Optimal Sitting and Sizing of Energy Storage Systems in a Smart Distribution Network Considering Network Constraints and Demand Response Program

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Demand response program (DRP) and energy storage systems (ESSs) are two main tools for load management in smart grids. They can make distribution networks more reliable without costly upgrades for substation construction or lines reinforcement. This work proposes an optimization framework of sitting and sizing of ESSs in a smart distribution network in the presence of DRP and considering renewable energy sources (RESs) effects and network constraints. The proposed objective function includes two terms: 1) minimizing the total investment costs of ESSs; 2) minimizing the cost of active losses and the power purchased from the upstream grid and diesel generators. DRP can reduce operation costs by shifting some loads from hours with high demand to hours with lower demand and so can reduce network losses and help in peak load shaving process. In order to solve the proposed optimization problem, a mixed-integer non-linear programming (MINLP) model is constructed and solved using DICOPT solver by GAMS optimization software. A modified 33-bus distribution network is considered, and the results of three different cases are compared. Finally, it can be noted that total cost of the network in case 2, with optimal ESSs allocation, is reduced by 4.9% compared with the base case, while this reduction is about 20% in case 3 with considering DRP beside ESSs allocation.

Keywords: *Optimal allocation, Energy storage systems, Demand response program, Load management, Smart distribution network.*

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Nomenclature

Sets

i, j	Index of buses
t	Index of time
h	Index of years
Δ	Set of buses with wind turbines
ρ	Set of buses with diesel generators
α	Set of buses with PV sources
γ	Set of buses with ESS

Variables

$P_{t,h}^{sub}$	Active power imported from the upstream grid at time t in year h
$Q_{t,h}^{sub}$	Reactive power imported from the upstream grid at time t in year h
$P_{t,h}^{loss}$	Active power losses due to flowing active power through line i-j at time t in year h
$P_{i,t,h}^{c/d}$	Power charged or discharged by ESS at time t and year h
$P_{i,t,h}^{DG}$	Power produced by the diesel generators at bus i at time t in year h
$u_{i,t,h}$	Binary condition of diesel generator units at bus i at time t in year h
$y_{i,t,h}$	A binary variable which is 1 if the unit is started up; vice versa is zero
$z_{i,t,h}$	A binary variable which is 1 if the unit is shut down; vice versa is zero
$P_{i,t,h}^{wind}$	Power produced by the wind turbine at bus i at time t in year h
$P_{i,t,h}^{PV}$	Power produced by the PV system at bus i at time t in year h
$TOU_{i,t,h}$	Amount of additional or reduced load at bus i at time t in year h (i.e. load shifting)
$D_{i,t,h}$	Minimum load at bus i supplied at time t in year h, which should be meet (considering shifted load)
$S_{i,j,t,h}$	Apparent power exchanged between buses i and j at time t in year h
$P_{i,j,t,h}$	Active power exchanged between buses i and j at time t in year h
$Q_{i,j,t,h}$	Reactive power exchanged between buses i and j at time t in year h

$V_{i,t,h}$	Voltage amplitude at bus *i* at time *t* in year *h*
$\delta_{i,t,h}$	Voltage angle at bus *i* at time *t* in year *h*
$SOC_{i,t,h}$	State of charge of ESS at bus *i* at time *t* in year *h*
$Cess_i$	Nominal ESS capacity installed at bus *i*
$Pess_i$	Nominal ESS power installed at bus *i*

Parameters

Power system

$S_{i,j}^{\max}$	Maximum capacity of apparent power flow at line *i-j*
$P_{sub}^{\max}$	Rated active power of upstream grid's transformer
$Q_{sub}^{\max}$	Rated reactive power of upstream grid's transformer
$Z_{i,j}$	Line impedance amplitude (between buses *i* and *j*)
$G_{i,j}$	Line conductance amplitude (between buses *i* and *j*)
$\theta_{i,j}$	Line impedance angle (between buses *i* and *j*)
$P_{i,t,h}^{load-DRP}$	Active load at bus *i* at time *t* in year *h*
$Q_{i,t,h}^{load}$	Reactive load at bus *i* at time *t* in year *h*
$DR^{\max}$	Percentage of customers who participated in DRP

Renewable resources (PV and Wind)

PV^{cap}	Rated power of PV installed at bus *i*
TA_t	Time availability of PVs at time *t*
$P_{wind_i}^{\max}$	The maximum rate of the wind turbine at bus *i*
V_{C-I}	The cut-in speed of wind turbines
V_{C-O}	The cut-out speed of wind turbines
V_R	The rated velocity of wind turbines
V_{wind_t}	Wind velocity at time *t*

ESS parameters

$SOC_{\min_i}$	Minimum SOC of ESS
σ	A constant value related to the minimum capacity of SOC
λ	A constant value related to power charge and discharge of ESS
η	Charge or discharge efficiency of ESS

Diesel generator

a_g, b_g, c_g	Diesel generators' cost coefficients
$P_{DG_i}^{\max}$	Maximum limit of power production by the diesel generators
$P_{DG_i}^{\min}$	The minimum limit of power production by the diesel generators
UR_i	Ramp up rate of diesel generators unit at bus *i*
DR_i	Ramp down rate of diesel generators unit at bus *i*
UT_i	Minimal up time of diesel generators unit at bus *i*
DT_i	The minimal downtime of diesel generators unit at bus *i*

Economic parameters

$Cost_{In.C}$	The investment cost of ESSs capacity
$Cost_{In.P}$	The investment cost of ESSs power
$Cost_{up}$	The cost related to buying energy from the upstream grid
$Cost_{DG}$	The cost related to buying energy from dispatchable DG units
$Cost_{loss}$	Loss payment cost
OPC	Operational cost
EIC	ESS investment cost
$\pi_{t,h}$	Energy price at time *t* in year *h*
CF_h	Cost factor in year h
p	Inflation rate
q	Interest rate

1. Introduction

The subject of active distribution system (ADS) or smart grid (SG) is used to refer to some kinds of intelligent electrical networks that consist of different types of energy generation resources (including RESs), communication infrastructures, smart meters, active or dispatchable loads and responsible demands, various types of ESS technologies and plug-in electrical vehicles (PEVs) [1-3]. ESSs are introduced as complementary devices in the SGs to manage the uncertainty of RESs output and improve power imbalance, power quality, reliability, and stability. There is various kind of ESSs may be used in the networks according to their characteristics [4].

