimal placement and scheduling of multi ESS are illustrated in the flowchart depicted in Fig. 1. It should be noticed that in this flowchart, N_{load_level} is the number of levels considered for daily load profile, and N_{bus} is the number of buses in the studied network. For each load level, the ESS is placed in all buses and optimal management of charging/discharging of the ESS is obtained. The best algorithm for charging/discharging ESS is obtained among different scenarios and the best place for ESS is obtained based on benefit of ESS for the network according to its location (Tables 1 and 2).

3 Simulation and Results

The proposed approach is applied to two standard test cases including 33-bus and 69-bus radial DNs in which the line data and bus data of these two systems can be found in [61], and [59], respectively. The economic and technical data related to load level, power price, power loss and system cost for both test systems are also extracted from [62]. This information is briefly presented in Table 3. Technical information of ESS is also illustrated in Table 4.

Simulations are performed in 4 different scenarios. In the first scenario, optimal placement and ESS scheduling are investigated. In the second scenario, optimal placement and scheduling of two ESSs are studied. In the third scenario, the ESS is placed in the system and only ESS management is considered. In the fourth scenario, effect of ESSE is investigated. All the scenarios are performed for both test systems.

3.1 Scenario 1: Optimal Placement and Scheduling of 1 ESS

In this scenario, optimal location and scheduling of an ESS are obtained. In order to investigate the effect of ESS efficiency, 5 different values are considered for ESS efficiency. The obtained results for both 33-bus and 69-bus test systems are shown in Tables 5, and 6, respectively.

A quick look reveals that the best place for ESS is almost near the first bus of the system, i.e., close to the upper grid. The reason is that in this location, power loss of the system in charging period does not vary dramatically. In other words, ESS can be considered as a load during the charging period. Thus, by installing ESS near the main grid, power required for charging ESS does not flow through the lines; this results in lower power loss. Moreover, lower voltage drops may occur in the system.

