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Optimal Placement, Sizing, and Daily Charge/Discharge of Battery Energy Storage in Low Voltage Distribution Network with High Photovoltaic Penetration

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Abstract:

Proper installation of rooftop photovoltaic generation in distribution networks can improve voltage profile, reduce energy losses, and enhance the reliability. But, on the other hand, some problems regarding harmonic distortion, voltage magnitude, reverse power flow, and energy losses can arise when photovoltaic penetration is increased in low voltage distribution network. Local battery energy storage system can mitigate these disadvantages and as a result, improve the system operation. For this purpose, battery energy storage system is charged when production of photovoltaic is more than consumers' demands and discharged when consumers' demands are increased. Since the price of battery energy storage system is high, economic, environmental, and technical objectives should be considered together for its placement and sizing. In this paper, optimal placement, sizing, and daily (24 hours) charge/discharge of battery energy storage system are performed based on a cost function that includes energy arbitrage, environmental emission, energy losses, transmission access fee, as well as capital and maintenance costs of battery energy storage system. All simulations are carried out in DIgSILENT and MATLAB linked together. Results show that by using the proposed approach, overvoltage

and energy losses are decreased, reverse power flow is prevented, environmental emission is reduced, and economic profit is maximized.

Keywords: Photovoltaic (PV), Battery energy storage system (BESS), Distribution network, Optimal planning and operation, high penetration.

1. Introduction

Recently, utilization of renewable energy sources (RES) in electrical networks is getting inevitable due to the global energy tension and environmental concerns of fossil-fuel-based electricity generation [1].

Photovoltaic (PV) generation is growing very fast while its cost is dropping rapidly [2]. Single phase rooftop PVs (<10 kW) owned by utility customers are being installed in low voltage (LV) distribution networks. The penetration of such PV systems is increased in many places throughout the world, including Iran, due to solar radiation, gradual elimination of energy subsidies, and government incentives.

Utilizing PV systems can help to reduce the dependence on conventional power plants, improve voltage profile, and decrease energy losses [3]. However, in the case of high PV penetration in LV distribution network, reverse power flow may occur when the PV production exceeds the consumers' load [4]. This situation may lead to overvoltage, increase of total harmonic distortion (THD) and fault current, blinding of protection and false tripping, risk of islanding operation [5], and decrease reliability [6].

To reduce the negative impacts of high PV penetration, there are two main approaches including conventional (commercially available) and emerging mitigation methods [1]. Reconductoring and on-load tap changing (OLTC) are examples of conventional methods. Emerging methods include reactive power (VAR) control by PV inverters, distributed energy storage systems, coordinated control between utility equipment and PV inverters, installation of devices such as dynamic voltage restorer (DVR) and distributed static compensator (DSTATCOM), etc.

Negative impacts of high PV penetration such as increased voltage magnitude, reverse power flow, and energy losses can be mitigated by optimal placement, sizing and/or charge/discharge scheduling of battery energy storage system (BESS). In this regard, many researchers have studied proper installation of energy storage in distribution networks with high PV penetration. In [7], optimal daily energy profiles of storage systems co-located with PV generation are calculated and it is shown that significant control abilities in peak shaving, voltage stability, and reducing distribution losses can be achieved. Optimal sizing of battery energy storage co-located with PV is evaluated in [8] for the goals such as voltage regulation. In another study, a coordinated hierarchical control scheme is presented for static synchronous compensators (STATCOM) and BESS in order to mitigate the overvoltage problem, but, cost/benefit analysis is not performed for the BESS [9]. Cost/benefit analysis is performed in [10] to determine the optimal location and size (without optimal operation) of community energy storage (CES) by considering energy arbitrage, peak power generation, energy loss reduction, upgrade deferral of transmission and distribution (T&D) systems, CO_2 emission reduction, and reactive power support. BESS is applied in [11] for peak shaving and smoothing the distribution load profile. To achieve these goals, a real time control is developed which performs smoothing and peak shaving, simultaneously. In [11], the economic purpose (price arbitrage) is not considered, therefore, BESS charge/discharge is only calculated for peak shaving. Authors of [12] proposed an algorithm that is capable of integrating sizing, placement, and operational strategies of BESS taking into account energy losses, but, without considering environmental emission. The minimum energy storage required to be installed in LV grid to prevent the overvoltage is calculated in [13]; optimal sizing and placement of BESS is calculated, but, daily charge/discharge is not considered. Authors of [14] proposed optimal sizing (without sitting) of BESS in the residential LV distribution network for peak shaving, valley filling, load balancing, and management of distributed RES. In [15], sizing energy storage based on Open Distribution Simulator (OpenDSS) is proposed, but, optimal sizing, sitting, and charge/discharge are not done simultaneously. Authors of [16] proposed a new framework to integrate CES units in an existing residential community system with rooftop PV units. In [16], the location, sizing, and operational characteristics of CES are calculated to minimize the annual energy loss, enhance load following control, and improve the voltage profile, respectively. In [17], a coordinated control of distributed BESS with traditional voltage regulators including the OLTC and step voltage regulators (SVR) is proposed, but, environmental effects are not analyzed. Authors of [18] discussed optimal sizing and operation of BESS to contribute to local distribution network operation through peak shaving, voltage control, and levelling out power production from RES. The work in [19], optimizes the size of

BESS based on a cost/benefit analysis when BESS is applied for voltage regulation and peak load shaving, but, optimal charge/discharge is not taken into account. Optimal planning and operation of energy storage is performed in [20] for peak shaving, reducing reverse power flow, and energy price arbitrage in distribution network with high penetration of RES, but, voltage regulation is not taken into account. In [21], the storage is utilized to compensate long-term and short-term voltage variations originated from sudden change of PV output. The strategy of charge/discharge is presented without any optimization. Authors of [22] determined the soft open point (SOP) of distribution network with the aim of optimal operation of energy storage to mitigate overvoltage arising from high RES penetration. A method is proposed in [23] to optimize the location and size of the distributed energy storage system (DESS). The optimization function is based on best economical investment without considering energy price arbitrage. In [24], by considering high RES penetration, optimal sizing and operation of BESS is proposed to maximize the house independence from the grid and minimize the power flow peaks from and to the grid. An optimization method is developed in [25] for allocation of BESS in distribution system considering capital, land-of-use, and installation costs without taking into account the benefit of energy price arbitrage. Authors of [26] proposed an optimal planning approach for distributed energy storage to achieve better economic solution considering total power losses, but, without analyzing environmental effects. In [27], an optimization model is presented to minimize the net present value (NPV) of BESS and energy losses while reduction of environmental emission is not considered. Optimal location, capacity, and power rating of batteries are calculated in [28] to determine the economic technology by considering high RES penetration. Authors of [29] presented a strategy for optimal integration of BESSs by considering voltage regulation and loss reduction without taking into account the benefit of energy price arbitrage. An approach for proper utilization of the energy storage system to mitigate the effects of intermittent nature of PV has been presented in [30], but, optimal BESS planning is not included.