The uncertain nature of RESs may lead to 1) deviation of voltage profile, 2) increasing of lines current over the limits, 3) disturbance of local voltage and 4) power production with high uncertainty which reduces system's reliability and increases the outages. The main idea behind storage is that these devices at the off-peak times (when the generation is more than demand) appear as passive loads and absorb excess power just like an active power cavity so by consuming extra power becomes overvoltage barrier; on the contrary, it can free up the stored power in a high-capacity mode at peak times. Ref. [5] represents the effects of ESS integration on power system flexibility and ramping capability with considering wind generation units. In deregulated power markets, the participation of ESS units in energy or ancillary services can be valuable for the private owners of such devices [6]. Resilience enhancement is achieved through optimal management of battery ESSs in [7].

Moreover, DRPs are other essential load management tools in SGs introduced recently in power systems and have attracted much attention. DRPs are applied to shift a specified amount of load at peak times to the other off-peak times in order to flatten the load curve or curtail unnecessary loads [8]. DRPs can help to moderate price spikes in the power market [9]. DRPs also help in peak shaving processes that can postpone highly cost investments for the construction of power plants or lines reinforcement [10]. Ultimately, they are complement tools for RESs to encounter with uncertainties and reduce the discarded power production [11]. Different types of DRP are introduced and analyzed by paper [12]. One of the most used DRP is Time of Use (TOU) based program, in which only some percentage of load would be curtailed at peak hours and will be shifted to off-peak times in order to make sure that the generation will be economical at that times [13].

For sum up, ESS and DRP utilization in power systems can achieve more benefits, such as peak load management, reliability enhancement, phase balancing, RES curtailment reduction, uncertainty management, etc. In order to achieve the mentioned benefits and given the high capital cost of ESSs and for considering economically viable, an optimal allocation which includes sitting and sizing of ESSs in microgrids or smart distribution networks is a crucial decision. In [14], optimal power flow (OPF) calculation is mentioned as a fundamental optimization tool for the operation and planning of SGs and power systems. So in this work, an ACOPF is proposed to create an optimization framework, in which optimal location and size of ESSs as well as optimal scheduling of ESS, DG units and power injection from the upstream grid, with and without DRP consideration would be determined.

1.1. Literature review

The main goal in the ESS optimal planning is to answer the following questions: 1) How many storage units are needed to be installed in the grid? 2) Where are the best locations for these units to be installed, or which buses are adequate? 3) How much is the optimal capacity and power rate of these units? 4) How should these units be operated to be profitable?

To answer these questions, some literatures investigate the optimal size and site of ESS units by heuristic algorithms such as, genetic algorithm (GA) [15], particle swarm optimization (PSO) [16], bat algorithm (BA) [17], cuckoo search algorithm (CKA) [18] and etc. Also, the combination of these methods referred to hybrid methods, are widely used by the researchers. A fuzzy expert system in combination of the genetic algorithm is used in [19], which seeks to find the optimal size of storages in a microgrid. A review on storage allocation methods and models is provided by [20], and also another group of algorithms for ESS planning is described in this paper, which is reputed to analytical methods. These methods are based on statistical and historical analyses and do not use a specific model. They are currently used only for optimal sizing of ESS. On the other hand, mathematical methods have attracted enormous attention in the power system operation and planning field, especially in ESS allocation planning. In this regard, OPF problem [21], dynamic programming [22] and stochastic programming [23] are some examples that can be found in literatures which aim to find the best location and sizing of ESS units, simultaneously.

A classical forward-backward load flow approach, which is designed for radial distribution systems, is used in [24], for location determination of ESS units in 12 and 33 bus systems with PV arrays. In [25], the allocation is done in a two-step process; in the first step, using the Clustering and Sensitivity Analysis algorithm (CSA), the candidate buses are specified for the ESSs placement. At the second step, OPF is used to determine the size of them. Paper [26] proposes stochastic mixed-integer programming for optimal sizing and locating of ESSs in a large scale system, where the objective is to minimize the sum of the expected operating cost and the investment cost of ESSs. In [27], the charge and discharge power curves are used for ESS sizing. Concerning loss reduction in a distribution network, battery storage allocation is investigated in [28]. The authors in [29], effort to minimize the operating costs of a microgrid, with a novel energy management technique, including economic strategies for the operation of system and sizing of battery storage. In many literatures, the topic of ESS sizing and sitting has been investigated by considering different RESs and DGs [30-32]. Optimal ESS sizing has been investigated through an OPF and with considering various uncertainties by [33]. A hybrid PSO-OPF based algorithm is proposed by [34]. Concerning the goals of optimization, operating cost minimization and reliability enhancement are the most considered goals in the papers, e.g., [19] or [27].

Although there are a large variety of publications in the ESS allocation topic, there are fewer references consider the optimal DRP and ESS planning or operation, simultaneously. In [35], the impacts of optimal scheduling of DRP as well as ESS units have been considered on procurement problem. Paper [36], proposes a stochastic optimization framework for energy management of a renewable-based isolated rural microgrid. In order to have a balance between demand and generation, a pumped-storage unit and a DRP have been used in this work. Also, the objective of [37] is to minimize the distribution losses payments with optimal ESS and DRP scheduling. The main assumption behind all of these papers is that ESSs capacities are known and the objective is optimal scheduling of these units or demand-side management tools utilization. In order to have a more obvious comparison between this work and other related works, some of them are mentioned in Table 1.

Table 1. Comparison between some of the related works

Ref.	Sizing	Sitting	DRP consideration	Network constraints consideration	RESs type	Dispatchable DG units	Loss payment consideration	Method
[19]	✓	×	×	×	Wind	✓	×	Fuzzy expert system
[34]	×	✓	×	✓	×	×	×	OPF
[38]	✓	×	✓	×	Wind	✓	×	Fuzzy expert system
[39]	✓	×	×	×	Wind	×	×	HAWE system analyze
[40]	✓	✓	×	✓	×	×	✓	PSO
[41]	✓	✓	×	✓	Wind	×	×	Hybrid Tabu search/PSO
[42]	✓	×	×	×	Wind	×	×	Analytical Algorithm
[43]	✓	✓	✓	✓	Wind	✓	×	GA
[44]	✓	✓	×	✓	Wind	✓	✓	OPF
This work	✓	✓	✓	✓	PV-Wind	✓	✓	OPF

As Table 1 shows, there are lots of literatures in the field of ESS planning, with various assumptions, goals, methods, and constraints. A majority of papers provide just one of the sizing or sitting of ESS units without considering a network as a test bed. It should be noted, while the ESSs have positive effects on power quality or reliability of the system, also they can increase the power losses by drawing more current from the DG units or the utility, especially at the off-peak times, so it should be addressed well in the optimization framework. While most of the abovementioned papers did not consider this important subject. Also, DRP consideration, as well as ESS planning, is a new topic, which there are not so many works in this field, as it can be concluded from Table 1. Moreover, the PV system generation is considered here, while others did not consider it. OPF problem is suitable for grid-connected devices such as ESSs because it can affiliate all parameters of a network such as voltage, loss, etc. together in a coherent scene.