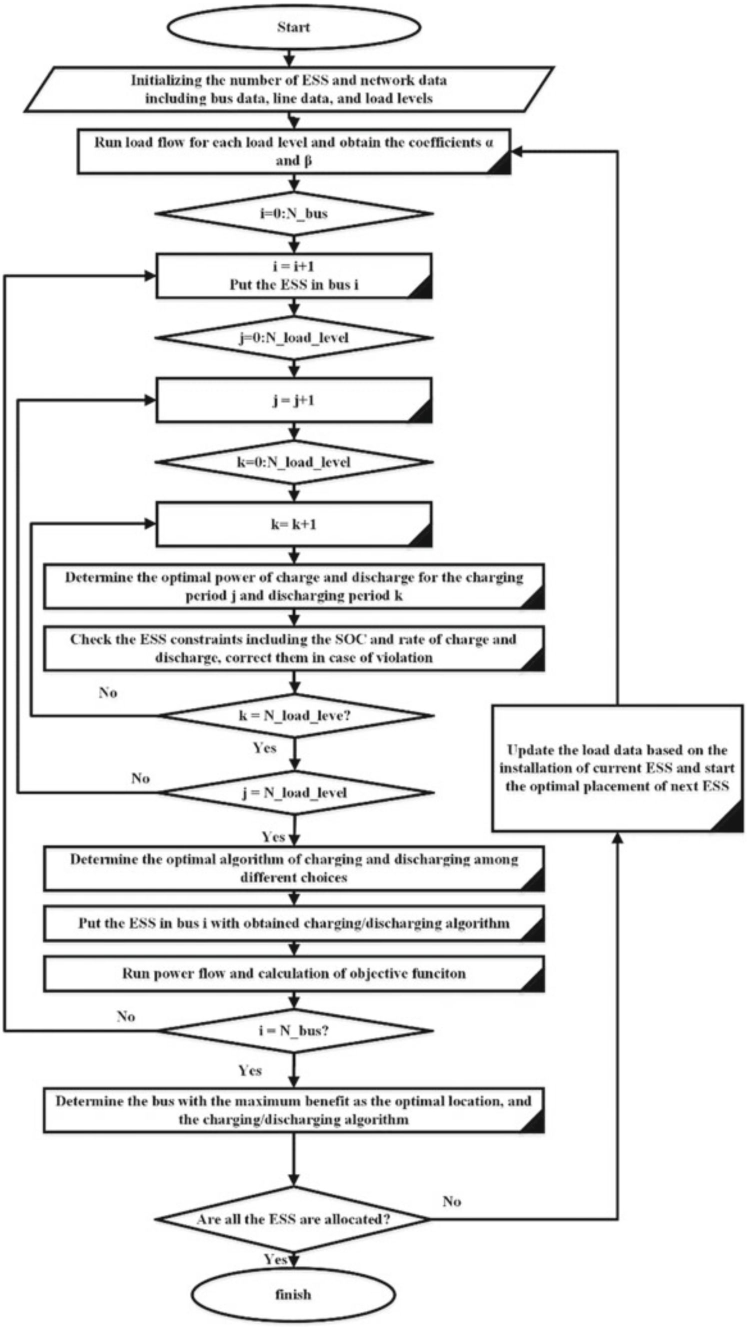

Fig. 1 The flowchart of optimal placement and ESS scheduling

Table 1 Technical and commercial information of 33 and 69 bus test systems

	LF	0.55	0.85	0.7	1	
	Load duration	6	6	6	6	
	Energy price	0.55	0.75	0.65	1	
Loss	69 bus	62.909	158.11	104.48	224.87	Net cost
	33 bus	59.45	148.73	98.52	210.97	
Cost	69 bus	207.6	711.5	407.48	1349.2	2675.7
	33 bus	196.22	669.3	384.25	1265.8	2518.3

Table 2 ESS technical information

	Maximum rate	Maximum capacity
33 bus	2500	10000
69 bus	2500	16000

Table 3 Optimal placement and scheduling of an ESS for different values of ESSE for 33-bus test case

η	Bus	LF	Status	Ch./D.Ch	Loss	Cost	Income	Benefit
1	5	0.55	Ch	1666	130	5929		3002
		0.85	D.Ch	−1666	101		7042	
		0.7	D.Ch	1666	183	7216		
		1	D.Ch	−1666	149		9105	
0.97	5	0.55	Ch	1692	131	6017		2541
		0.85	D.Ch	−1641	185		6928	
		0.7	Ch	1692	101	7321		
		1	D.Ch	−1641	149		8952	
0.94	5	0.55	Ch	1718	133	6109		2073
		0.85	D.Ch	−1616	102		8798	
		0.7	Ch	1718	187	7430		
		1	D.Ch	−1616	150		6814	
0.9	5	0.55	Ch	1757	179	6391		1288
		0.85	–		148	384		
		0.7	–		98	669		
		1	D.Ch	−1581	125		8733	
0.85	5	0.55	Ch	1807	138	6422		831
		0.85	–	–	148	669		
		0.7	–	–	98	384		
		1	D.Ch	−1536	152		8307	

Table 4 Optimal placement and scheduling of an ESS for different values of ESSE for 69-bus test case

η	Bus	LF	Status	Ch./D.Ch	Loss	Cost	Income	Ben.
1	47	0.55	Ch	2500	63	8459		5572
		0.85	D.Ch	−2500	158		10,539	
		0.7	Ch	2500	104	10,159		
		1	D.Ch	−2500	224		13,652	
0.97	47	0.55	Ch	2538	63	8584		4904
		0.85	D.Ch	−2462	158		10,370	
		0.7	Ch	2538	105	10,308		
		1	D.Ch	−2462	224		13,427	
0.94	47	0.55	Ch	2500	63	8459		4021
		0.85	D.Ch	−2352	104		9874	
		0.7	Ch	2500	157	10,159		
		1	D.Ch	−2352	224		12,765	
0.9	9	0.55	Ch	2500	148	8739		2713
		0.85	D.Ch	−2246	121		9564	
		0.7	Ch	2500	204	10,549		
		1	D.Ch	−2246	174		12,436	
0.85	7	0.55	Ch	2500	63	8694	–	1788
		0.85	–	–	158	711	–	
		0.7	–	–	104	407	–	
		1	D.Ch	−2116	224		11,601	

Thus, the ESS is placed in the buses close to the upper grid and the optimal strategy is to charge the ESS in low power price period and discharge in high price time.

It can also be inferred from the tables that ESSE has a significant influence on total benefit of optimal ESS scheduling. As can be seen, a mere 3% increase in ESSE increases the total benefit by 15% and 13% for 33-bus and 69 bus test cases, respectively. The differences between total benefit of both test systems in the case of ESSE of 100 and 85% are staggering. Moreover, the load factor (*LF*) does not influence charging or discharging rate of ESS. However, income of the network for higher LFs is bigger.