In the present work, it is assumed that distribution system operator (DSO) has got the ownership of BESS. Optimal placement, sizing, and operation of BESS are taken into account in LV distribution network considering high PV penetration. Optimal planning and operation of BESS is performed based on a cost function in order to make the BESS installation economical. In addition, sizing and sitting are done simultaneously with daily charge/discharge. Also, the objectives including energy price arbitrage, transmission access fee, energy losses, and environmental emission are taken into account simultaneously. The objective (cost) function consists of these objectives, and capital and maintenance costs of BESS. In this objective function, loss reduction and environmental benefits are converted to economic benefits. Other technical goals including reverse power flow and voltage regulation are considered as constraints.

Benefits of energy price arbitrage, environmental emission, and transmission access fee are maximized when BESS is charged in low energy price, emission rate, and transmission access fee and discharged while these rates are high. On the other hand, overvoltages that occur due to high penetration of PV are decreased by charging the BESS when PV systems produce maximum energy. Therefore, the optimal charge/discharge of BESS is complicated. In this paper, an auxiliary objective function is defined for increasing energy price arbitrage, reducing transmission access fee and environmental emission, and mitigating undesired impacts of high PV penetration by considering BESS constraints.

DIgSILENT and MATLAB are linked together because modeling of network equipment such as transformer, feeder, load, and power flow study are more accurate and realistic in DIgSILENT while MATLAB provides more powerful optimization tools.

2. BESS modeling

In the case of high PV penetration in LV distribution network, reverse power flow may occur when the PV production exceeds the consumers' load. This situation may lead to overvoltage and increase energy losses [4] (Fig. 1).

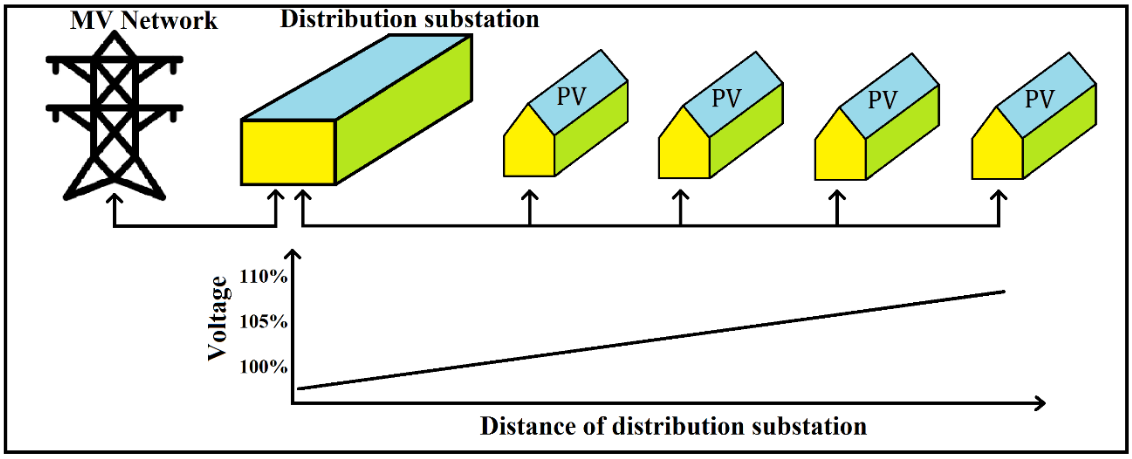

Fig. 1. Overvoltage by high penetration of PV

BESS can mitigate these disadvantages. Recently, thanks to the technological developments, the price of BESS is decreased, but still is high. As a result, economic, environmental, and technical objectives should be considered for planning and operation of BESS, in order to ensure its affordable utilization. Also, it should be noted that storing energy may take several hours. Furthermore, BESS should charge and discharge during each day. As a result, BESS needs to have features such as efficiency [31], low self-discharge, high cycle life, and low price.

Among popular BESS, the main drawback of Lead-acid batteries is their limited cycle life and the main disadvantage of Nickel–cadmium (Ni–Cd) cells is the presence of toxic heavy metal Cadmium [32]. Lithium-ion (Li-ion) batteries are mainly an option in short time scale applications, due to their relatively high daily self-discharge, between 1 to 5%. Vanadium Redox Battery (VRB) is a special type of flow batteries. Due to small self-discharge [32] per day, it is suitable for long storage duration such as hours or months. Also, VRB have the highest cycle life, and thus, are adopted in this paper. The cycle life is about 12000 [33] even if the battery depth of discharge (DoD) is 100%.

Technical parameters of VRB are summarized in Tables 1 [34].

TABLE 1. Technical parameters of VRB

Discharge time	Self-discharge per day	Suitable storage duration	Cycle life (cycles)	Efficiency (%)	specific energy (Wh/kg)	energy density (Wh/l)
Seconds–10 h	Small	Hours–months	12,000+	75	10–30	16–33

Considering losses of transformer, power convertor system (PCS), battery, and pumping, the VRB efficiency is assumed about 75% [35]. Since the specific energy and energy density are low, VRB is suitable for small and medium scale applications.

The cost of VRB is divided into module and electrolyte cost including the tank. The VRB has a low module cost and a relatively high electrolyte cost [36].

2.1. Capital and Maintenance Cost

BESS cost consists of capital and maintenance costs. Capital cost includes battery and power electronic system price. This cost is shown in (1)

$$C_{BESS} = \left(C_S S_{max} + C_{W_S} W_{max}\right) \quad (1)$$

where C_S includes PCS and balance of plant (BOP) costs. S_{max} is maximum power of BESS, C_{W_S} is the battery cost, and W_{max} is the maximum energy capacity of BESS. The PCS cost consists of the power converter, breaker, transformer, and all equipment necessary for serving the load and isolating the BESS. The BOP cost includes grid connection at the point of common coupling (PCC), land, and improvements (e.g., access, services, etc.) [37].

Maintenance and operating cost is shown in (2)

$$C_{M\&O} = (C_{Mf} S_{max} + C_{Mv} W_{max}) \quad (2)$$

where C_{Mf} and C_{Mv} are the fixed and variable costs for maintenance and operation.

Fixed operation and management costs include projected annual costs for BESS parts and labor, annual property taxes, and insurance. These costs for the PCS include standby losses and VRB maintenance in accordance with vendor recommendations. Variable operation and management costs include standby losses [37].

Maintenance activities include confirming the operability of system protective devices, calibrating sensors and instrumentation, inspecting for unusual vibrations, noise or odors, inspecting for abnormal conditions of connecting cables and piping, inspecting insulation resistance, servicing the battery controller, pumps, fans, and other system components [37].

