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Maximizing DISCO profit in active distribution networks by optimal planning of energy storage systems and distributed generators

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ABSTRACT

Energy storage systems (ESSs) are generally planned based on the active power. While, reactive power is another important aspect of the ESSs that has not been adequately addressed and discussed. Moreover, ESSs are often managed individually, but coordinated planning on the ESSs and distributed generators (DGs) may result in more suitable outcomes. In order to address these issues, a coordinated ESS and DG planning is presented in this paper. In the proposed planning, the place and capacity of the ESSs and DGs are determined at the same time. The active and reactive powers are included in the planning for both the ESSs and DGs. In other words, the optimal active and reactive capacities are denoted for both the ESSs and DGs on the network. The proposed coordinated ESS and DG planning is carried out on a radial distribution network under deregulated electricity market. Objective function of the proposed planning is to maximize the profit of distribution company (DISCO) subject to the secure operation of the network. The planning is expressed as a nonlinear, mixed integer optimization problem and solved by advanced PSO as a strong Meta-heuristic optimization technique. Simulation results demonstrate the great impacts of the proposed planning on the network. The results demonstrate the priority of the proposed coordinated DG and ESS planning compared to the individual ESS planning. Additionally, it is verified that considering reactive power of the DGs and ESSs changes the results of the planning and provides more realistic and reasonable outputs. The proposed planning significantly increases DISCO profit while guarantees the safe operation of the network through satisfying several security constraints.

1. Introduction

In the past decade, grid-scale energy storage systems (ESSs) have experienced a rapid growth in both technical maturity and cost effectiveness [1,2]. Although the main motivation for the ESS technology advancement was to better renewable energy smoothing and time shift, but, these new emerging devices offer more applications and benefits than it expect [3,4]. Applications of the ESSs in various subsystems of the power systems are considered and reviewed well in the literature [5–7]. ESSs have been widely applied in generation [8–11], transmission [12,13], and distribution sectors [14] of the electric power systems. Distribution network as one the structural units of the electric power system also benefits from some achievable applications of the ESSs in this network [14]. Applications of these devices in distribution networks can be broadly stated as peak shaving [15,16], energy time shift or load leveling [17], renewable energy smoothing [18,19], renewable energy capacity firming [20], renewable energy time shift [21,22], congestion relief [23], network expansion deferral [24], short and long term voltage support [25,26], load control and management [27,28], reliability improvement [29], loss reduction [30], and reserve power [31].

In order to take applications out of an ESS unit in the distribution network as much as possible, first it should be planned optimally. Despite possessing diverse applications in distribution grids, an ESS unit counts as an expensive electric equipment compared to other ones in the grid. Employing multiple synergic applications of the ESS helps to enhance its cost effectiveness. Also, optimal ESS planning in distribution gird will increase its benefits and justify high investment costs.

In this context, optimal ESS allocation as a new planning problem in conventional and active distribution networks has been considered as the focus of research works. As one of the first works in this field, the authors in [32] have proposed a method for allocating ESSs in distribution networks with high wind penetration in order to maximize the benefits for both the DG owner and the utility. The goal of the planning is to minimize wind curtailment in addition to minimizing annual electricity cost. As stated by the authors, the added value for the utility includes take advantage of the price arbitrage, loss reduction,

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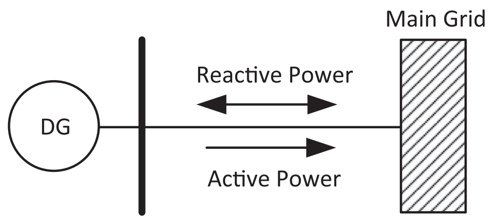

Fig. 1. Direction of active and reactive powers of the DG connected to the main grid.

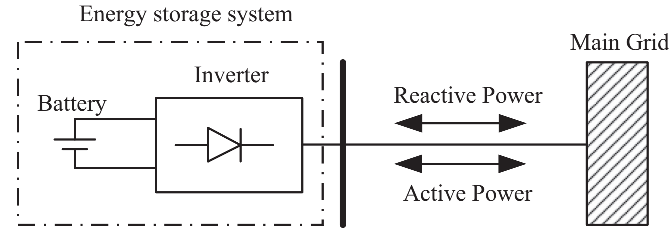

Fig. 2. Direction of active and reactive powers of the ESS connected to the main grid.

peak shaving, and improved system reliability where the added value to the DG owners includes payment for the amount of spilled energy. In [33] a methodology is proposed to optimally size and site battery-based ESS through a cost-benefit analysis in order to maximize the DISCO's profit from energy transactions, system planning, and operation cost savings. The considered benefits for the ESS installation in this works are maximizing the total economic benefits of the DISCO and to reduce the electric energy procurement cost risk that rises from price volatility, balance generation with consumption to reduce the energy exchanges at the substation, and minimizing total power losses. In [34] a joint ESS and controllable switches planning model in distribution network with the objective of minimizing overall cost including investment cost, operation cost, network losses, power interruption cost, and maximizing arbitrage is proposed. Authors in [35] aim to maximize DISCO profit in an electricity market environment through optimal planning of the ESSs. The DISCO profit is formulated as revenue equal to selling energy to the costumers minus buying energy from the upstream grid which is maximized by optimal allocating ESSs considering ESS installation and operation cost in the objective function. The ESSs are also allocated in active distribution networks in order to provide energy balance and grid support [36]. In this work, the authors have defined a multi-objective optimization framework in which various technical and economic goals are addressed comprising: network voltage deviations, feeders/lines congestions, network losses, cost of supplying loads from external grid, cost of ESS investment and maintenance, load curtailment, and stochasticity of loads and renewables productions.