3.2 Scenario 2: Optimal Placement and Scheduling of 2 ESSs

In this scenario, optimal placement and scheduling of multi ESSs (2 ESSs) are investigated. Similar to the previous scenario, the optimizations are performed for different values of ESS efficiency. The optimization results are listed in Tables 7 and 8 for

Table 5 Optimal placement and scheduling of two ESSs for different values of ESSE for 33-bus test case

η	Bus	LF	Status	Ch./D.Ch	Loss	Cost	Income	Ben.
1	0.55	5	Ch	1666	142	11,472		7491
		19	Ch	1666				
	0.85	5	D.Ch	−1666	101		14,542	
		19	D.Ch	−1666				
	0.7	5	Ch	1666	197	13,772		
		19	Ch	1666				
	1	5	D.Ch	−1666	147		19,113	
		19	D.Ch	−1666				
0.97	0.55	5	Ch	1692	144	11,648		6397
		19	Ch	1692				
	0.85	5	D.Ch	−1641	101		14,313	
		19	D.Ch	−1641				
	0.7	5	Ch	1692	200	13,981		
		19	Ch	1692				
	1	5	D.Ch	−1641	148		18,807	
		19	D.Ch	−1641				
0.94	0.55	5	Ch	1723	147	11,861		5341
		19	Ch	1723				
	0.85	5	D.Ch	−1611	102		14,045	
		19	D.Ch	−1611				
	0.7	5	Ch	1723	202	14,234		
		19	Ch	1723				
	1	5	D.Ch	−1611	148		18,447	
		19	D.Ch	−1611				
0.9	0.55	5	Ch	1757	149	12,089		5248
		19	Ch	1757				
	0.85	5	D.Ch	−1581	102		13,768	
		19	D.Ch	−1581				
	0.7	5	Ch	1757	205	14,506		
		19	Ch	1757				
	1	5	D.Ch	−1581	149		18,076	
		19	D.Ch	−1581				
0.85	0.55	5	Ch	1807	153	12,436		4048
		19	Ch	1807				
	0.85	5	–		148	669.3		

(continued)

Table 5 (continued)

η	Bus	LF	Status	Ch./D.Ch	Loss	Cost	Income	Ben.
		19	–					
	0.7	5	–		98	384.2		
		19	–					
	1	5	D.Ch	−1536	150		17,538	
		19	D.Ch	−1536				

33-bus and 69-bus test systems, respectively. As expected, the best places for ESSs are determined to be close to the main grid. The results show that power loss of the system during charging period is nearly 10% higher than the previous scenario. In other words, increase in ESS capacity increases the power for charging ESS which results in higher losses. Power loss of the system during discharging period is approximately the same for both cases. However, total benefit of the system in the case of two ESSs is much higher than its value for one ESS. In other words, increase in ESS capacity enhances performance of the system. A higher ESS capacity means a higher load during low power price and higher generation in high power price. This surely increases benefit of system's power supply.

3.3 *Scenario 3: ESS Scheduling*

This scenario investigates the situation of scheduling one ESS. In other words, in this situation, ESS is placed in the system and the proposed approach is only performed for optimal ESS scheduling. In this scenario, the ESS efficiencies of 85 and 95% are considered. The predefined place for ESS is considered to be on buses 30 and 33 for 33-bus and 69-bus test systems, respectively. The results of optimal ESS scheduling for both 33-bus and 69-bus test systems are listed in Table 9. As can be seen, since location of ESS is not optimal, power loss is higher than its value compared to the case where the ESS is placed in the optimal location. For instance, the power loss of 33-bus test case for ESSE of 85% during charging mode is 242.65 for the case of non-optimal location and 138 for optimal placement of ESS. Total benefit of the system for optimal location is nearly 9 times higher than benefit of the case with non-optimal location for ESSE of 85%. Thus, optimal placement of ESS can affect system performance significantly. It is also obvious that as ESSE improves from 85 to 95%, the total benefit increases drastically.