2.2. BESS Constraints

For the best performance, the daily charged and discharged energies by considering BESS efficiency should be equal. This constraint is expressed as (3)

$$\sum_{i=1}^{24}\left(P_i^{B,d} - \eta_{BESS} \times P_i^{B,c}\right) = 0 \tag{3}$$

where $P_i^{B,d}$ and $P_i^{B,c}$ are discharge and charge rates of BESS in i[th] hour and η_{BESS} is BESS efficiency. As shown in inequalities of (4) the maximum power and energy capacity of BESS should be considered.

$$0 \le P_i^{B,d} \le S_{max} \; , 0 \le P_i^{B,c} \le S_{max} \quad \forall i \qquad , \quad \sum_{i=1}^{24} P_i^{B,d} \le W_{max} \tag{4}$$

Table 2 shows the economic parameters of the battery used [35].

TABLE 2. VRB parameters

C_S ($/kW)	426
C_{W_S} ($/kWh)	100
C_{Mf} ($/kW)	9
C_{Mv} ($/kWh)	0

3. Optimization function and constraints

As mentioned before, when PV penetration in LV distribution network increases, some problems may occur. Local BESS can improve these disadvantages. On the other hand, in order to ensure affordable BESS utilization, this paper introduces a cost function to increase benefit and mitigate the disadvantages. This cost function is expressed as (5) based on NPV:

$$CF = \sum_{n=1}^{N}\left([(B_{ARB} + B_{ENV} + B_{LOSS}) \times 365 + B_{TRANS} \times 12 - C_{M\&O}] \times \left(\frac{1+ir}{1+dr}\right)^{n}\right) - C_{BESS} \tag{5}$$

where B_{ARB} is energy price arbitrage benefit, B_{ENV}, B_{LOSS}, and B_{TRANS} are the profit of reducing environmental emissions, energy losses, and transmission access fee, respectively. As explained later, energy price arbitrage, environmental emission, and energy losses reductions are defined as daily profits which are multiplied by 365 to calculate the annual benefit. Similarly, since transmission access fee is set monthly, its benefit is multiplied by 12 to provide the annual profit. $C_{M\&O}$ is the maintenance and operation cost. Since BESS benefits and costs occur during the planning and operation horizon (here, N=25 years with respect to PV life expectancy [38] and BESS cycle life [33]), its value is multiplied by $\left(\frac{1+ir}{1+dr}\right)^{n}$ to calculate the present value. ir and dr are inflation and discount rates (respectively equal to 1.5% and 9% [39]) and n is the year that these benefits and costs occur. C_{BESS} is the capital cost. In order to optimize these benefits and costs more accurately, in this economic objective function, environmental benefit (B_{ENV}) and technical benefit (B_{LOSS}) are converted to economic benefits by rates of damage cost for emission and daily energy price (these rates are defined in Sections 3.2 and 3.4). In the following section, these benefits and costs are introduced.

3.1. Benefit of Energy Price Arbitrage

Energy price in restructured distribution systems is different for different periods; therefore, distribution company should charge and discharge BESS in low and high energy price, respectively to ensure a cost-effective BESS installation. The benefit of energy price arbitrage is expressed as (6), where $p_{r_{EN,i}}$ is the hourly energy price.

$$B_{ARB} = \sum_{i=1}^{24} \left(\left(P_i^{B,d} - P_i^{B,c} \right) \times p_{r_{EN,i}} \right) \quad (6)$$

3.2. Benefit of Environmental Emission Reduction

Traditional power plants are important sources for greenhouse (CO_2, CH_4, and N_2O) and toxic gases (SO_2, NO_2, and CO) [40]. Damage cost of power plant air pollutant covers health and environmental effects [41]. In this paper, climate changes are considered to model the damage cost of environmental emission. Most damages of climate changes are referred to CO_2 [42]. Damage cost for CO_2 can be divided into market and nonmarket impacts [43]. In this paper, it is assumed that damage cost for CO_2 is equal to 0.0257 $\frac{\$}{kg}$ [44]. CO_2 emission rate from marginal power plants is different for different hours of the day (see Fig. 2). BESS could be charged at the time of base load, i.e. less emission rate, and discharged in peak load to reduce environmental emission. On the other hand, PVs reduce greenhouse gas emission [45]. Therefore, emission rate of PV as a clean power plant can be set to zero. By increasing PV penetration, reverse power flow occurs in some hours. As previously mentioned, reverse power flow is prevented by optimization constraint. For this purpose, BESS should be charged in the periods with reverse power flow (i.e. charging with zero emissions rates in the time of surplus PV generation). Therefore, this energy does not cause environmental emission. As a result, the benefit can be expressed as

$$B_{ENV} = \sum_{i=1}^{24} \left(\left(P_i^{B,d} - P_i^{B,c} + P_i^{rev} \right) \times EMI_{rate,i} \times p_{r_{ENV}} \right) \quad (7)$$

where P_i^{rev} is hourly reverse power flow (divided by the number of batteries) before optimization, $EMI_{rate,i}$ is hourly CO_2 emission rate for typical operation schedule of power plants in a day, and $p_{r_{ENV}}$ is the damage cost of CO_2 emission.

3.3. Benefit of Transmission Access Fee

In deregulated power systems, distribution company should pay the transmission access fee for using transmission equipment. Transmission access fee varies at different hours of a day. Distribution company could charge and discharge BESS respectively in low and high access fees. Similar to benefit of environmental emission, no transmission access fee should be paid for BESS charging by reverse power. This benefit is expressed as below

$$B_{TRANS} = \sum_{i=1}^{24} \left(\left(P_i^{B,d} - P_i^{B,c} + P_i^{rev} \right) \times p_{r_{TRANS,i}} \right) \quad (8)$$

where $p_{r_{TRANS,i}}$ is hourly transmission access fee considered as the average value per month.

3.4. Benefit of Loss Reduction

When PV penetration is increased, the local energy production may be more than consumers'demand. As a result, power is reversed to the transmission network and voltage magnitude and energy losses may be increased. To cope with this problem, BESS is charged when production of PV is more than consumers'demand and discharged when consumers' demand is increased. This benefit can be modeled as (9)

$$B_{LOSS} = \sum_{i=1}^{24} \left(P_{LOSS\_LESS_i} \times p_{r_{EN,i}} \right) \quad (9)$$

where $P_{LOSS\_LESS_i}$ is hourly loss reduction in a day.

3.5. Technical Constraints

Technical constraints include voltage magnitude of the distribution system buses and reverse power flows expressed as (10)

$$0.95 < V_i^k < 1.05 \quad \forall i, \forall k \in N_b \quad , \quad P_i^{act} \leq 0 \quad \forall i \quad (10)$$

where V_i^k is per unit phase a bus voltage at node k of the studied network with N_b nodes and hour i of a day. Also, P_i^{act} is phase a active power of distribution transformer (MV/LV) at hour i of a day (i.e. active power should be negative which is equal to power consumption).