1.2. Contributions

In this paper, an optimization framework is proposed to obtain the optimal site and size of ESSs in a smart distribution network while DRP and network constraints are considered. PV systems and wind turbines in this work are included as renewable-based generation units, and diesel generators are considered as non-renewable based energy generators. The proposed optimization model minimizes operation and losses costs as well as total ESS investment cost. Time-of-use based DRP has been considered as well as the ESS optimal sitting and sizing problem in the proposed paper. Finally, the contributions of the presented paper can be summarized as follows.

1. Optimal ESS sizing and sitting are done by considering the effects of TOU based DRP.

2. The obtained ESS capacities are forced to be an integer, so that be a feasible solution in practice.

3. Different types of distributed generators are considered.

4. Power losses minimization is considered as one term of objective function.

1.3. Paper organization

The organization of this paper is as follow: In Section 2, the optimal power flow is described and the problem formulation is presented. Section 3 provides a case study. Section 4 presents the obtained results and comparisons. Finally, the paper is concluded in Section 5, and the future works are also expressed.

2. Problem formulation

In this paper, an optimization model has been proposed for optimal sitting and sizing of ESS in a smart distribution network in the presence of DRP. For devices connected to the network, locating includes, various analyses of the effects of equipment on the network, so mathematical methods like power flow or optimal power flow are recommended.

2.1. Optimal power flow problem

OPF methods are useful in active distribution systems for the purpose of planning or operating. OPF methods include nonlinear equations and constraints, which make them non-convex problems. In transmission systems, a linear approximation of OPF can be used accurately, which is called DCOPF; but in distribution networks, the use of this approximation will be inaccurate due to the large proportion of R/X of lines; according to [45], using an ACOPF is unavoidable. The main difficulty with ACOPF is the dimension of the grid, and so in some cases, a multi-period power flow should be solved. There are two general approaches to deal with this problem; one is to use the meta-heuristic methods and the second is using convex relaxations of OPF problem such as semi-definite programming (SDP) or second-order cone programming (SOCP) which convexify the feasible region enclosed by power flow equations [46, 47]. Both of SOCP and SDP can be used for radial networks [46, 47]. For large-scale power systems, e.g., distribution network, SOCP would perform much faster than SDP. There is no guarantee with heuristic methods to give a global optimum solution and also impose a heavy computational load on large scale systems with numerous constraints [45]. So in a distribution system with many connections, branches and loads, these methods are not suitable, and the use of convex relaxation is superior. In this regard literatures [45] and [48] solve ESS allocation problem in a distribution system and transmission system, respectively, using SOCP relaxation for the OPF problem.

Since the dimension of the studied distribution system in this paper, is not so large and a limited time horizon is investigated, also by considering the fact that the time of computation is not so critical for planning problems, there is no need to use SDP or SOCP relaxations in this work, because despite their acceleration, they create a gap between the original and relaxed model [49].

2.2. Objective Function

Equation (1) is the proposed objective function and includes ESS investment cost (EIC) and operation cost (OPC) which are presented in equations (2) and (3), respectively.

$$\min \quad OF = EIC + OPC \tag{1}$$

$$EIC = \sum_{i\in\gamma} (Cess_i \times Cost_{In.C} + Pess_i \times Cost_{In.P}) \tag{2}$$

$$OPC = Cost_{up} + Cost_{loss} + Cost_{DG} \tag{3}$$

$$Cost_{up} = \sum_{h=1}^{5} (CF_h \times 365 \times \sum_{t=1}^{24} P_{t,h}^{sub} \times \pi_{t,h}) \tag{4}$$

$$Cost_{loss} = \sum_{h=1}^{5} (CF_h \times 365 \times \sum_{t=1}^{24} P_{t,h}^{loss} \times \pi_{t,h}) \tag{5}$$

$$Cost_{DG} = \sum_{h=1}^{5} (CF_h \times 365 \times \sum_{i\in\rho,t} (a_g (P_{i,t,h}^{DG})^2 + b_g P_{i,t,h}^{DG} + c_g)) \tag{6}$$

$$CF_h = \frac{(1+p)^h}{(1+q)^h} \qquad h = 1,2,3,4,5 \tag{7}$$

Total operational costs including the cost of purchased power for demand procurement, power losses cost, and operational cost of diesel generators are presented by equations (4), (5) and (6), respectively. It is assumed that the investments accomplished during the first years and so did not be multiplied by 365. Equation (7) defines the CF factor, which is needed for economic calculations, i.e., net present value calculation.

2.3. ACPF Constraints

$$P_{t,h}^{loss} = \sum_{i,j} 0.5 \times G_{i,j} \times (V_{i,t,h}^2 + V_{j,t,h}^2 - 2V_{i,t,h} V_{j,t,h} \cos(\delta_{i,t,h} - \delta_{j,t,h})) \qquad ,\forall t,h \tag{8}$$

$$P_{i,j,t,h} = \frac{V_{i,t,h}^2}{Z_{i,j}} \cos(\theta_{i,j}) - \frac{V_{i,t,h} V_{j,t,h}}{Z_{i,j}} \cos(\delta_{i,t,h} - \delta_{j,t,h} + \theta_{i,j}) \qquad ,\forall i,j,t,h \tag{9}$$

$$Q_{i,j,t,h} = \frac{V_{i,t,h}^2}{Z_{i,j}} \sin(\theta_{i,j}) - \frac{V_{i,t,h} V_{j,t,h}}{Z_{i,j}} \sin(\delta_{i,t,h} - \delta_{j,t,h} + \theta_{i,j}) \qquad ,\forall i,j,t,h \tag{10}$$

$$P_{t,h}^{sub} + P_{i\in\Delta,t,h}^{wind} + P_{i\in\rho,t,h}^{DG} + P_{i\in\alpha,t,h}^{PV} - P_{i,t,h}^{load-DRP} + \eta \times P_{i,t,h}^{c/d} = \sum_{j=1}^{N_{bus}} (\frac{V_{i,t,h}^2}{Z_{i,j}} \cos(\theta_{i,j}) - \frac{V_{i,t,h} V_{j,t,h}}{Z_{i,j}} \cos(\delta_{i,t,h} - \delta_{j,t,h} + \theta_{i,j})) \quad ,\forall i,t,h \tag{11}$$

$$Q_{t,h}^{sub} - Q_{i,t,h}^{load} = \sum_{j=1}^{N_{bus}} (\frac{V_{i,t,h}^2}{Z_{i,j}} \sin(\theta_{i,j}) - \frac{V_{i,t,h} V_{j,t,h}}{Z_{i,j}} \sin(\delta_{i,t,h} - \delta_{j,t,h} + \theta_{i,j})) \quad ,\forall i,t,h \tag{12}$$

$$-S_{i,j}^{\max} \le S_{i,j,t,h} \le S_{i,j}^{\max} \qquad ,\forall i,j,t,h \tag{13}$$

$$-P_{sub}^{\max} \le P_{t,h}^{sub} \le P_{sub}^{\max} \qquad ,\forall t,h \tag{14}$$

$$-Q_{sub}^{\max} \le Q_{t,h}^{sub} \le Q_{sub}^{\max} \qquad ,\forall t,h \tag{15}$$

$$0.9^{p.u.} \le V_{i,t,h} \le 1.0^{p.u.} \qquad ,\forall i,t,h \qquad (16)$$

$$-\frac{\pi}{2}^{rad} \le \delta_{i,t,h} \le \frac{\pi}{2}^{rad} \qquad ,\forall i,t,h \qquad (17)$$