The SOC, charging and discharging rate of ESS after optimal management for two different efficiencies including 95% (i.e. case 1), and 85% (i.e. case 2) are depicted in Fig. 2 for IEEE-33 bus test system and 69 bus test system. As can be seen, ESS with efficiency of 85% is not charged and discharged between 7 A.M to 18 P.M. In other words, during these hours, utilizing ESS is not economical. The reason is that

Table 6 Optimal placement and scheduling **of** two ESSs for different values of ESSE for 69-bus test case

η	LF	Bus	Status	Ch/D.Ch	Loss	Cost	Income	Benefit
1	0.55	36	Ch	2500	63.2	16,710		13818
		47	Ch	2500				
	0.85	36	D.Ch	−2500	158		21,788	
		47	D.Ch	−2500				
	0.7	36	Ch	2500	105	19,911		
		47	Ch	2500				
	1	36	D.Ch	−2500	224		28,651	
		47	D.Ch	−2500				
0.97	0.55	36	Ch	2500	63.7	16,710		12,255
		47	Ch	2500				
	0.85	36	D.Ch	−2425	158		21,118	
		47	D.Ch	−2425				
	0.7	36	Ch	2500	105	19,911		
		47	Ch	2500				
	1	36	D.Ch	−2425	224		27,758	
		47	D.Ch	−2425				
0.94	0.55	36	Ch	2500	63	16,710		10,411
		47	Ch	2500				
	0.85	36	D.Ch	−2337	158		20,328	
		47	D.Ch	−2337				
	0.7	36	Ch	2500	105	19,911		
		47	Ch	2500				
	1	36	D.Ch	−2337	224		26,704	
		47	D.Ch	−2337				
0.9	0.55	36	Ch	2500	63.7	16,710		8560
		47	Ch	2500				
	0.85	36	D.Ch	−2249	158		19,535	
		47	D.Ch	−2249				
	0.7	36	Ch	2500	105	19,911		
		47	Ch	2500				
	1	36	D.Ch	−2249	224		25,647	
		47	D.Ch	−2249				
0.85	0.55	36	Ch	2500	135	16,946		6342
		47	Ch	2500				
	0.85	36	–		104	407		

(continued)

Table 6 (continued)

η	LF	Bus	Status	Ch/D.Ch	Loss	Cost	Income	Benefit
		47	–					
	0.7	36	–		158	711		
		47	–					
	1	36	D.Ch	−2125	182		24,407	
		47	D.Ch	−2125				

Table 7 Optimal scheduling of an ESS for different values of ESSE

	η	Bus	LF	Status	Ch/D.Ch	Loss	Cost	Inc.	Ben.
33	0.95	30	0.55	Ch	1513	244	5802		1144
			0.85	D.Ch	−1438	125		7875	
			0.7	Ch	1150	244	5441		
			1	D.Ch	−1093	90		4512	
	0.85	30	Ch	Ch	1505	242	5769		92.2
			0.85	–	–	127	1053		
			0.7	–	–	98.5	669		
			1	D.Ch	−1280	148		6915	
69	0.95	33	0.55	Ch	2294	123	7980		1539
			0.85	D.Ch	−2179	128		−8882	
			0.7	Ch	1444	243	6136		
			1	D.Ch	−1372	205		6774	
	0.85	33	0.55	Ch	1837	101	6399		359
			0.85	–	–	158	711		
			0.7	–	–	104	407		
			1	D.Ch	−1562	248		7878	

Table 8 Critical values of efficiency

Discharging period→ Charging period↓	1	2	3	4
1	–	0.77066	0.83285	0.73491
2	1.2987	–	1.1719	0.83863
3	1.2007	0.85329	–	0.79026
4	1.3607	1.1925	1.2654	–

Table 9 Critical values of efficiency

Discharging period / Charging period	1	2	3	4
1	–	0.83625	0.78757	0.7125
2	1.2012	–	1.2378	0.79994
3	1.2697	0.85786	–	0.89546
4	1.4035	1.2514	1.1167	–