4. Optimal management approach

A solution method that combines the genetic algorithm with linear programing method (GALP) is proposed in this paper to find the optimal solution for number, placement, sizing, and scheduling of BESS [35]. In [35], GA is used to transform the cost function to an LP that can be solved by Simplex Method. GA and LP are run only in MATLAB. Modeling of network equipment such as transformer, feeder, load, and power flow study are more accurate and realistic in DIgSILENT than MATLAB. In addition, since data exchange between these two applications is time consuming, running GA in DIgSILENT increases the speed of optimization. Also, running LP in MATLAB is simpler than DIgSILENT. Therefore, in the present paper, GA and system modeling are performed in DIgSILENT and LP is run in MATLAB.

These software programs are linked together and results of one are used by the other.

The load demand expressed as per unit is shown in Fig. 2 that is measured by a power analyzer introduced in Section 5. To get hourly load demand, maximum demand of all buses are multiplied by load demand of Fig. 2. This figure also illustrates the daily measured power production of the PV in per unit. The rated powers of PV systems are multiplied by PV production of Fig. 2 to calculate hourly power production. Hourly CO_2 emission factor from marginal power plants, extracted from [46], is shown in Fig. 2, too.

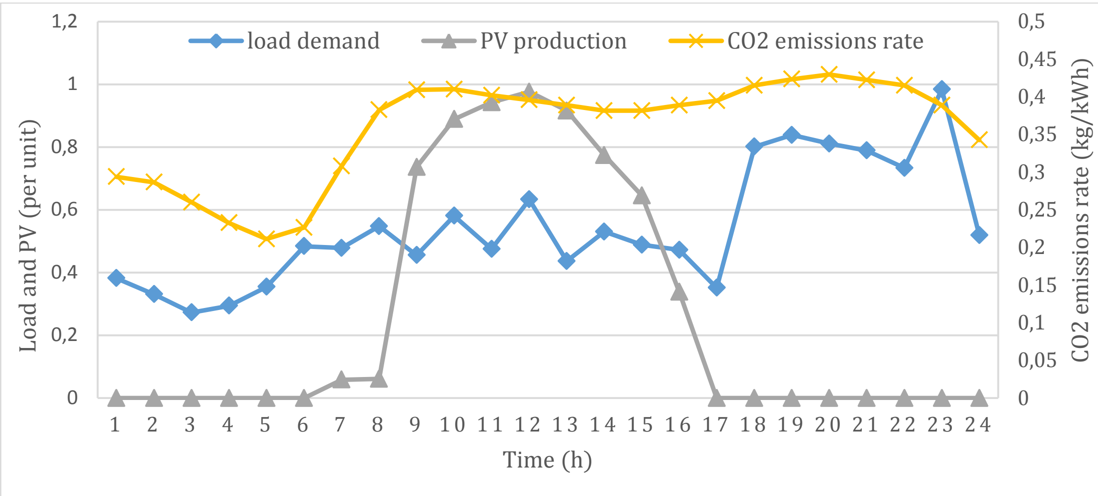

Fig. 2. Load demand (pu), PV daily power production (pu), and hourly CO_2 emission factor

Assumed hourly energy price [47] and transmission access fee [35] are shown in Fig. 3.

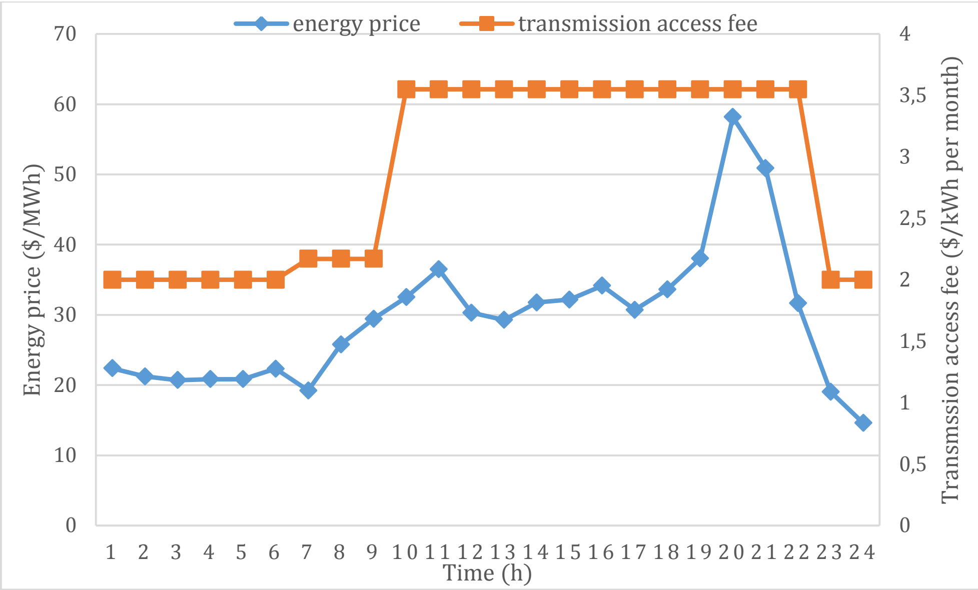

Fig. 3. Hourly energy price and transmission access fee

According to (6)-(8), the benefits are maximized when BESS charges in midnight because energy price, emission rate, and transmission access fee are lower than noon and sundown (see Figs. 2 and 3). On the other hand, overvoltage that is occurred by high penetration of PV is decreased when BESS is charged around noon (see Fig. 2) because PV systems produce maximum energy. As a result, optimal daily charge/discharge of BESS can be determined by an auxiliary objective function that is shown in (11). In this auxiliary objective function that should be maximized, constraints (3) and (4) should be taken into account.

$$OF = \sum_{i=1}^{24}\left(\left(\mathrm{P_i^{B,d}} - \mathrm{P_i^{B,c}}\right) \times \left[-\alpha \times \mathrm{P_{PV,i}}^{\mathrm{pu}} + (1-\alpha) \times \left(\frac{\mathrm{pr_{EN,i}}}{1000} + \left(\mathrm{EMI_{rate,i}} \times 0.0257\right) + \frac{\mathrm{pr_{TRANS,i}}}{30}\right)^{\mathrm{pu}}\right]\right) \tag{11}$$

where $\mathrm{P_{PV,i}}^{\mathrm{pu}}$ is the daily power production of the PV (pu) and α is a parameter ensuring that overvoltage is decreased and benefit of energy price arbitrage, environmental, and transmission access fee is increased. In order to convert all units to $^{\$}/_{kWh}$, $\mathrm{pr_{EN,i}}$ and $\mathrm{pr_{TRANS,i}}$ are divided by 1000 and 30, respectively, and

$EMI_{rate,i}$ is multiplied by 0.0257 (i.e. damage cost for CO_2). With $\alpha = 1$ the weighting factor of energy price, emission rate, and transmission access fee factor is equal to zero, therefore BESS will be scheduled based on the PV production. Because of negative sign in front of PV production factor, in order to maximize auxiliary objective function, BESS is scheduled in the opposite of PV production to charge surplus PV production. Thus, with $\alpha = 1$, only overvoltage is reduced. With $\alpha = 0$, the weighting factor of PV production is equal to zero. Therefore, because of positive sign in front of (1-α), BESS is scheduled to reduce emission rate and transmission access fee and increase energy price arbitrage. The optimal α is calculated between 0 and 1 based on objective functions (5) and (11).