Authors in [37–39] have addressed ESS planning in active distribution networks with various objectives and considerations including system expansion deferral, loss minimization, and price arbitrage [37], improving system reliability, defer system upgrades, and take advantage of price arbitrage in addition to a probabilistic approach in order to consider the uncertainty of system components [38], and joint optimal ESS planning and load shedding in order to tackle system contingencies [39]. In another work a multi-objective framework is proposed in order to take advantages of the ESS comprising voltage regulation, cost of supplying load from external grid, loss reduction, load curtailment reduction, and congestion alleviation [40]. In [41] a two-stage iterative planning method based on multi-period AC optimal power flow is proposed to reduce curtailment from renewable resources while managing congestion level and voltage deviations through the optimal control of storage, on-load tap changers (OLTCs), DG power factor, and DG curtailment. The battery ESSs are planned in [42] in order to minimize investment, operation, and maintenance cost of the ESS in addition to minimization of reliability cost and a penalty factor associated with the deviation from voltage and flow limits. In this work the point estimate method (PEM) is employed to handle probabilistic optimal power flow uncertainties. The work in [29] aims to improve system reliability (modeled by ENS index) in spite of ESS investment and operation cost. In [43] a non-parametric chance-constrained optimization model is proposed to operate and plan ESSs in distribution networks considering uncertainty from different sources including DGs, EVs, and residential loads. Authors in [44,45] in the form of a two part work have proposed a novel stochastic-programming-based model to minimize net social benefit through jointly expand distribution network and distributed generators while considering planning of storage devices and price-dependent demand response programs. In [46] an optimization framework is proposed to optimally plan storage devise in distribution networks intending minimizing ESSs investment and operation cost. Also, a chance-constrained stochastic formulation is formed in order to ensure maximum wind power utilization level. Application of the ESSs to optimally controlling voltage of the distribution network buses is addressed in [47]. In this work, a heuristic optimization strategy based on voltage sensitivity analysis is proposed to prevent over-voltages and under-voltages in a radial low voltage distribution network. Besides load balancing, the ESS in [31] are used to provide different kinds of operating reserve services in presence of high wind power penetration, including spinning reserve, upward and downward regulation reserves. Finally, in [48] which is an extension of [42], a new model which is based on point estimate method (PEM) is proposed as a tool to tackle the uncertainty of the load, the wind-based distributed generation (WDG), and PEVs. Furthermore, with the purpose of challenge voltage control benefit of the storage units, considered distribution network is equipped to the tap-changer and the capacitor banks.

Considering above literature review, this paper addresses a coordinated ESS and DG planning in deregulated electricity market incorporating both the active and reactive powers. The proposed planning finds the optimal capacity and place of the ESSs and DGs for maximizing DISCO profit. Both the active and reactive powers of the ESSs and DGs are included in the planning. Based on the proposed planning, ESSs and DGs can be utilized for supplying only reactive power, only active power, and both the active and reactive powers at the same time. The proposed planning maximizes DISCO profit, while it considers safe operation of the network. The planning results demonstrate the efficiency of the proposed coordinated ESS and DG planning for DISCO profit maximization. The proposed planning not only improves the economic features of the network, but also enhances the technical characteristics of the system, e.g., improving voltage profile and reducing the losses.

2. Distributed generators and energy storage systems

Distributed generators (DG) aims at locally production of the electrical energy close to the load centers. DGs are mainly discussed and regarded as active power producers, while they can produce active and reactive powers at the same time [49]. A typical DG is depicted in Fig. 1. It is clear that DG not only can produce active power, but also it can inject or absorb reactive power at the same time, and it may even be utilized as a reactive power compensator. When DG works as a reactive power compensator, the output active power produced by DG is set on the zero and DG only produces the reactive power. DG is mainly modeled as a PQ or PV bus. In PQ model, the active and reactive powers produced by DG are fixed, and then power flow is carried out. In this model, DG is considered as a load with specified P and Q. However, in the PV model, only the active power of DG is fixed and the reactive power is produced so that the voltage of the bus will be fixed on a desired value typically 1 per-unit [49].

Energy storage systems (ESS) are also one of the efficient systems to produce locally active and reactive powers. Fig. 2 shows the direction of active and reactive powers of the ESS connected to the main grid. It is

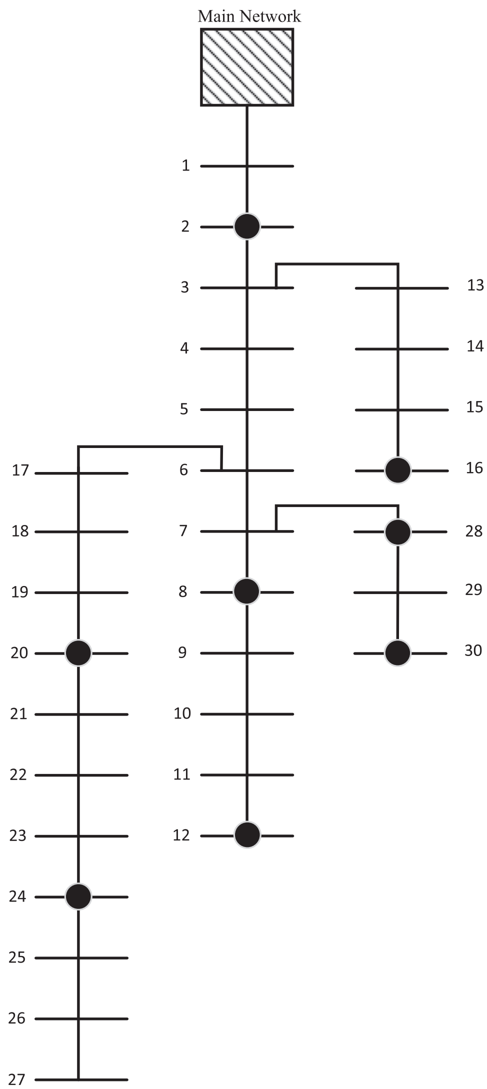

Fig. 3. Single line diagram of the distribution network.

clear that ESS can produce and consume both the active and reactive powers at the same time. The ability of ESS for storing active power from the main grid and then restoring this energy to the upstream network significantly improves power system characteristics and performances. The ESS can also be modeled as a PQ or PV buses such as DG. However, there is only one difference between DG and ESS, the active power of ESS can be positive (discharging state) or negative (charging state), but the active power of DG is always positive. It is worth remarking that the reactive power of both the DG and ESS can be positive (absorbing reactive power on inductive mode) or negative (supplying reactive power on capacitance mode) [29,35,50].