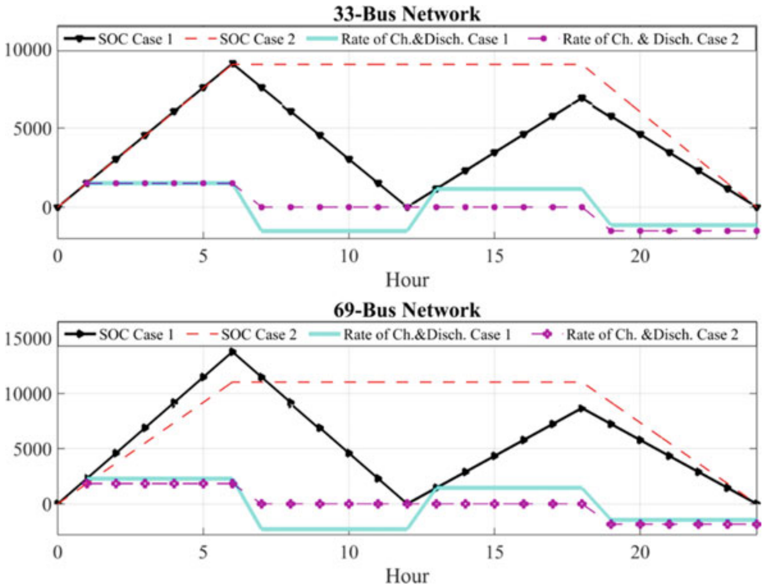

Fig. 2 SOC and rate of charge and discharge of ESS after management for case 1: efficiency of 95% and case 2: efficiency of 85% for both test systems

the critical efficiency (i.e. η critical) is higher than 85%; thus, any ESS with lower efficiency is not reasonable to be used.

3.4 Scenario 4: Investigating Effect of ESSE on System Cost Reduction

In this scenario, the effect of ESSE on system cost is investigated. This investigation is performed for both test systems.

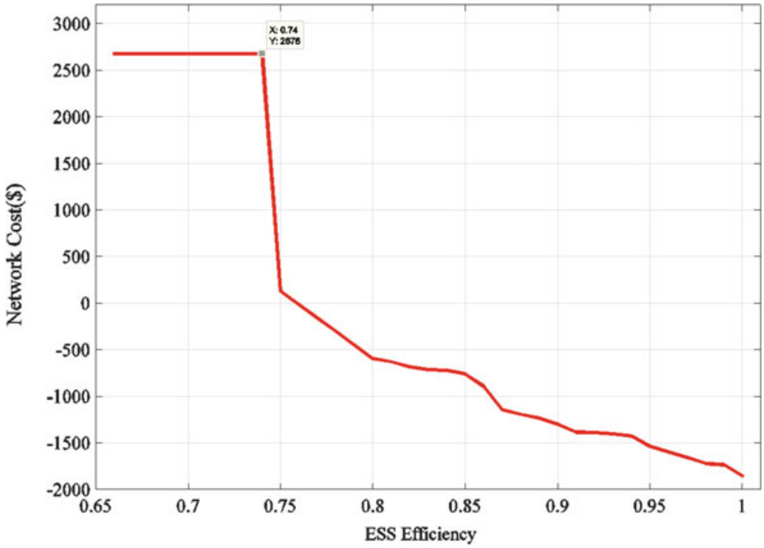

Fig. 3 Cost variation regarding ESSE for 69-bus test system

3.4.1 69-Bus Test Case

In this system, it is assumed that an ESS is placed at bus 33. The critical efficiency for charging in a period and discharging in another period is shown in Table 8. As expected, the optimal performance occurs when efficiency is higher than critical efficiency. For instance, when ESSE is 85%, the best situation occurs when the critical efficiency is minimum. The critical efficiencies which are shown in Tables 8 and 9 reveal that charging and discharging are economical, when ESSE is higher than critical value.

Variations of system cost regarding ESSE are depicted in Fig. 3. It is obvious that the critical efficiency is 73.49%. Any efficiency lower than this value does not affect system costs. Efficiencies higher than this value up to nearly 75% decrease the system cost dramatically. Any efficiency higher than 75% would be economically beneficial for the network.

3.4.2 33-Bus Test Case

In this system, ESS is placed on bus 30. Critical efficiencies of the ESS for charging and discharging in the mentioned bus are listed in Table 9. The cost variation regarding ESSE is presented in Fig. 4. As can be seen, the critical efficiency is 71.25%. Any efficiency higher than this value decreases system cost. Moreover, efficiencies higher than 84% not only decrease the cost, but they are also beneficial.