In the first step of solving method, GA is run in DIgSILENT program language (DPL) and initial values of S_{max}, W_{max}, and α are determined and fed to MATLAB. Then, an auxiliary objective function that is shown in (11) is solved by the LP with considering constraints (3) and (4), therefore, optimal daily charge/discharge of BESS are calculated and fed to DIgSILENT. In the next step, number and placement of BESS are determined by GA in DPL. Then, the cost function of (5) is calculated considering the voltage magnitude and reverse power flow constraint obtained by unbalanced 3 phase load flow in DIgSILENT. This procedure continues for a preset maximum number of iteration (30 here). The flowchart of this method is shown in Fig. 4.

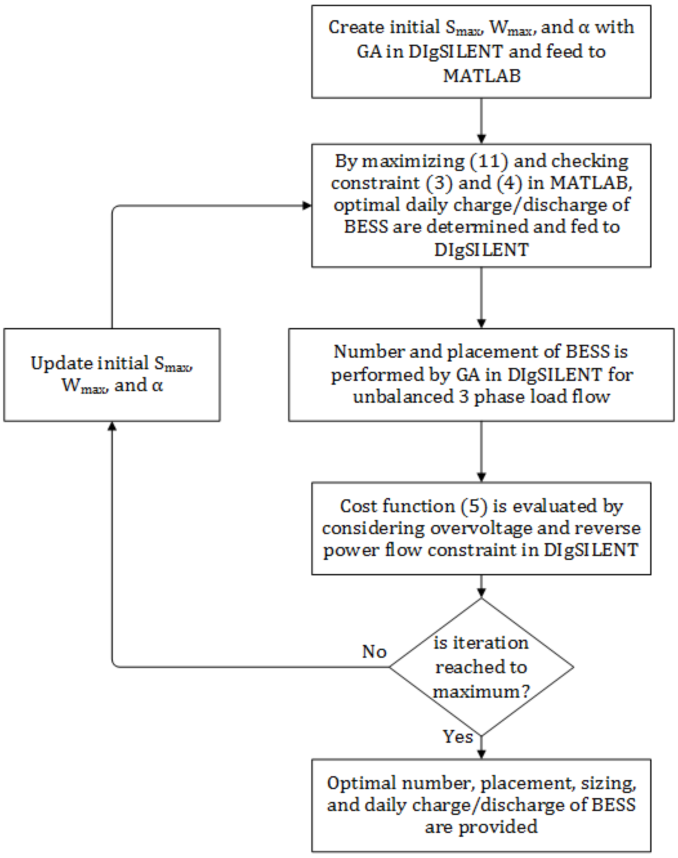

Fig. 4. Optimization flowchart

5. Simulation results

Fig. 5 portrays an unbalanced LV distribution system located in Yazd province, Iran. This system is connected to a medium voltage system through a 20 kV/ 0.4 kV transformer feeding 137 residential loads. In this network, 2 single phase PV systems each with the capacity of 5 kW are connected between phase *a* and neutral and located at the end of feeders. In the real distribution network, there are two PV systems named PV1 and PV2, however, PV3 and PV4 each with the capacity of 5 kW are also connected to the simulation study to make the effect of PV high penetration more pronounced. Furthermore, PV3 and PV4 are also connected between phase *a* and neutral to better evaluate their impact on voltage magnitude and feeder power.

In the simulation study, the impact of PV penetration increased to 93% (20 kW) is evaluated; PV penetration is defined as the ratio of total PV rating power to maximum apparent power of load. In this regard, note that total maximum active and reactive load for phase *a* of the distribution transformer is 19.6 kW and 9 kVAr, equal to 21.6 kVA.

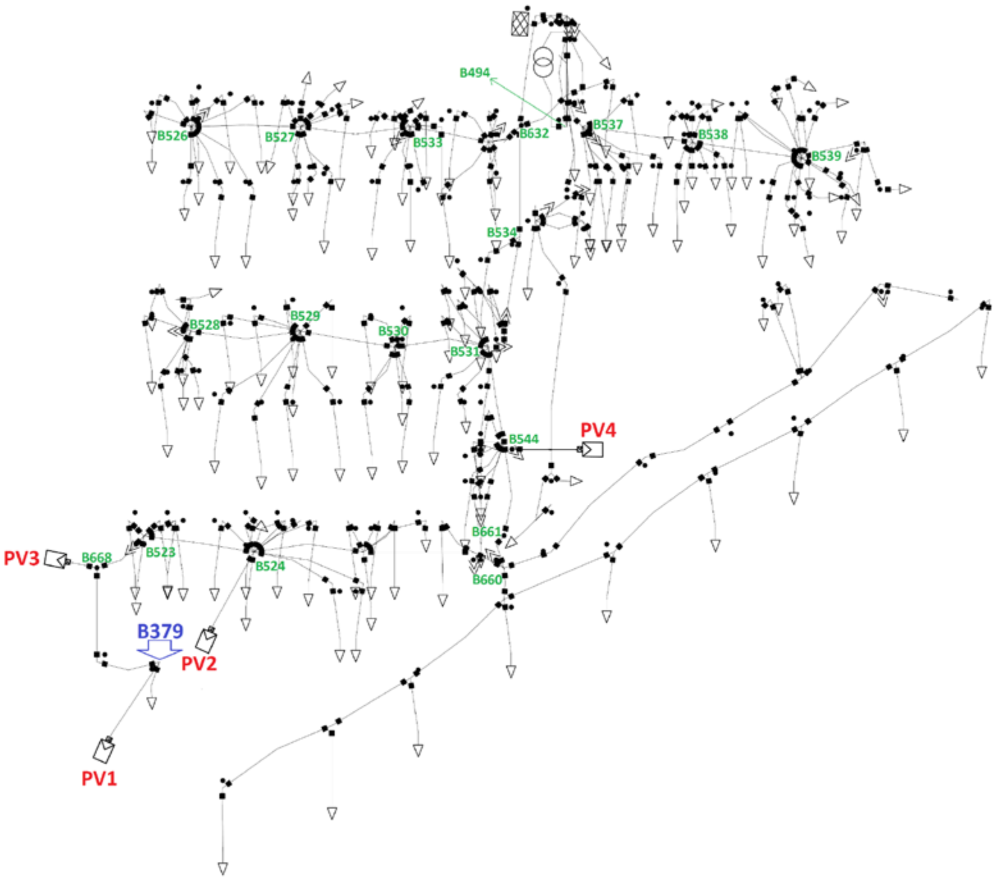

Fig. 5. Unbalanced LV distribution system located in Yazd province, Iran

In order to analyze the impact of PV on this distribution network, three power analyzers (CHAUVIN-ARNOUX C.A 8335) are used for measurement of PV1 and PV2 production as well as the imported active power at LV side of distribution transformer (phases *a* and *b*) within 10 days. The measured per unit data are shown in Fig. 6.