Equation (8) denotes the active power losses in the network; (9) and (10) show the exchanged power between the connected buses at each time; (11) and (12) show the power balance at each time for active and reactive power, respectively. Equations (13)-(17) define limits on network variables.

2.4. Distributed Generation

$$0 \le P_{i,t,h}^{PV} \le PV^{cap} \times TA_t \qquad ,\forall i \in \alpha, t, h \qquad (18)$$

$$P_{i,t,h}^{wind} = \begin{cases} 0 & V_{wind_t} < V_{C-I} \\ P_{wind_i}^{\max} \times \dfrac{V_{wind_t} - V_{C-I}}{V_R - V_{C-I}} & V_{C-I} < V_{wind_t} < V_R \\ P_{wind_i}^{\max} & V_R < V_{wind_t} < V_{C-O} \\ 0 & V_{wind_t} > V_{C-O} \end{cases} \qquad (19)$$

$,\forall i \in \Delta, t, h$

$$P_{DG_i}^{\min} \times u_{i,t,h} \le P_{i,t,h}^{DG} \le P_{DG_i}^{\max} \times u_{i,t,h} \qquad ,\forall i \in \rho, t, h \qquad (20)$$

$$P_{i,t,h}^{DG} - P_{i,t-1,h}^{DG} \le UR_i \times (1 - y_{i,t,h}) + P_{DG_i}^{\min} \times y_{i,t,h} \qquad ,\forall i \in \rho, t, h \qquad (21)$$

$$P_{i,t-1,h}^{DG} - P_{i,t,h}^{DG} \le DR_i \times (1 - z_{i,t,h}) + P_{DG_i}^{\min} \times z_{i,t,h} \qquad ,\forall i \in \rho, t, h \qquad (22)$$

$$\sum_{k=t}^{t+UT_i-1} u_{i,t,h} \ge UT_i \times y_{i,t,h} \qquad ,\forall i \in \rho, t, h \qquad (23)$$

$$\sum_{k=t}^{t+DT_i-1} (1 - u_{i,t,h}) \ge DT_i \times z_{i,t,h} \qquad ,\forall i \in \rho, t, h \qquad (24)$$

$$y_{i,t,h} - z_{i,t,h} = u_{i,t,h} - u_{i,t-1,h} \qquad ,\forall i \in \rho, t, h \qquad (25)$$

$$y_{i,t,h} + z_{i,t,h} \le 1 \qquad ,\forall i \in \rho, t, h \qquad (26)$$

Equation (18) limits the PV production to be available just in sunny hours of a day. Equation (19) models the wind turbines production and (20) describes the power limit on diesel generators, while (21)-(22) show the ramp rates of diesel generators, and (23)-(24) model the minimum up/down time constraints of diesel generators. Furthermore, (25)-(26) show the constraints on commitment states of units. The start-up cost of diesel generators assumed to be negligible.

2.5. ESS Constraints

$$SOC_{i,t,h} = SOC_{i,t-1,h} + P_{i,t,h}^{c/d} \quad ,\forall i \in \gamma, h, t > 1, t \ne 24 \qquad (27)$$

$$SOC_{i,t=1,h} = SOC_{i,t=24,h} = SOC_{\min_i} = \sigma C_{ess_i}, \forall i \in \gamma, h \qquad (28)$$

$$SOC_{\min_i} \le SOC_{i,t,h} \le C_{ess_i} \qquad ,\forall i \in \gamma, t, h \qquad (29)$$

$$-\lambda C_{ess_i} \le P_{i,t,h}^{c/d} \le \lambda C_{ess_i} \qquad ,\forall i \in \gamma, t, h \qquad (30)$$

Equation (27) shows the state of charge (SOC) for the ESSs at each time, from (28), the amount of state of charge at the beginning and the end of time horizon (24-hours) should be a constant value. Equation (29), limits the amount of SOC for each ESS. In (30), $P_{i,t,h}^{c/d}$ is a decision variable which shows the charging or discharging values of each one of ESSs; when an ESS is in charging statue, its sign is negative (acts as a load), and when ESS is in discharging statue, its sign would be positive (acts as an active power generator). So there is no need to add another equation to show that charging and discharging processes should not occur simultaneously and just by adding one variable this concept is realized. η, σ and λ are constant values which equal to 1, 0.5 and 0.4, respectively.

2.6. DRP Constraints

$$P_{i,t,h}^{load-DRP} = D_{i,t,h} - TOU_{i,t,h} \qquad ,\forall i,t,h \qquad (31)$$

$$\sum_{t=1}^{24} D_{i,t,h} = \sum_{t=1}^{24} P_{i,t,h}^{load-DRP} \qquad ,\forall i,h \qquad (32)$$

$$-DR^{\max} \times D_{i,t,h} \le TOU_{i,t,h} \le DR^{\max} \times D_{i,t,h} \quad ,\forall i,t,h \qquad (33)$$

Equation (31) is used to show the concept of TOU, which $TOU_{i,t,h}$ shows the amount of shifted load at each hour. Based on the definition of the equation, the sign of $TOU_{i,t,h}$ at each bus i and at a time t will be positive if the loads have been transferred to time t and vice versa. It can be concluded from (32) that the base load that needs to be met is a constant for each day and just some percent of it, is transferred from peak periods to off-peak periods. In simple words, the increase and decrease of load should be equal during the day for each bus. It should be noted that the maximum amount of load increase/decrease, i.e. $DR^{\max}$, of the base load is equal to 20% in the presented paper in (33).

All of the equations and constraints are modeled in the GAMS software environment, which a standard NLP model used for doing an ACPF on the distribution network. Due to the existence of the DG units, there are binary variables, and the full model is solved as a MINLP model [50].