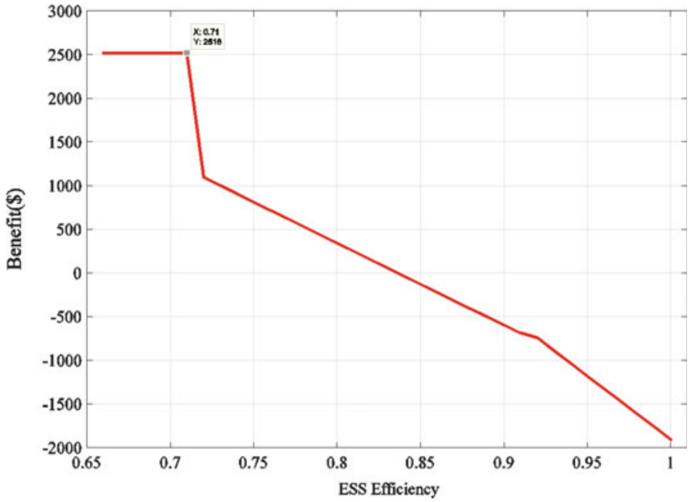

Fig. 4 Cost variation with regards to ESSE for 33-bus test system

4 Conclusion

Regarding increase of renewable energy resources integration in distribution networks, utilization of energy storage system experienced a dramatic increase. Thus, optimal management of these apparatuses especially in conventional distribution networks, is so important. In this chapter, a novel analytical approach for optimal management of energy storage system is proposed. In the proposed approach, the objective function of optimal placement and ESS scheduling is reducing system operation cost; while system constraints are satisfied. In the proposed approach, power loss, power price and load level are considered. The exact optimal operation point is obtained by analytical method and a closed-form equation is achieved. Advantage of the proposed approach compared to previous ones is that the exact operation point is obtained. Moreover, because of closed-form equation, procedure of calculating the proposed approach is much lower than the previous methods. Furthermore, in this chapter, effect of energy storage system efficiency on optimal performance of the ESS is investigated. Critical efficiency is also obtained analytically. Using this equation, minimum energy storage system efficiency can be obtained based on system condition. In other words, the technical requirement of ESS needed for a system can be obtained by the proposed approach. The proposed approach can be applied to different storage systems.

References

1. Nazir H, Batool M, Osorio FJB, Isaza-Ruiz M, Xu X, Vignarooban K, Phelan P, Kannan AM (2019) Recent developments in phase change materials for energy storage applications: a review. Int J Heat Mass Transf 129:491–523
2. Umair MM, Zhang Y, Iqbal K, Zhang S, Tang B (2019) Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storage: a review. Appl Energy 235:846–873
3. Palacios A, Cong L, Navarro ME, Ding Y, Barreneche C (2019) Thermal conductivity measurement techniques for characterizing thermal energy storage materials: a review. Renew Sustain Energy Rev 108:32–52
4. Keck F, Lenzen M, Vassallo A, Li M (2019) The impact of battery energy storage for renewable energy power grids in Australia. Energy 173:647–657
5. Bayon A, Bader R, Jafarian M, Fedunik-Hofman L, Sun Y, Hinkley J, Miller S, Lipiński W (2018) Techno-economic assessment of solid–gas thermochemical energy storage systems for solar thermal power applications. Energy 149:473–484
6. Cutter E, Haley B, Hargreaves J, Williams J (2014) Utility scale energy storage and the need for flexible capacity metrics. Appl Energy 124:274–282
7. Solomon AA, Kammen DM, Callaway D (2014) The role of large-scale energy storage design and dispatch in the power grid: a study of very high grid penetration of variable renewable resources. Appl Energy 134:75–89
8. Johnston L, Díaz-González F, Gomis-Bellmunt O, Corchero-García C, Cruz-Zambrano M (2015) Methodology for the economic optimisation of energy storage systems for frequency support in wind power plants. Appl Energy 137:660–669
9. Santos JM, Moura PS, de Almeida AT (2014) Technical and economic impact of residential electricity storage at local and grid level for Portugal. Appl Energy 128:254–264
10. Lyons PF, Wade NS, Jiang T, Taylor PC, Hashiesh F, Michel M, Miller D (2015) Design and analysis of electrical energy storage demonstration projects on UK distribution networks. Appl Energy 137:677–691
11. Luo X, Wang J, Dooner M, Clarke J (2015) Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 137:511–536
12. Das T, Krishnan V, McCalley JD (2015) Assessing the benefits and economics of bulk energy storage technologies in the power grid. Appl Energy 139:104–118
13. Strbac G (2008) Demand side management: Benefits and challenges. Energy Policy 36:4419–4426
14. Lawder MT, Suthar B, Northrop PWC, De S, Hoff CM, Leitermann O, Crow ML, Santhanagopalan S, Subramanian VR (2014) Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications. Proc IEEE 102:1014–1030
15. Li Z, Guo Q, Sun H, Wang J (2015) Storage-like devices in load leveling: Complementarity constraints and a new and exact relaxation method. Appl Energy 151:13–22
16. Bradbury K, Pratson L, Patiño-Echeverri D (2014) Economic viability of energy storage systems based on price arbitrage potential in real-time US electricity markets. Appl Energy 114:512–519
17. Arghandeh R, Woyak J, Onen A, Jung J, Broadwater RP (2014) Economic optimal operation of Community Energy Storage systems in competitive energy markets. Appl Energy 135:71–80
18. Pearre NS, Swan LG (2015) Technoeconomic feasibility of grid storage: mapping electrical services and energy storage technologies. Appl Energy 137:501–510
19. Cho J, Kleit AN (2015) Energy storage systems in energy and ancillary markets: A backwards induction approach. Appl Energy 147:176–183
20. Li C-H, Zhu X-J, Cao G-Y, Sui S, Hu M-R (2009) Dynamic modeling and sizing optimization of stand-alone photovoltaic power systems using hybrid energy storage technology. Renew Energy 34:815–826