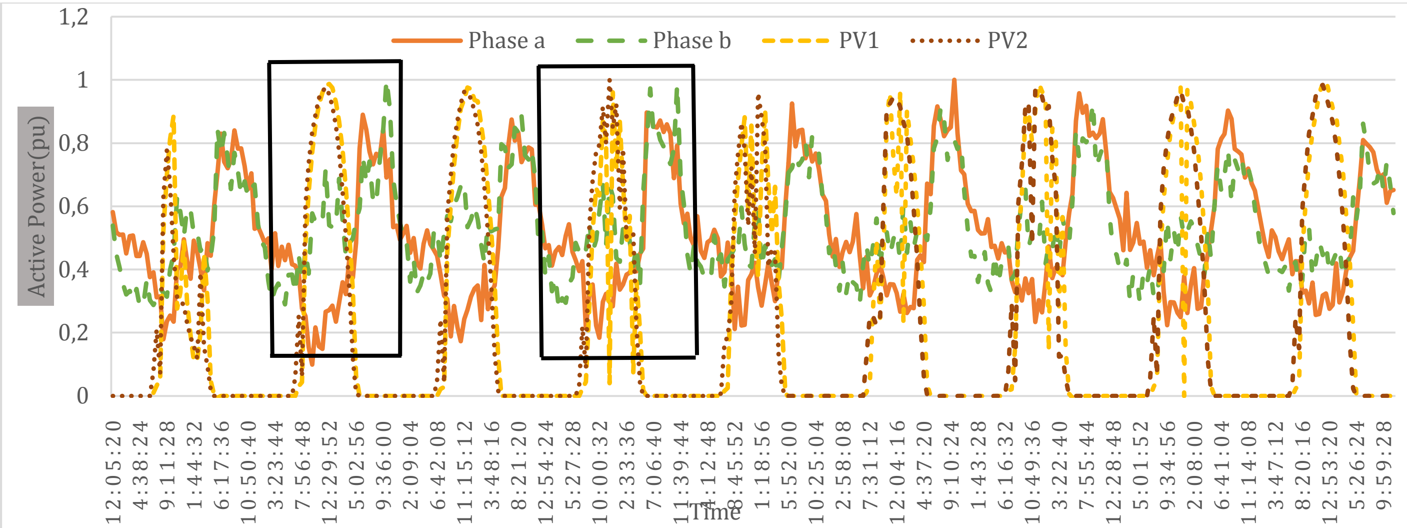

Fig. 6. PV1 and PV2 production (pu) and imported active power (pu) of phases *a* and *b*

It can be seen that imported power (from transmission system) of phase *a* is decreased during the PV production and its reduction is more on sunny days. To analyze the worst case, PV production is modeled by the second day (see Fig. 2). Load demand could be modeled by imported power in the situation where is not affected by PVs production. Since two PV systems are connected to phase *a*, phase *b* imported power is considered for load demand modeling. For example, the fourth day phase *b* imported power is used to model load demand (see Fig. 2)

Simulation scenarios are presented in Table 3.

TABLE 3. Simulation cases

Case	Description
1	Without PV and BESS
2	PV penetration=46% (PV1 and PV2) without BESS
3	PV penetration=93% (PV1, PV2, PV3, and PV4) without BESS
4	PV penetration=93% (PV1, PV2, PV3, and PV4) with optimal placement, sizing, and daily charge/discharge of BESS

It should be noted that all powers and voltages are calculated for phase *a*. The total daily energy losses, total reverse power flow, and maximum and minimum hourly voltage magnitudes for these cases are reported in Table 4.

TABLE 4. Comparison of cases

Case	Penetration	Total daily energy losses (kWh)	Total daily reverse power flow (kWh)	Maximum and minimum voltage hourly magnitude of B379 (pu)
1	0%	14.3	-	0.95 and 0.99
2	46%	16.3	0.6	0.95 and 1.03
3	93%	21.3	46.6	0.95 and 1.06
4	93%	18	-	0.95 and 1.04

Figs. 7 and 8 display phase *a* voltage profile at the furthest bus (B379) from transformer and imported power from transmission network for Cases 1-4, respectively.

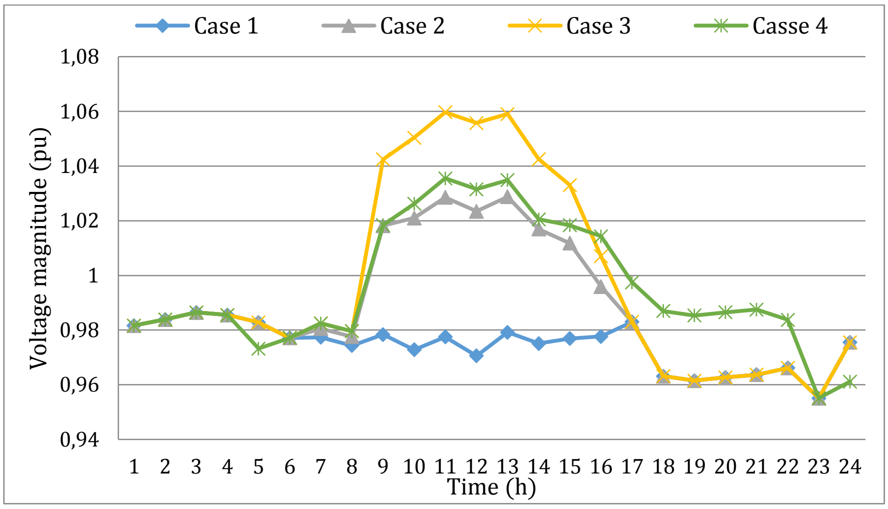

Fig. 7. Phase *a* voltage profiles of B379 in Cases 1-4

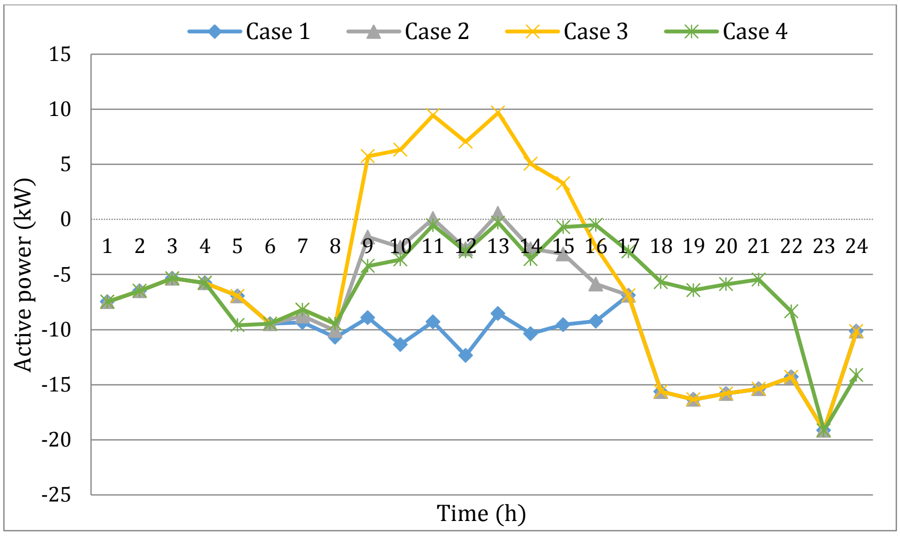

Fig. 8. Imported power from transmission network in Cases 1-4

Case 1

As shown in Table 4 and Figs. 7 and 8, the voltage magnitude at bus B379 drops to 0.95 pu at peak load. Undervoltage happens on 11 pm. The total daily energy loss is 14.3 kWh and power flow does not reverse to transmission network in any hour.