Table 1
Candidate ESSs of the planning.

Parameter	Value
Candidate active powers for ESSs (kW)	25–50–75–100
Candidate reactive powers for ESSs (kVar)	25–50–75–100
Candidate capacities for ESSs (kWh)	200–400–600–800
Investment cost for capacity ($/kWh)	81
Investment cost for rated power ($/kVA)	805
Operation cost ($/kVA)	0.02

Table 2
Candidate DGs of the planning.

Parameter	Value
Candidate active powers for DGs (kW)	25–50–75–100
Candidate reactive powers for DGs (kVar)	25–50–75–100
Investment cost ($/kVA)	1150
Operation cost for active power ($/kWh)	0.189
Operation cost for reactive power ($/kVar)	0.021

Table 3
Load levels and energy price for the period of 24 h.

Hour (s)	1–5	6–8	9–10	11–14	15–16	17–20	21–22	23–24
Load (%)	50	60	70	80	90	100	90	70
Active power price (kWh)	0.14	0.14	0.22	0.22	0.30	0.30	0.30	0.22
Reactive power price (kVar.h)	0.028	0.028	0.044	0.044	0.060	0.060	0.060	0.044

3. Mathematical formulation of the problem

In this paper, DGs and ESSs are optimally planned to increase the profit of DISCO. Both the active and reactive powers are included in the planning and an appropriate cost is included for both the active and reactive powers. The profit of DISCO and its relative formulations are given through (1) to (8) and discussed in the following.

$$DIS_{PRO} = [DP_P + DP_Q] - [IN_{ESS} + OM_{ESS} + IN_{DG} + OM_{DG}] \quad (1)$$

$$DP_P = \left[\sum_{t=1}^{T} (\alpha_p \times Pr_t \times SA_t - Pr_t \times PA_t)\right] \times TC \quad (\$/year) \quad (2)$$

$$DP_Q = \left[\sum_{t=1}^{T} (\alpha_q \times Qr_t \times SR_t - Qr_t \times PR_t)\right] \times TC \quad (\$/year) \quad (3)$$

$$IN_{ESS} = [(V_{ESS} \times C_{ESS} \times IC_{ESS}) + (V_{ESS} \times S_{ESS} \times IS_{ESS})] \times EAC \quad (\$/year) \quad (4)$$

$$EAC = \left(\frac{r \times (1+r)^{LT}}{(1+r)^{LT} - 1}\right) \quad (5)$$

$$OM_{ESS} = \left[\sum_{t=1}^{T} (S_{ESS}^{t} \times OC_{ESS}^{t})\right] \times TC \quad \$/year \quad (6)$$

$$IN_{DG} = [(V_{DG} \times S_{DG} \times IC_{DG})] \times EAC \quad (\$/year) \quad (7)$$

$$OM_{DG} = \left[\sum_{t=1}^{T} (P_{DG}^{t} \times OCP_{DG}^{t} + Q_{DG}^{t} \times OCQ_{DG}^{t})\right] \times TC \quad \$/year \quad (8)$$

The net profit of DISCO is given by (1). Where, two first terms indicate the profit from selling active and reactive powers, respectively. Four next items represent the DISCO costs including installation cost of ESS, operation and maintenance cost of ESS, installation cost of DG, and operation-maintenance cost of DG, respectively. The profit from selling active power is expressed as (2). Where, P_{rt} and SA_t indicate the price ($) and amount of active power (kW) that is sold to the loads at hour t, PA_t signifies the active power (kW) that is purchased from the main grid at hour t, α_p denotes the DISCO profit percentage from selling active power, T indicates the hours in a 24 h cycle, and TC is used to convert the daily cost to the annual cost. A similar profit is also defined for the reactive power as (3). Where, Q_{rt} and SR_t show the price ($) and amount of reactive power (kVar) that is sold to the loads at hour t, PR_t displays the active power (kVar) that is purchased from the

Table 4
Active and reactive powers of the installed ESSs on the network.

Bus no.	2		8		16		20	
	P (kW)	Q (kVar)	P (kW)	Q (kVar)	P (kW)	Q (kVar)	P (kW)	Q (kVar)
ESS	100	100	100	100	50	75	75	100

Table 5
Active and reactive powers of the installed DGs on the network.

Bus no.	2		8		20		24	
	P (kW)	Q (kVar)	P (kW)	Q (kVar)	P (kW)	Q (kVar)	P (kW)	Q (kVar)
DG	100	50	100	50	100	50	100	50

upstream network at hour t, and α_q represents the DISCO profit percentage from selling reactive power to the consumers.

The installation cost of the ESS is defined by (4) comprising two terms; first term shows the installation cost of the ESS capacity (battery) and the second term presents the installation cost of the inverter. Where, V_{ESS}, C_{ESS}, and IC_{ESS} are the installed ESSs, capacity of the ESSs (kWh), and installation cost of the ESSs capacity (battery) ($/kWh), respectively. As well, S_{ESS} and IS_{ESS} are rated power of the ESS (kVA), and installation cost of the inverter ($/kVA), respectively. EAC (equivalent annual cost) is defined by (5) and is used to convert the total cost to the annual cost. Where, r and LT demonstrate the discount rate and the asset life time, respectively. As well, the operation-maintenance cost of the ESS is given by (6). Where, S^t_{ESS} indicates the rated apparent power of the ESS (kVA) at hour t and OC^t_{ESS} presents the operational cost at hour t ($/kVA).