3. Case study

In this paper to avoid heavy computational load, a 24-hour time horizon is considered and assumed that the loads in each bus are the average consumption for one year. These 24 hours will be a representative of the full year and a five years planning is considered. The annual interest and inflation rates are selected 0.2 and 0.1, respectively. It is assumed that active and reactive power consumption data for each bus, are the average values for one-year consumption. So by multiplying them by 365, the annual consumption will be obtained. Also since the problem is a location-time problem, it is required to make a correspondence between each hour and the demand for each bus. To make this correspondence, loads in each bus would be multiplied by a constant which models real loading conditions. The maximum number of ESS units in this system considered to be five units. Here the investment cost of ESSs is supposed 400,000 \$/MWh/year and 11,000 \$/MW/year, as referred in [43]. Also, some ESS technologies' investment costs can be found in the paper [51]. A modified 33-bus distribution network, with lines information and load demands, as described in [24] and [43], respectively, is used in this work with a nominal voltage of *Vbase*=12.66KV, which is depicted in Fig. 1. It should be noted that there is a 5% increase in power consumption per year. It is assumed that maximum capacity which can be allocated in the network is 15 MWh.

The medium voltage feeder is assumed to be a 100 MVA transformer. Hourly energy prices which will be paid by Distribution

System Operator (DSO) to buy energy from power plants are also provided in [43]. It is assumed in this network, five PV systems, four diesel generators, and three wind turbines do exist, which are located and sized randomly.

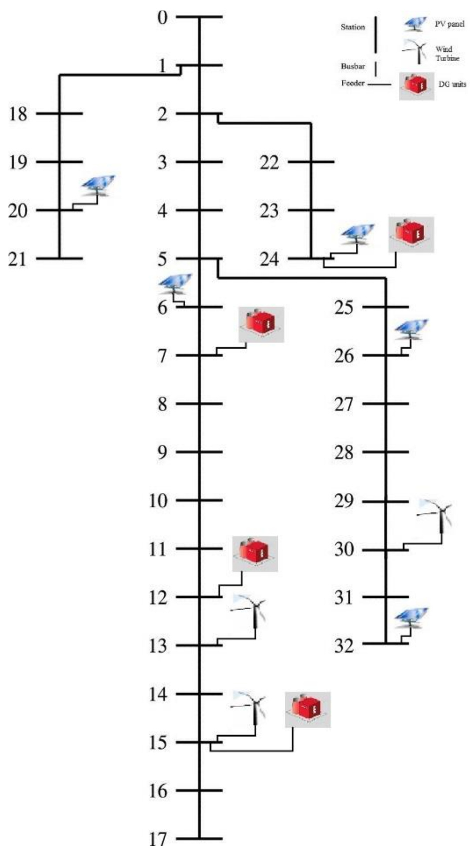


Fig. 1. Single diagram of IEEE 33 bus network [24].

Location of these units is delineated in Fig. 1, and the information of these power generators are expressed in Table 2 for the 33-bus system.

Table 2. Distributed generators' information installed on 33-bus network

	Location (Bus)	Capacity (kW)
PV Panels	6	20
	20	30
	24	120
	26	10
	32	90
Wind Turbines	13	3000
	15	3000
	30	3000
Diesel Generators	7	3500
	12	3000
	15	3000
	24	4100

Information about time availability of PV systems (the hourly generation factors, referred to TA) and wind speed at each hour exist in Table 3. Diesel generators' cost function coefficients are the same as mentioned in [43].

Table 3. Time-dependent information

Time (Hour)	TA	Wind speed (mile/hour)	Time (Hour)	TA	Wind speed (mile/hour)	Time (Hour)	TA	Wind speed (mile/hour)
1	0	7.95	9	0.90	6.45	17	0.95	9.35
2	0	8.8	10	0.95	5.1	18	0.8	10
3	0	9.65	11	0.98	4.35	19	0.4	9
4	0	10.55	12	1	4.7	20	0	8.5
5	0	9.45	13	1	5.1	21	0	7.4
6	0.50	8.45	14	1	6.2	22	0	7
7	0.60	7.15	15	1	7.2	23	0	6.75
8	0.80	6.4	16	0.98	8	24	0	7.15

4. Results

To highlight the technical and financial benefits of ESS and DRP on the network operation and planning, three study cases have been evaluated, and the results are compared.

Case 1: Base case, without ESS and DRP

Case 2: Optimal sitting and sizing of ESS without DRP effects

Case 3: Optimal sitting and sizing of ESS with considering DRP

4.1. Case 1: without ESS and DRP

This case is the same as a simple optimal power flow in a distribution network; while, the objective function includes the summation of costs of the drawn power from the upstream grid and the total cost of losses in distribution lines. In this case, DRP effects and the sitting and sizing of ESSs are neglected. Total operating cost including the costs of purchased power and diesel generators as well as power losses is $ 110,180,000.

4.2. Case 2: Optimal sitting and sizing of ESS without considering DRP

As it was raised, in this paper, the sizing and sitting of ESSs simultaneously will be done, using an ACOPF algorithm. Figure 2 shows the calculated size of storage units for each bus including nominal capacity. Prioritized buses for storage placement are also detected. The total capacity of ESS which is needed to be installed is 15 MWh. The total cost including the costs of purchased power, diesel generators and also power losses as well as costs related to ESSs in five years, is $ 105,130,000. Table 4 shows the detailed results and obtained costs for each case. The net reduction in costs is 1,010,000 $/year.

4.3. Case 3: Optimal sitting and sizing of ESS with considering DRP

This case shows the effects of considering a DRP on the ESS allocation procedure. Figure 3 shows the calculated size of storage units for each bus including nominal capacity. Prioritized buses for storage placement, are also detected. The total capacity of ESS which is needed to be installed, is 15 MWh. Total cost including the costs of purchased power, diesel generators and also power losses as well as costs related to ESSs for five years is $ 89,151,100. Table 4 shows the detailed cost results obtained for each case. The net reduction in costs is $ 4,206,000, which is shown in the last column of Table 4.