Cases 2 and 3

As shown in Table 4 and Figs. 7 and 8, by increasing PV penetration to 93%, the total daily energy losses increase and reverse power flow occur which the total daily values of Cases 2 and 3 are 0.6 kWh and 46.6 kWh, respectively. Also, the overvoltage at B379 is 1.06 pu in Case 3, that is marginally upper than voltage limit (i.e. +5%)

Case 4

In this case, the PV penetration is 93%. Based on the optimization results, Table 5 indicates optimal number, sizing, placement, and α of BESSs in LV distribution network.

TABLE 5. Candidate BESS

BESS Number	Power (kW)	Energy (kWh)	Bus Placement	α (%)
1	6	26	B530	61
2	4	26	B524	36

Simulation results indicate that by using both BESSs, voltage magnitude is limited within ±5% and power flow does not reverse to transmission system (as shown in Table 4 and Figs. 7 and 8).

As can be seen in Table 5, the energy capacity of BESSs is equal to 26 kWh; with respect to the specific energy and energy density range of VRB (see Table 1), weight and space required for each VRB are at least 900 kg and 800 m^3, respectively.

The optimal daily charge/discharge of BESSs are shown in Fig. 9.

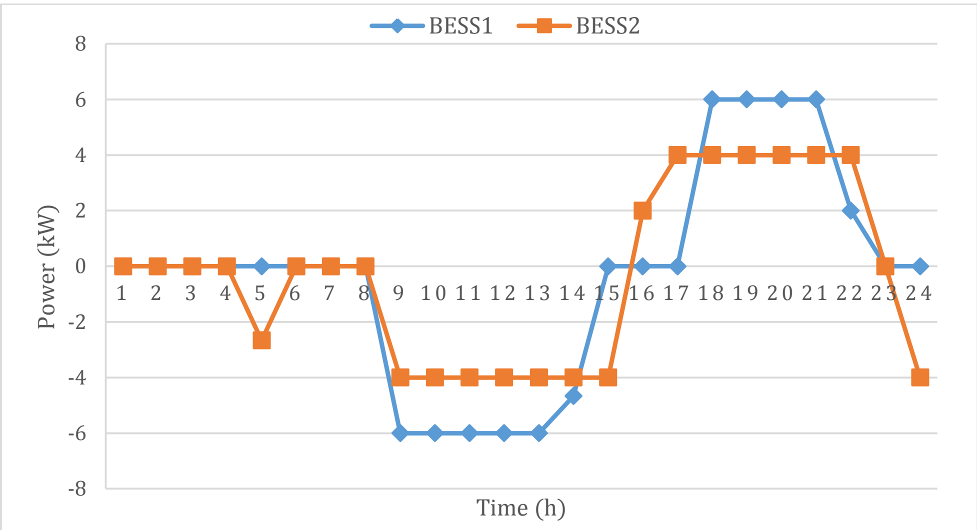

Fig. 9. Optimal daily charge/discharge of BESS

As depicted in Fig. 9, both BESSs are charged during high output of PV to decrease reverse power flow and overvoltage. Also, since BESS2 have less α rate, it is charged at low energy price, emission rate, and transmission access fee (5 am and

24 am) to maximize net benefit. On the other hand, BESS1 is only charged when PV production is high because of the higher α rate compared with BESS2. Furthermore, both BESSs are discharged at high energy price, emission rate, and transmission access fee to maximize the net benefit. Also, due to the BESS losses, the charged energy is more than discharged energy; accordingly if the BESS efficiency increases, the economic profit will be higher. As a result, in addition to self-discharge, cost, and cycle life of BESS, efficiency is an important factor in choosing battery type.

It can be inferred from Fig. 7 that in Case 4 during PV production, voltage magnitude is lower than Case 3 and stays within allowable limit due to proper charging of BESS. Undervoltages at 5 am and 24 am are more pronounced in Case 4 compared to Case 3 because BESS2 is charged in these hours to increase economic benefit. However, these undervoltages are within allowable limit. On the other hand, voltage magnitude in Case 4 during peak load, is higher than Case 3. As a result, the voltage profile in Case 4 is smoother than that of Case 3. In Fig. 10, hourly voltage magnitudes of some buses in Case 4 are shown.

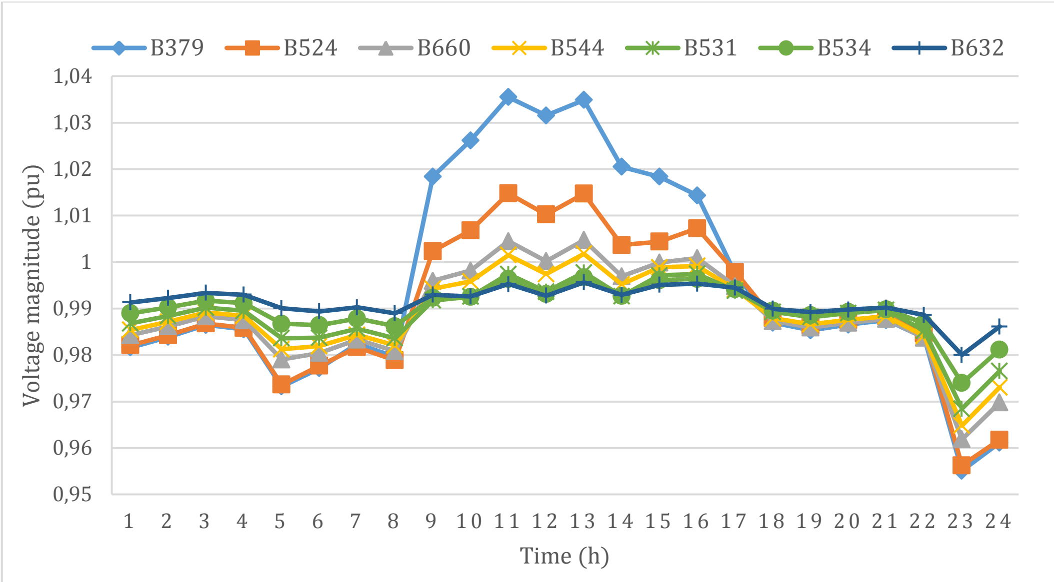

Fig. 10. Hourly voltage magnitude of Case 4

As can be seen in Fig. 10, by increasing PV penetration, voltage magnitude is increased in buses that are further from transformer; however, voltage magnitude is limited to ±5%.