21. Rahbar K, Chai CC, Zhang R (2016) Energy cooperation optimization in microgrids with renewable energy integration. IEEE Trans Smart Grid
22. Sechilariu M, Wang B, Locment F (2013) Building integrated photovoltaic system with energy storage and smart grid communication. IEEE Trans Indus Electron 60:1607–1618
23. Ma T, Yang H, Lu L (2014) A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island. Appl Energy 121:149–158
24. Belmili H, Haddadi M, Bacha S, Almi MF, Bendib B (2014) Sizing stand-alone photovoltaic–wind hybrid system: Techno-economic analysis and optimization. Renew Sustain Energy Rev 30:821–832
25. Hosseinalizadeh R, Shakouri H, Amalnick MS, Taghipour P (2016) Economic sizing of a hybrid (PV–WT–FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: case study of Iran. Renew Sustain Energy Rev 54:139–150
26. Zhou W, Lou C, Li Z, Lu L, Yang H (2010) Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Appl Energy 87:380–389
27. Bernal-Agustín JL, Dufo-Lopez R (2009) Simulation and optimization of stand-alone hybrid renewable energy systems. Renew Sustain Energy Rev 13:2111–2118
28. Yang H, Zhou W, Lu L, Fang Z (2008) Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm. Sol Energy 82:354–367
29. Kellogg WD, Nehrir MH, Venkataramanan G, Gerez V (1998) Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems. IEEE Trans Energy Convers 13:70–75
30. Nelson DB, Nehrir MH, Wang C (2006) Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems. Renew Energy 31:1641–1656
31. Vigna KR, Gomathi V, Ekanayake JB, Tiong SK (2019) Modelling and simulation of variable speed pico hydel energy storage system for microgrid applications. J Energy Storage 24:100808
32. Arani AAK, Gharehpetian GB, Abedi M (2019) Review on energy storage systems control methods in microgrids. Int J Electr Power Energy Syst 107:745–757
33. Firouzmakan P, Hooshmand R-A, Bornapour M, Khodabakhshian A (2019) A comprehensive stochastic energy management system of micro-CHP units, renewable energy sources and storage systems in microgrids considering demand response programs. Renew Sustain Energy Rev 108:355–368
34. Brahman F, Honarmand M, Jadid S (2015) Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system. Energy Build 90:65–75
35. Nguyen HK, Bin Song J, Han Z (2015) Distributed demand side management with energy storage in smart grid. IEEE Trans Parallel Distributed Syst 26:3346–3357
36. Wu X, Hu X, Moura S, Yin X, Pickert V (2016) Stochastic control of smart home energy management with plug-in electric vehicle battery energy storage and photovoltaic array. J Power Sourc 333:203–212
37. Kumar C, Zhu R, Buticchi G, Liserre M (2018) Sizing and SOC management of a smart-transformer-based energy storage system. IEEE Trans Indus Electron 65:6709–6718
38. Zhou B, Li W, Chan KW, Cao Y, Kuang Y, Liu X, Wang X (2016) Smart home energy management systems: concept, configurations, and scheduling strategies. Renew Sustain Energy Rev 61:30–40
39. Erdinc O, Paterakis NG, Pappi IN, Bakirtzis AG, Catalão JPS (2015) A new perspective for sizing of distributed generation and energy storage for smart households under demand response. Appl Energy 143:26–37
40. Rahbar K, Xu J, Zhang R (2015) Real-time energy storage management for renewable integration in microgrid: an off-line optimization approach. IEEE Trans Smart Grid 6:124–134
41. Anvari-Moghaddam A, Monsef H, Rahimi-Kian A (2015) Optimal smart home energy management considering energy saving and a comfortable lifestyle. IEEE Trans Smart Grid 6:324–332
42. Tummuru NR, Mishra MK, Srinivas S (2015) Dynamic energy management of renewable grid integrated hybrid energy storage system. IEEE Trans Industr Electron 62:7728–7737