The installation cost of the DG is given by (7). Where, V_{DG}, C_{DG}, and IC_{DG} are the installed DGs, rated power of the DG (kVA), and installation cost of the DG ($/kVA), respectively. It is worth mentioning that rated power of the DG includes both active and reactive powers. Additionally, operation-maintenance cost of the DG is specified by (8) consisting of two terms. First term shows operation cost for the active power (or fuel cost) and the second term presents operation cost for the reactive power (or no load operation). Where, P^t_{DG} shows active power of the DG (kW) at hour t, OCP^t_{DG} gives operational cost at hour t ($/kW), Q^t_{DG} indicates the reactive power of DG (kVar) at hour t, and OCQ^t_{DG} presents the operational cost at hour t ($/kVar).

3.1. Standard formulation as a constrained optimization problem

The proposed problem for DISCO profit maximization can be expressed as a standard constrained optimization problem given by (9) to (21). Objective function (9) represents the DISCO profit as defined before. The constraints are given through (10) to (21).

The maximum capacity of ESSs (kWh) and the rated power of inverter (kVA) are restricted by (10) and (11). The relationship between active and reactive powers in inverter are given by (12). The ESS capacity is expressed by (13). Where, P_{ESS}, Q_{ESS}, and T_{ch} show active power of ESS, reactive power of ESS, and charging time, respectively. The efficiency of the storage system is defined as (14), where, E_{disch}, E_{ch}, and η_{ESS} demonstrate the discharged energy, charged energy, and the efficiency, respectively. The energy balancing is defined by (15). Apparent power of the DG (kVA) is restricted by (16) and relationship between active and reactive powers is defined by (17). Where, P_{DG} and Q_{DG} show active and reactive powers of the DG. Power flow problem is defined by constraints (18) and (19); where, k indicates bus number and n signifies set of all buses in the network, input active and reactive powers to the buses are given by P_{in} and Q_{in}, and output active and reactive powers from the buses are denoted by P_{out} and Q_{out}. Voltage boundaries are given by (20); where, V_k, $V_k{}^{max}$ and $V_k{}^{min}$ are the voltage and its maximum and minimum bounds at bus k. Line capacity is limited by (21); where, S_L and S_L^{max} show the apparent power and its threshold on the line.

$$\text{Max} \quad \{DIS_{PRO}\} \tag{9}$$

S.T.

$$C_{ESS} \le C_{ESS}^{max} \tag{10}$$

$$S_{ESS} \le S_{ESS}^{max} \tag{11}$$

$$S_{ESS} = \sqrt{P_{ESS}^2 + Q_{ESS}^2} \tag{12}$$

$$C_{ESS} = P_{ESS} \times T_{ch} \tag{13}$$

$$E_{disch} \le E_{ch} \times \eta_{ESS} \tag{14}$$

$$E_{ESS}^{t=0} = E_{ESS}^{t=T} \tag{15}$$

$$S_{DG} \le S_{DG}^{max} \tag{16}$$

$$S_{DG} = \sqrt{P_{DG}^2 + Q_{DG}^2} \tag{17}$$

$$\sum_{k=1}^{n} P_{in}^k = \sum_{k=1}^{n} P_{out}^k \tag{18}$$

$$\sum_{k=1}^{n} Q_{in}^b = \sum_{k=1}^{n} Q_{out}^b \tag{19}$$

$$V_k^{min} \le V_k \le V_k^{max} \tag{20}$$

$$S_L \le S_L^{max} \tag{21}$$

4. Solving the problem by Meta-heuristic optimization technique

The proposed problem for maximizing profit is solved by particle swarm optimization (PSO) as a strong Meta-heuristic optimization technique. The proposed PSO is a modified and advanced version of the conventional PSO and it has been successfully applied to solve such problems [49,51,52]. The proposed modified-adaptive PSO solves the problem through following steps:

Step 1: An initial population is generated and input data of the problem are defined. The particles in the population specify active and reactive powers of the DGs and ESSs.
Step 2: One particle in the population is chosen for evaluating.
Step 3: The DGs and ESSs related to the current particle are installed on the network. Then active and reactive powers of the DGs and ESSs are fixed on the values indicated by current particle. As

Table 6
Annual profit of DISCO under different planning.

	Annual profit of DISCO ($/year)
Without ESSs and DGs	115,117
Only with DGs	163,024
Only with ESSs	158,123
With both the ESSs and DGs	183,020

well, charging and discharging states of the ESSs are considered as follows: during high-cost hours (on-peak hours), the ESSs works on discharging state and for the period of low-cost hours (off-peak hours) they works on charging state.

Step 4: Based on the model presented in the previous step, power flow is carried out under all load levels. Forward-backward method is utilized for performing power flow in distribution network [53].

Step 5: Constraints of the problem are checked for current particle and it should satisfy all constraints. If even one of the constraints is violated, the particle is removed and algorithms goes to step 2.

Step 6: Objective function of the problem is calculated for current particle.

Step 7: Proposed steps 1–5 are performed for all particles in the population and objective function is computed for all particles. Eventually, the best particle in the population is recorded.

Step 8: Convergence criterion of the optimization technique is assessed. If the condition is met, algorithm is over, otherwise, population is renewed and the process is repeated.

5. Illustrative test system

A radial 30 bus distribution network is considered as test system. Fig. 3 shows the test system and the candidate buses for installing DG or ESS are signified by solid black circles. Data of the network including line and loading data can be found in [53]. Base apparent power and base voltage of the system are 10 MVA and 11 kV, respectively. Candidate ESSs and DGs are given in Tables 1, 2. It is clear that both the active and reactive powers are included in the planning. Table 3 shows load levels, active power price, and reactive power price for the duration of 24 h. The DISCO profit rate is 15%. Bus voltages are limited on 0.9 and 1.1 per-unit. Discount rate and the asset life time are regarded as 20% and 5-year, respectively. ESSs are scheduled to work on charging state at hours 1–8 and on discharging state at hours 15–22.