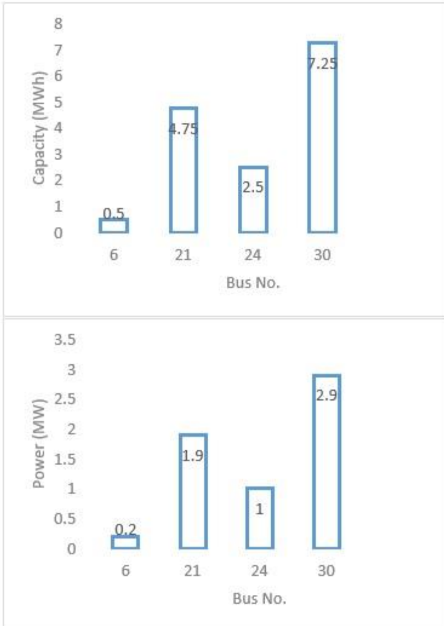


Fig. 2. ESS optimal nominal capacity and power for case 2

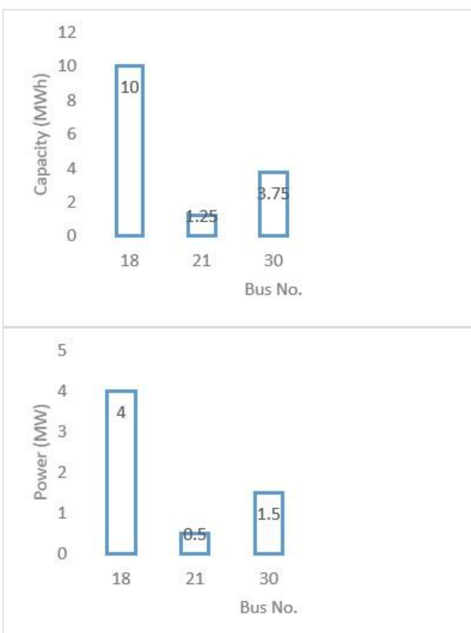


Fig. 3. ESS optimal nominal capacity and power for case 3

Table 4. Objective function values

Cases	Investment costs ($)	Operational costs ($/year)	Percentage of reduction of operational cost (%)
1. Base case (Without ESS and DRP)	0.0	22036510	0.0
2. With only ESS optimally sized and placed (cost of ESS construction added)	405000	20945890	4.94
3. ESS optimization with considering DRP (incentive and construction costs added)	405000	17749220	19.45

In the following, the technical effects of ESS and DRP are also considered in a five-year horizon, and the results are depicted in figures 4-9. In the legends, Yi shows the ith year of operation.

As can be seen in Fig. 4, in off-peak hours with low energy prices, the power consumption in case 3, is more than the base case. This is because of existing DRP and ESSs in the network. In contrast at peak hours, the consumption is reduced which is economical. The loads are shifted from peak hours to the off-peak hours using ESS time-shifting ability and TOU based DRP. Also, the load demand for the 5th year is higher than the others, because of annually increasing in power consumption, which has been addressed previously. In case 3 compared to case 2, DRP utilization can make load reduction an average of 5 MW for all years. Also, ESS units have time-shifting capability, but loss reduction assumption prohibits large charging at off-peak times and discharging at peak times. While in DRPs, some percentage of the load is assumed to be curtailable, and by this mean, absolute of operating cost reduction is more than loss payment increment.

As can be seen in Fig. 5, for off-peak hours the imported active power in cases 2 and 3, is more than the consumption of base case and this is caused by the shifted loads or ESSs charging processes. In contrast at peak times, the purchased active power from the upstream grid with high price is decreased significantly compared to case 1; even this imported power reaches to zero for case 3 at peak times with appropriate management of ESSs and DRP. This is occurred because of the capability of ESSs in storing of exceed renewable produced power at off-peak times (especially by PVs) and releasing it back to the grid at peak times and also by the load shifting actions of DRP.

From Fig. 6, it can be concluded that the purchasing power from dispatchable DG units has little differences among the cases, and this little difference is also caused by load increment at each year. Because of existing renewable generations in the network with negligible operation cost, it is economical to buy energy from diesel generators, only when there is a power lack. The main difference between cases 2/3 and case 1 is ESS power requests at off-peak times.

Figure 7 shows the amount of total active power losses in the system. As it was mentioned before, one of the terms in the objective function is the active power losses payments, and the proposed optimization seeks to minimize it. With this regard, it can be seen in this figure, due to the high-power consumption at off-peak times, the active losses are higher than the on-peak times, and this is economical because the energy price is usually lower at off-peak times. Also, case 3 has the least active losses compared to cases 1 and 2. The active loss mostly depends on the line's current, and the currents are related to the demands of each year, so the annual increment of losses is logical.

It is decided to depict one bus voltage profile, which is a far end bus. Figure 8 shows the voltage profile of the 17th bus for all of the mentioned study cases. As can be seen, for off-peak times, case 3 has the least voltage compared to the others. This is because of load shifting to those hours with low energy prices and charging of ESS units; however, at peak times, the voltage level of this bus is the highest at case 3. The voltage level is decreasing as the load consumption increases every year. It should be noted that in this paper, the voltage profile improvement is not considered in the objective function. One can extend the proposed model to achieve higher voltage profiles in the network.

Figure 9 depicts the charged and discharged power of ESS units for both cases. It is worth mentioning that the optimal scheduling of charging or discharging of ESS units is obtained through the optimization running process. In this figure, if an ESS unit draws power from the grid (charging), then it appears with a negative sign and vice versa. In case 2, there are four candidate buses for ESS installation. As all of the curves show, for each year, at off-peak times, the ESS is forced to be charged and then at the peak times, its stored energy is released. Because the planning in this work is considered to be static planning, and the required capacity is invested at the first year, the curves of power charging/discharging for the first year are different from the rest years, and their charging/discharging curves are overlapped. Also, the installed capacities have influenced the rates of charged/discharged powers.