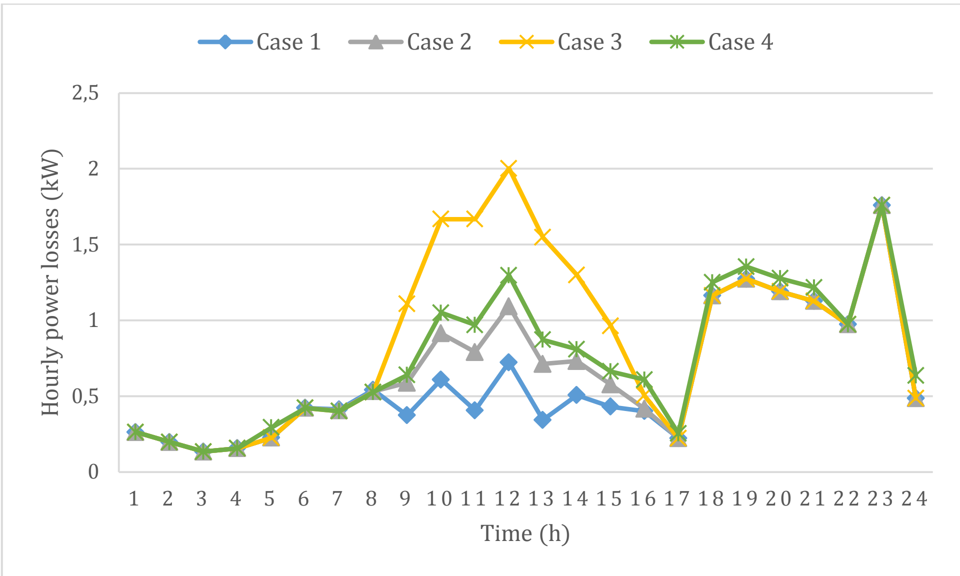

Fig. 11. Hourly power losses in Cases 1-4

The hourly power losses are shown in Fig. 11. It is observed in this figure that by increasing PV production in Cases 2 and 3, losses increase during PV production and in Case 4, the losses decrease compared with Case 3, because of BESS optimization. However, due to the BESS charging and discharging in Case 4, hourly losses increases at 4-6 am and 18-22 pm intervals.

The net benefit, daily reductions of losses, and environmental emissions are shown in Table 6.

TABLE 6. Net benefit, daily reductions of losses, and environmental emissions

Net benefit	**Daily reductions of losses**	**Daily reduction of environmental emissions**
7877.4 ($)	3.3 (kW)	13.4 (kg)

Table 6 shows that proper BESS planning and operation is beneficial and environmental emission is reduced. Also, daily energy losses decrease.

The convergence analysis of GA is performed and the results are shown in Fig. 12.

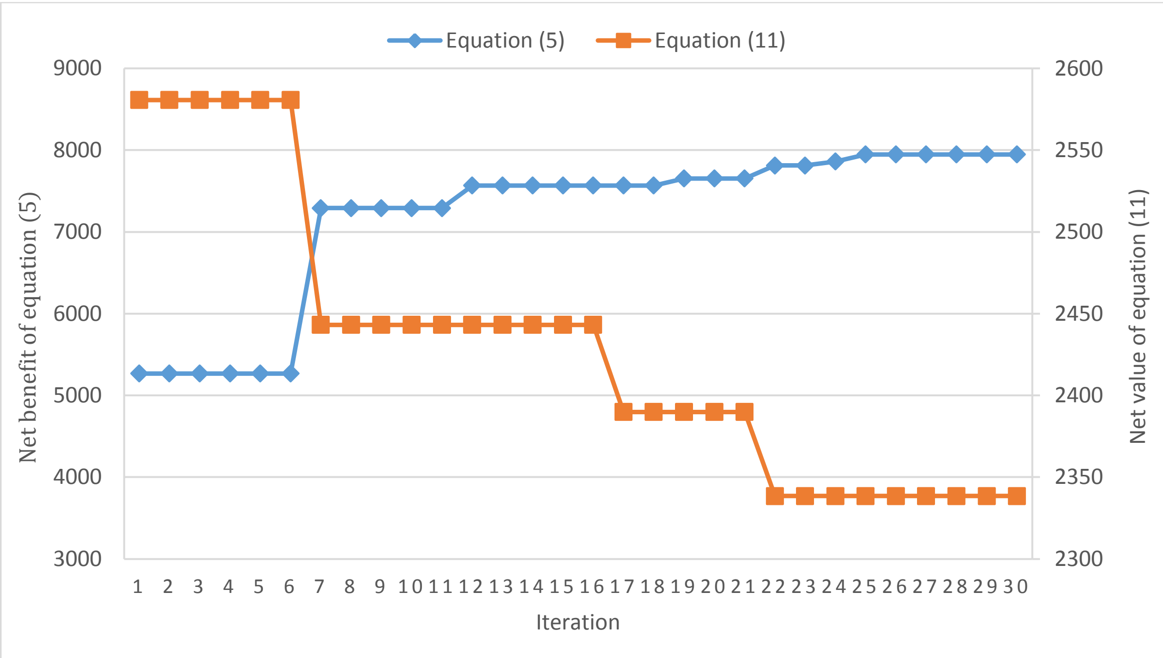

Fig. 12. Optimization process of GA

The population size and maximum iteration are 200 and 30, respectively. It can be seen that the iteration number is enough because the slope of increasing net benefit decreases gradually during iterations. Also, it is observed in Fig. 12 that by increasing the net benefit of (5), the value of (11) that models BESS operation benefit is decreased. Therefore, increasing benefit of operation does not lead to increase in net benefit of BESS optimization because net benefit also depends on capital and maintenance costs of BESS, loss reduction benefit, and technical constraints.

6. Conclusion

This paper proposed an optimal method for simultaneous placement, sizing, and daily charge/discharge of battery energy storage system which improved the performance of the distribution network to mitigate disadvantages of high photovoltaic penetration. Technical and environmental benefits were converted to economic benefit and thus, problem was expressed as a cost function. The optimization includes this cost function, an auxiliary objective function, and constraints of battery energy storage system, reverse power flow, and voltage magnitude. The optimization problem has been solved using genetic algorithm with linear programing method through linking DIgSILENT with MATLAB. Simulations were performed for a real unbalanced three phase distribution system and the results indicated the efficiency and viability of the proposed battery energy storage system optimization. It was shown that the battery energy storage system planning and operation was affordable and environmental emission was reduced.

Also, the results showed that proposed optimization limited the voltage magnitude of all buses in allowable range and prevented reverse power flow to transmission network. The energy losses were also decreased because of battery charging by surplus power of photovoltaics.

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