6. Simulation results

The proposed methodology for DG and ESS planning is carried out on the given test system and the results are listed in Tables 4, 5. Tables 4, 5 show the installed ESSs and DG on the network, respectively. Where, active power, reactive power, and bus numbers are indicated as the output of the planning. It is clear that the proposed planning denotes the place and size of the ESSs and DGs at the same time. Annual profit of DISCO is also listed in Table 6. In order to show the impact of the ESSs and DGs on the network, several cases are studied in Table 6. The results demonstrate that installing DGs increases the profit by 42% and installing ESSs rises the profit by 37%, while installing DGs and ESSs at the same time results in increasing the profit by 59%. As a result, the proposed planning for installing ESSs and DGs at the same time including both reactive and active power leads to more profit. Besides, the amount of the profit (i.e., 60% per year) is significant and puts emphasis on the usefulness of the proposed coordinated ESS-DG planning.

In order to demonstrate the technical impacts of the ESS-DG planning on the network operation, profile of voltage over all buses is depicted in Fig. 4. The result validates that installing ESSs and DGs has improved the voltage profile on all buses, and the network operation under the proposed planning is significantly safer and better than the network without ESSs and DGs. As from the voltage profile, ESSs and DGs have improved the voltage stability margin of the network.

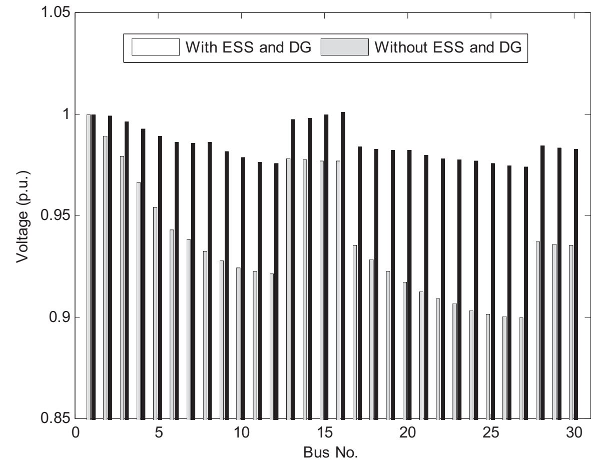

Fig. 4. Voltage profile on all buses of the network.

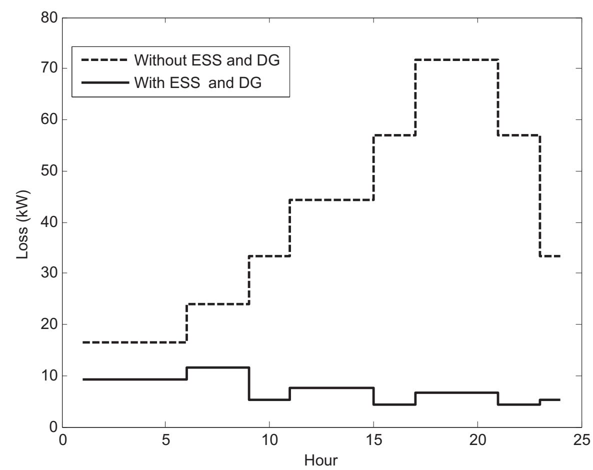

Fig. 5. Active power losses of the network for the duration of 24 h.

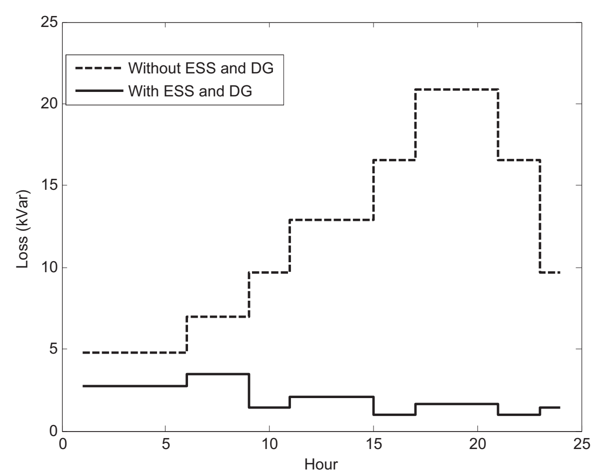

Fig. 6. Reactive power losses of the network for the duration of 24-h.

Figs. 5, 6 display active and reactive power losses of the network for the duration of 24-h. It is clear that the network equipped with ESSs and DGs benefits from fewer losses and both the active and reactive power losses are considerably reduced. The results also indicate that by

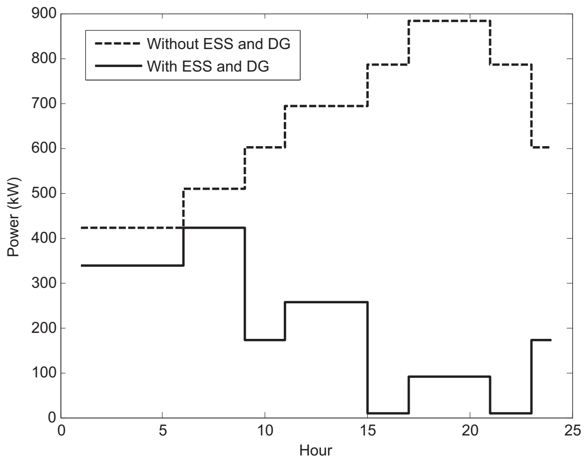

Fig. 7. Received active power from the main grid for the duration of 24 h.