43. Song Z, Hofmann H, Li J, Hou J, Han X, Ouyang M (2014) Energy management strategies comparison for electric vehicles with hybrid energy storage system. Appl Energy 134:321–331
44. Shen J, Khaligh A (2015) A supervisory energy management control strategy in a battery/ultracapacitor hybrid energy storage system. IEEE Trans Transp Electri 1:223–231
45. Mendis N, Muttaqi KM, Perera S (2014) Management of battery-supercapacitor hybrid energy storage and synchronous condenser for isolated operation of PMSG based variable-speed wind turbine generating systems. IEEE Trans Smart Grid 5:944–953
46. Hu X, Johannesson L, Murgovski N, Egardt B (2015) Longevity-conscious dimensioning and power management of the hybrid energy storage system in a fuel cell hybrid electric bus. Appl Energy 137:913–924
47. Rahiminejad A, Faramarzi D, Hosseinian SH, Vahidi B (2017) An effective approach for optimal placement of non-dispatchable renewable distributed generation. J Renew Sustain Energy 9:15303
48. Bennett CJ, Stewart RA, Lu JW (2015) Development of a three-phase battery energy storage scheduling and operation system for low voltage distribution networks. Appl Energy 146:122–134
49. Shen X, Zhu S, Zheng J, Han Y, Li Q, Nong J, Shahidehpour M (2015) Active distribution network expansion planning integrated with centralized and distributed Energy Storage System. In: Power and energy society general meeting, 2015 IEEE. IEEE, pp 1–5
50. Levron Y, Guerrero JM, Beck Y (2013) Optimal power flow in microgrids with energy storage. IEEE Trans Power Syst 28:3226–3234
51. Gayme D, Topcu U (2013) Optimal power flow with large-scale storage integration. IEEE Trans Power Syst 28:709–717
52. Bose S, Gayme DF, Topcu U, Chandy KM (2012) Optimal placement of energy storage in the grid. In: Decision and control (CDC), 2012 IEEE 51st annual conference on, IEEE, pp 5605–5612
53. Nick M, Cherkaoui R, Paolone M (2014) Optimal allocation of dispersed energy storage systems in active distribution networks for energy balance and grid support. IEEE Trans Power Syst 29:2300–2310
54. Tang Y, Low SH (2017) Optimal placement of energy storage in distribution networks. IEEE Trans Smart Grid
55. Sousa T, Morais H, Vale Z, Faria P, Soares J (2012) Intelligent energy resource management considering vehicle-to-grid: a simulated annealing approach. IEEE Trans Smart Grid 3:535–542
56. Zhang X, Tan S-C, Li G, Li J, Feng Z (2013) Components sizing of hybrid energy systems via the optimization of power dispatch simulations. Energy 52:165–172
57. Yang P, Nehorai A (2014) Joint optimization of hybrid energy storage and generation capacity with renewable energy. IEEE Trans Smart Grid 5:1566–1574
58. Forooghi Nematollahi A, Dadkhah A, Asgari Gashteroodkhani O, Vahidi B (2016) Optimal sizing and siting of DGs for loss reduction using an iterative-analytical method. J Renew Sustain Energy 8:55301
59. Hung DQ, Mithulananthan N, Lee KY (2014) Optimal placement of dispatchable and nondispatchable renewable DG units in distribution networks for minimizing energy loss. Int J Electr Power Energy Syst 55:179–186
60. Hung DQ, Mithulananthan N (2013) Multiple distributed generator placement in primary distribution networks for loss reduction. IEEE Trans Indus Electron 60:1700–1708
61. Georgilakis PS, Hatziargyriou ND (2013) Optimal distributed generation placement in power distribution networks: models, methods, and future research. IEEE Trans Power Syst 28:3420–3428
62. Khalesi N, Rezaei N, Haghifam M-R (2011) DG allocation with application of dynamic programming for loss reduction and reliability improvement. Int J Electr Power Energy Syst 33:288–295