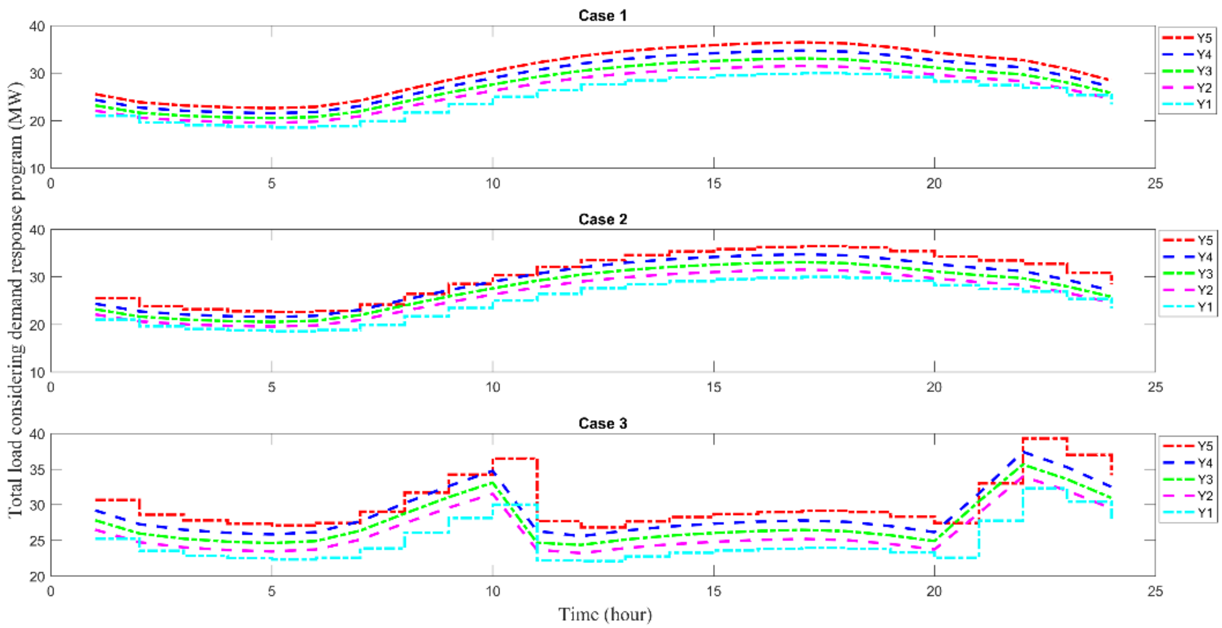


Fig. 4. Total demand consumption in cases with/out DRP

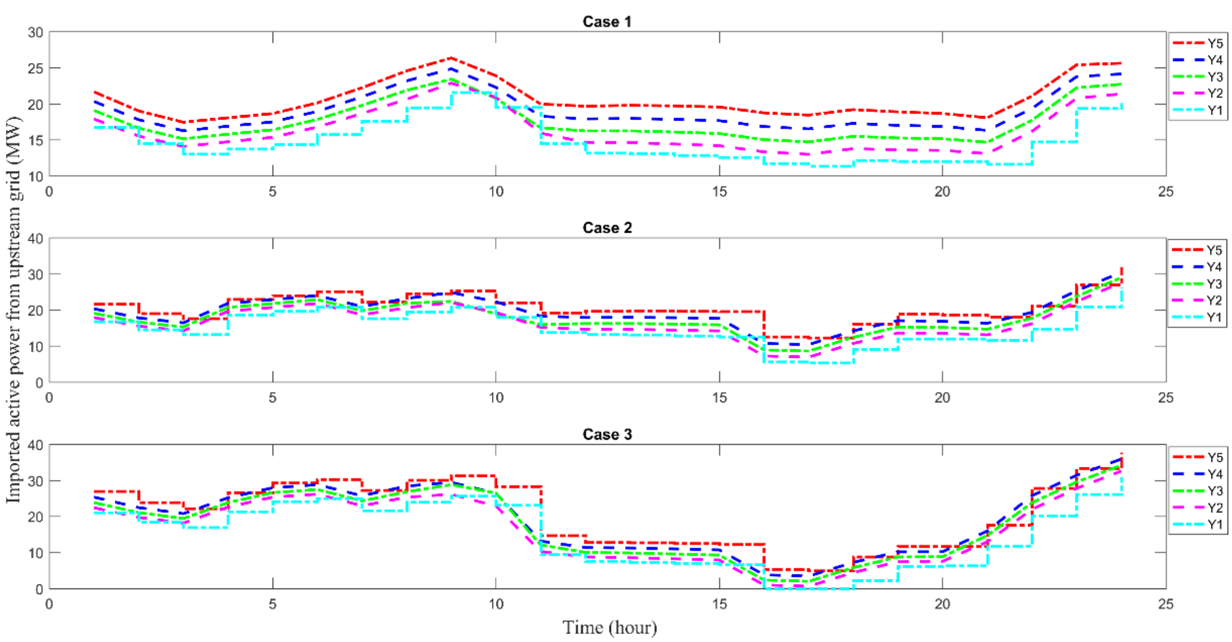


Fig. 5. Imported active power from the upstream grid for three cases

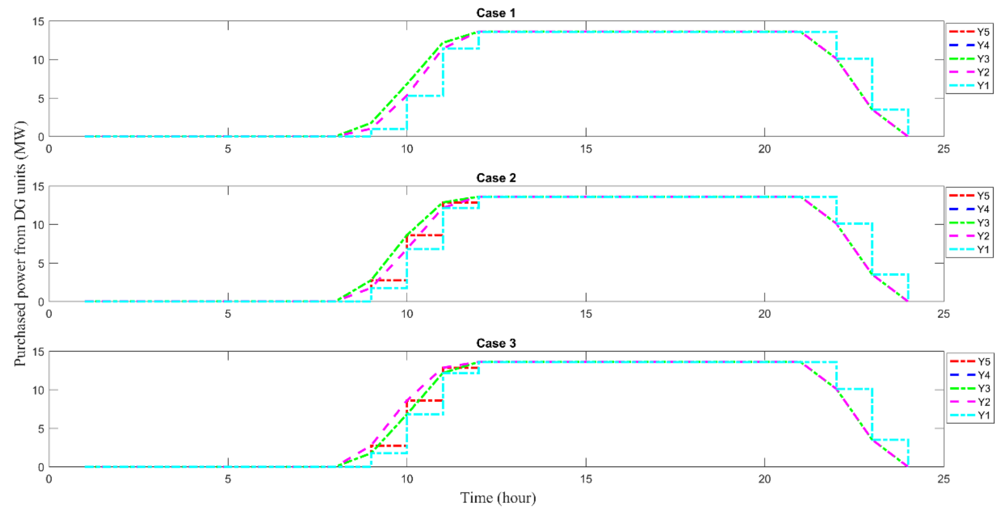


Fig. 6. The total provided active power by diesel generators

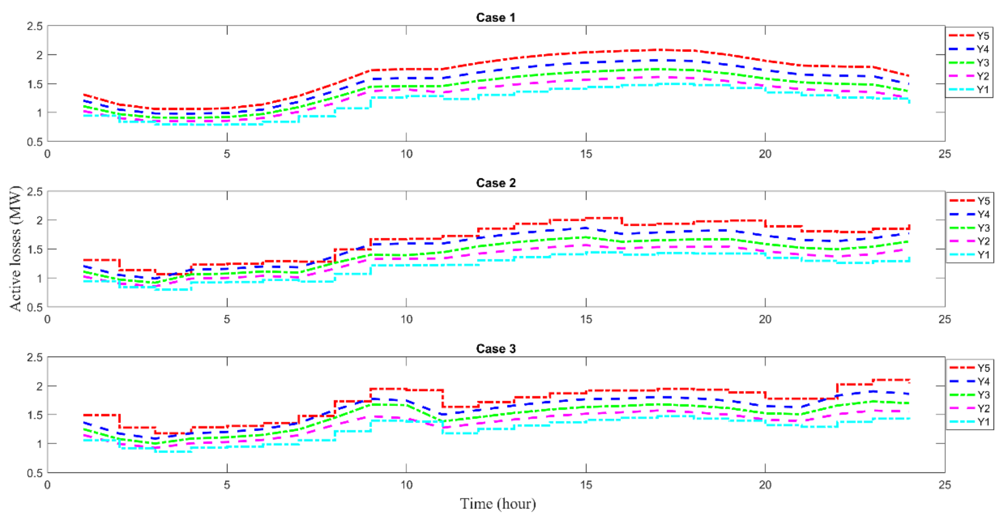


Fig. 7. Total active power losses

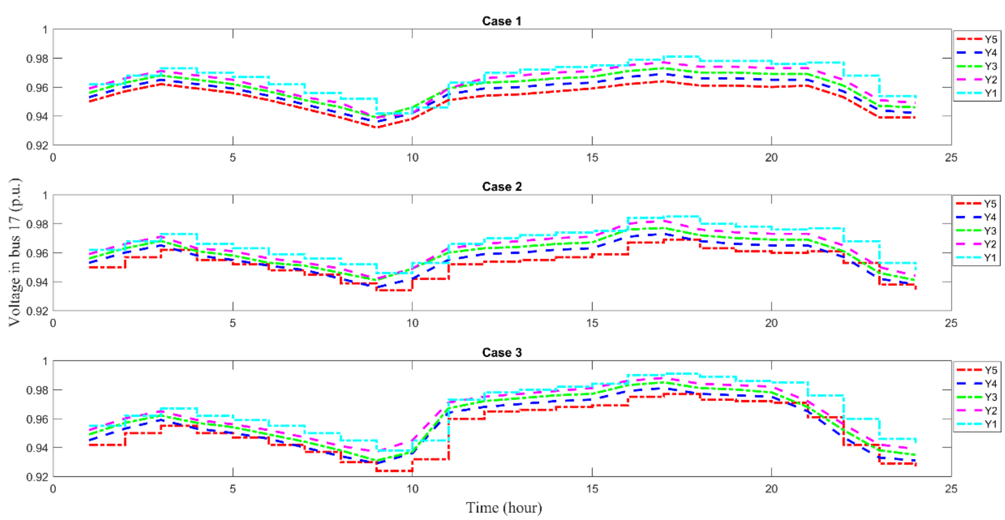
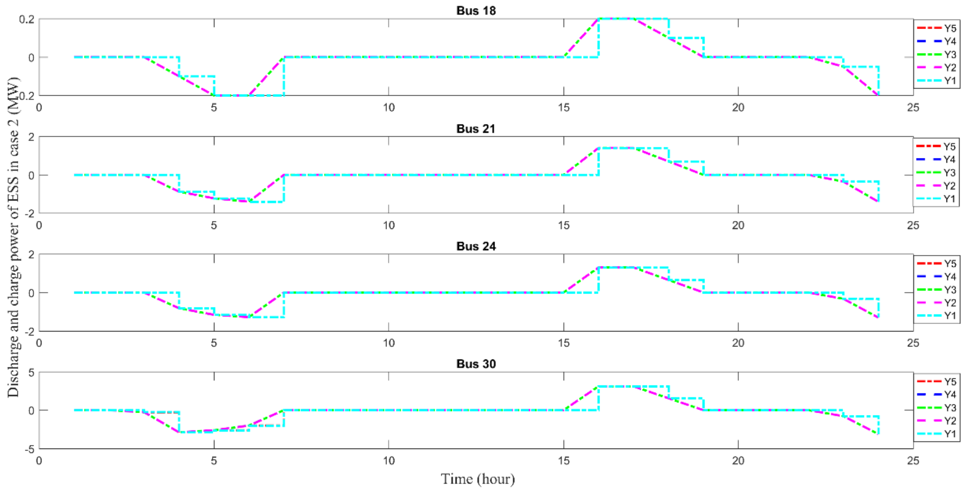
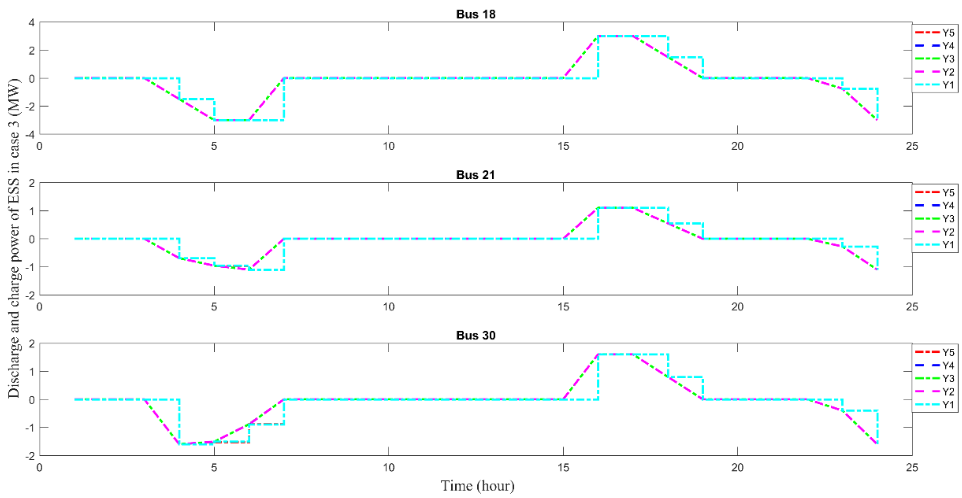


Fig. 8. Voltage profile of bus No. 17



(a) Case 2



(b) Case 3

Fig. 9. Charge and discharge of installed ESS units in cases 2 and 3

5. Conclusion

This paper proposed an optimization framework to obtain the optimal capacity and location of ESS units in a smart distribution network with considering DRP effects. The model included four different objectives: 1) minimization of the total power purchasing (from the upstream grid or DG units), 2) minimization of the total cost of power losses payment, 3) finding optimal ESS capacities and power rates with respect to their investment cost, and 4) finding an optimal scheduling of ESSs as well as DRP. A modified 33 bus IEEE test system and different renewable and non-renewable DGs were considered. Obtained results for three different cases were compared with each other. According to the obtained results, the total cost of the network for five years in case 1, was $ 110,182,550 and this value in case 2, considering ESS investment, fell to $ 105,134,450. Moreover, for case 3 with DRP consideration, the total cost was equal to $ 89,151,100. It can be concluded that the optimal scheduling of ESS and DRP together in case 3, can reduce the network costs by 15.2 % in comparison with case 2, and by 19 % in comparison with case 1. While in case 2, with only ESS allocation the save was about 4.6% in comparison with case 1. The higher save in case 3 is because of DRP consideration. DRP had shifted some percentage of the consumption from peak times with high energy prices to off-peak times with lower energy prices.

As future works, the authors are interested in the investigation of uncertainty modeling of renewable-based generation outputs and load forecasts in the ESS planning problem. The optimal allocation and scheduling of ESS units for participation in the power market environments are another remarkable fields which will be investigated in next works.

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