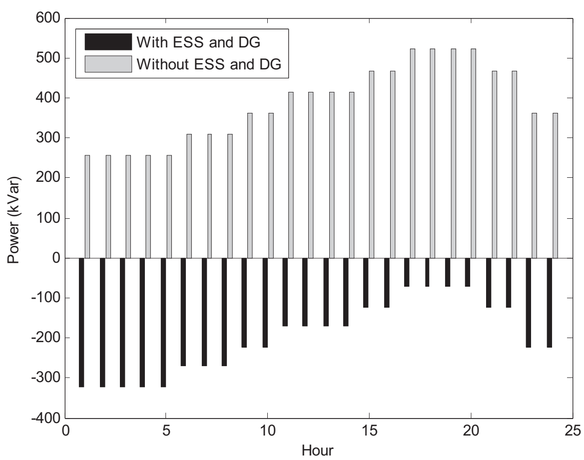

Fig. 8. Received reactive power from the main grid for the duration of 24 h.

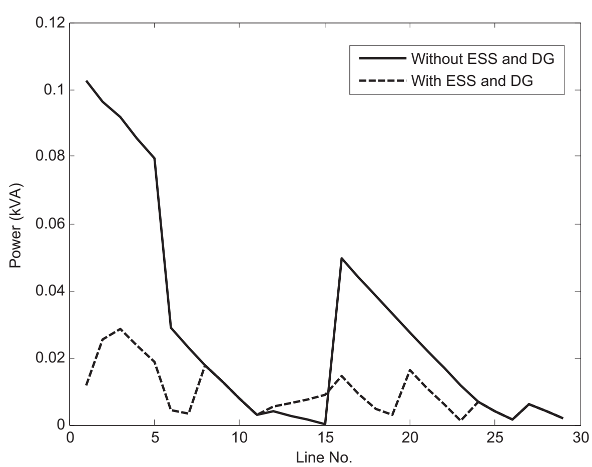

Fig. 9. Profile of the apparent power over the lines of the network.

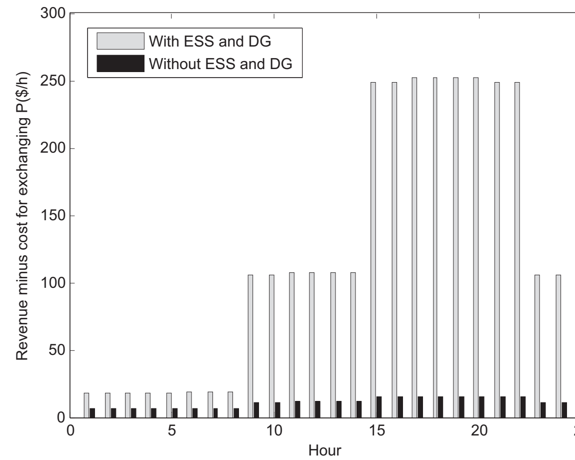

Fig. 10. Income from selling active power to the loads minus cost of purchasing active power from the upstream network at each hour of the day.

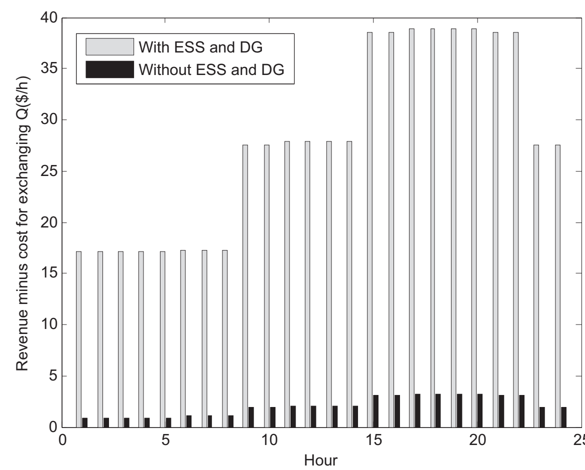

Fig. 11. Income from selling reactive power to the loads minus cost of purchasing active power from the upstream network at each hour of the day.

moving toward the greater load levels, the impacts of the DGs and ESSs on the loss are more significant. Where, losses in the network without the DGs and ESSs is hugely greater than the network installed with them. This issue is mainly due to installing the ESSs on the network. Because in the network installed with the DGs and ESSs, the demand is supplied by DGs and ESSs during peak load levels and the flow in lines is reduced. On the other hand, in the network without DGs and ESSs, the load is supplied by receiving the power from the upstream network and as a result, the flow in lines is increased and results in rising the losses. This issue can be discussed in more details by Fig. 7 that shows the received active power from the main grid for the duration of 24 h. It is clear that the received active power from the grid in the network without the ESSs and DGs is greatly more that the network installed with the DGs and ESSs. As well, the received reactive power from the main grid is depicted in Fig. 8. It is clear that the network does not receive the reactive power from the network, but, it sends the reactive power to the main grid. As a result of injecting reactive power to the main grid, the losses in the network is reduced, DISCO makes more profit from selling reactive power to the main grid, and voltage profile is improved.

As stated above, the flow in lines is reduced by installing the DGs and ESSs. This issue is depicted in Fig. 9. Where, the flows in lines are compared for both the network with and without DGs and ESSs. It is clear that the network with DGs and ESSs contains less flow in lines and the lines are not congested. In contrast, the network without ESSs comprises more flow in lines and the capacity of the lines is mostly occupied. Increasing flow in the lines (i.e., the congested lines) leads to several shortcomings such as increasing losses, reducing flexibility and adequacy, reducing reliability, and reducing the ability of the network for supporting future load growth.

In order to provide more details on the DISCO profit, Figs. 10, 11 show the difference between revenue and cost at each hour of the day. In other words, the income of selling power to the loads minus the cost of purchasing power from the upstream network is depicted here. It should be remarked that these figures do not include the operation and installation costs of DGs and ESSs and they only comprise the revenue and cost for exchanging active and reactive powers. It can be seen that profit (revenue minus cost) is increased at peak load levels and this issue is due to optimal installing the ESSs on the network. Moreover, the profit of active power is more than reactive power as demonstrated by Fig. 11.

7. Conclusions

This paper addresses an optimal approach to install the ESSs and DGs in active distribution networks under electricity market environment. The design variables of the problem are active and reactive power capacities of the ESSs and DGs. Objective function of the problem is to maximize the DISCO profit subject to security constraints of the network. Problem is expressed as a standard optimization problem and solved using PSO approach. The results are carried out on a typical distribution network and indicate the efficiency and viability of the proposed coordinated ESSs and DGs planning including active and reactive powers. It is shown that the profit is increased as 42%, 37%, and 59% by installing DGs, ESSs, and coordinated ESSs-DGs, respectively. Therefore, this result emphasizes on the efficiency of the proposed coordinated planning for installing ESSs and DGs at the same time. As well, the results indicate that the installed DGs and ESSs improve the voltage profile over all buses and ensure safe operation of the network. The network losses are also reduced by installing DGs and ESSs due to reducing flow in lines of the network.

References

[1] Hemmati R, Saboori H. Emergence of hybrid energy storage systems in renewable energy and transport applications – A review. Renew Sustain Energy Rev 2016;65:11–23.

[2] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. Renew Sustain Energy Rev 2009;13:1513–22.

[3] Díaz-González F, Sumper A, Gomis-Bellmunt O, Villafáfila-Robles R. A review of energy storage technologies for wind power applications. Renew Sustain Energy Rev 2012;16:2154–71.

[4] Ibrahim H, Ilinca A, Perron J. Energy storage systems—Characteristics and comparisons. Renew Sustain Energy Rev 2008;12:1221–50.

[5] Koohi-Kamali S, Tyagi VV, Rahim NA, Panwar NL, Mokhlis H. Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review. Renew Sustain Energy Rev 2013;25:135–65.

[6] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 2015;137:511–36.

[7] Kuravi S, Trahan J, Goswami DY, Rahman MM, Stefanakos EK. Thermal energy storage technologies and systems for concentrating solar power plants. Prog Energy Combust Sci 2013;39:285–319.

[8] Hemmati R, Saboori H, Jirdehi MA. Multistage generation expansion planning incorporating large scale energy storage systems and environmental pollution. Renew Energy 2016;97:636–45.

[9] Hemmati R, Saboori H, Saboori S. Stochastic risk-averse coordinated scheduling of grid integrated energy storage units in transmission constrained wind-thermal systems within a conditional value-at-risk framework. Energy 2016;113:762–75.

[10] Hemmati R, Saboori H, Saboori S. Assessing wind uncertainty impact on short term operation scheduling of coordinated energy storage systems and thermal units. Renew Energy 2016;95:74–84.

[11] Hemmati R, Saboori H. Short-term bulk energy storage system scheduling for load leveling in unit commitment: modeling, optimization, and sensitivity analysis. J Adv Res 2016;7:360–72.

[12] Rosso ADD, Eckroad SW. Energy storage for relief of transmission congestion. IEEE Trans Smart Grid 2014;5:1138–46.

[13] Vargas LS, Bustos-Turu G, Larra F. x00Ed. Wind Power Curtailment and Energy Storage in Transmission Congestion Management Considering Power Plants Ramp Rates. IEEE Trans Power Syst, 30 2015; 2015. p. 2498–506.

[14] Zidar M, Georgilakis PS, Hatziargyriou ND, Capuder T, Škrlec D. Review of energy storage allocation in power distribution networks: applications, methods and future research. Savoy Place in London, England: IET Generation, Transmission & Distribution: Institution of Engineering and Technology; 2016. p. 645–52.

[15] Sigrist L, Lobato E, Rouco L. Energy storage systems providing primary reserve and peak shaving in small isolated power systems: an economic assessment. Int J Electr Power Energy Syst 2013;53:675–83.

[16] Zhao P, Wang J, Dai Y. Capacity allocation of a hybrid energy storage system for power system peak shaving at high wind power penetration level. Renew Energy 2015;75:541–9.

[17] Papic I. Simulation model for discharging a lead-acid battery energy storage system for load leveling. IEEE Trans Energy Convers 2006;21:608–15.

[18] Zhang S, Mishra Y, Shahidehpour M. Fuzzy-Logic Based Frequency Controller for Wind Farms Augmented With Energy Storage Systems. IEEE Trans Power Syst 2016;31:1595–603.

[19] Solomon AA, Kammen DM, Callaway D. Investigating the impact of wind–solar complementarities on energy storage requirement and the corresponding supply reliability criteria. Appl Energy 2016;168:130–45.

[20] Abdelrazek SA, Kamalasadan S. Integrated PV Capacity Firming and Energy Time Shift Battery Energy Storage Management Using Energy-Oriented Optimization. IEEE Trans Ind Appl 2016;52:2607–17.

[21] Parra D, Gillott M, Norman SA, Walker GS. Optimum community energy storage system for PV energy time-shift. Appl Energy 2015;137:576–87.

[22] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. Appl Energy 2015;137:545–53.

[23] Khani H, Zadeh MRD, Hajimiragha AH. Transmission congestion relief using privately owned large-scalelarge-scale energy storage systems in a competitive electricity market. IEEE Trans Power Syst 2016;31:1449–58.

[24] Samper M, Flores D, Vargas A. Investment Valuation of Energy Storage Systems in Distribution Networks considering Distributed Solar Generation. IEEE Lat Am Trans 2016;14:1774–9.

[25] Wang Y, Tan KT, Peng XY, So PL. Coordinated Control of Distributed Energy-Storage Systems for Voltage Regulation in Distribution Networks. IEEE Trans Power Deliv 2016;31:1132–41.

[26] Shen YW, Ke DP, Sun YZ, Kirschen DS, Qiao W, Deng XT. Advanced Auxiliary control of an energy storage device for transient voltage support of a doubly fed induction generator. IEEE Trans Sustain Energy 2016;7:63–76.

[27] Bo S, Dragicevic T, Andrade F, Vasquez JC, Guerrero JM. Provision of flexible load control by multi-flywheel-energy-storage system in electrical vehicle charging stations. 2015 IEEE Power Energy Soc Gen Meet 2015:1–5.

[28] Ludwig M, Haberstroh C, Hesse U. Exergy and cost analyses of hydrogen-based energy storage pathways for residual load management. Int J Hydrog Energy 2015;40:11348–55.

[29] Saboori H, Hemmati R, Jirdehi MA. Reliability improvement in radial electrical distribution network by optimal planning of energy storage systems. Energy 2015;93(Part 2):2299–312.

[30] Saboori H, Abdi H. Application of a grid scale energy storage system to reduce distribution network losses. In: Proceedings of the 18th Conference on Electrical Power Distribution Networks (EPDC). p. 1-5; 2013.

[31] Qin M, Chan KW, Chung CY, Luo X, Wu T. Optimal planning and operation of energy storage systems in radial networks for wind power integration with reserve support. IET Gener, Transm Distrib 2016;10:2019–25.

[32] Yun-feng D. Optimal allocation of energy storage system in distribution systems. Procedia Eng 2011;15:346–51.

[33] Zheng Y, Dong ZY, Luo FJ, Meng K, Qiu J, Wong KP. Optimal Allocation of Energy Storage System for Risk Mitigation of DISCOs With High Renewable Penetrations. IEEE Trans Power Syst 2014;29:212–20.

[34] Lv B, Yan W. Coordinated planning model of BESS and controllable switches in distribution. Electron Lett 2014;50:1479–80.

[35] Saboori H, Hemmati R. Optimal management and planning of storage systems based on particle swarm optimization technique. J Renew Sustain Energy 2016;8:024105.

[36] Nick M, Cherkaoui R, Paolone M. Optimal allocation of dispersed energy storage systems in active distribution networks for energy balance and grid support. IEEE Trans Power Syst 2014;29:2300–10.

[37] Awad ASA, Fouly THME-, Salama MMA. Optimal ESS allocation for load management application. IEEE Trans Power Syst 2015;30:327–36.

[38] Awad ASA, Fouly THME-, Salama MMA. Optimal ESS allocation for benefit maximization in distribution networks. IEEE Trans Smart Grid 2015:1–11.

[39] Awad ASA, Fouly THME-, Salama MMA. Optimal ESS allocation and load shedding for improving distribution system reliability. IEEE Trans Smart Grid 2014;5:2339–49.

[40] Nick M, Cherkaoui R, Paolone M. Optimal siting and sizing of distributed energy storage systems via alternating direction method of multipliers. Int J Electr Power Energy Syst 2015;72:33–9.

[41] Alnaser SW, Ochoa LF. Optimal sizing and control of energy storage in wind power-richpower-rich distribution networks. IEEE Trans Power Syst 2016;31:2004–13.

[42] Sedghi M, Ahmadian A, Aliakbar-Golkar M. Optimal storage planning in active distribution network considering uncertainty of wind power distributed generation. IEEE Trans Power Syst 2016;31:304–16.

[43] Hejazi H, Mohsenian-Rad H. Energy storage planning in active distribution grids: a chance-constrained optimization with non-parametric probability functions. IEEE Trans Smart Grid 2016:1, [-].

[44] Asensio M, Quevedo PMd, Munoz-Delgado G, Contreras J. Joint distribution network and renewable energy expansion planning considering demand response and energy storage, Part I: stochastic programming model. IEEE Trans Smart Grid 2016:1, [-].

[45] Asensio M, Quevedo PMd, Munoz-Delgado G, Contreras J. Joint distribution network andRenewable energy expansion planning considering demand response and energy storage?? Part II: Numerical results and considered metrics. IEEE Trans Smart Grid 2016:1, [-].

[46] Zhang Y, Dong ZY, Luo F, Zheng Y, Meng K, Wong KP. Optimal allocation of battery energy storage systems in distribution networks with high wind power penetration. IET Renew Power Gener: Inst Eng Technol 2016:1105–13.

[47] Giannitrapani A, Paoletti S, Vicino A, Zarrilli D. Optimal allocation of energy

storage systems for voltage control in LV distribution networks. IEEE Trans Smart Grid 2016:1.

[48] Ahmadian A, Sedghi M, Aliakbar-Golkar M, Elkamel A, Fowler M. Optimal probabilistic based storage planning in tap-changer equipped distribution network including PEVs, capacitor banks and WDGs: a case study for Iran. Energy 2016;112:984–97.

[49] Hemmati R, Hooshmand R-A, Taheri N. Distribution network expansion planning and DG placement in the presence of uncertainties. Int J Electr Power Energy Syst 2015;73:665–73.

[50] Saboori H, Hemmati R, Abbasi V. Multistage distribution network expansion planning considering the emerging energy storage systems. Energy Convers Manag 2015;105:938–45.

[51] Hemmati R, Hooshmand R-A, Khodabakhshian A. Coordinated generation and transmission expansion planning in deregulated electricity market considering wind farms. Renew Energy 2016;85:620–30.

[52] Hemmati R, Hooshmand R-A, Khodabakhshian A. Market based transmission expansion and reactive power planning with consideration of wind and load uncertainties. Renew Sustain Energy Rev 2014;29:1–10.

[53] Eminoglu U, Hocaoglu MH. A new power flow method for radial distribution systems including voltage dependent load models. Electr Power Syst Res 2005;76:106–14.