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A soft computing technique based on PSO algorithm and energy management strategy for optimal allocation and placement of PVDG-BES units

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ABSTRACT

In the pursuit of achieving a harmonious equilibrium between electricity production and consumption, the integration of distribution generators (DG) has garnered substantial attention. Yet, the escalated integration of DG systems has given rise to the predicament of reverse power flow, instigating elevated system power losses and voltage profile distortions. Thus, an imperative emerges to judiciously apportion and dimension DG systems, complemented by the incorporation of battery energy storage (BES) systems, as a remedial measure against these challenges. In this scholarly work, we present an innovative approach rooted in a precise energy management strategy (EMS) aimed at the adept allocation and capacity optimization of PVDG-BES systems. The study employs a two-step optimization methodology, the former facet of which expounds on the influence of BES system integration on grid power losses and voltage profiles during stable operational conditions. Subsequently, a pioneering optimization technique is formulated in the latter facet to identify the optimal siting and capacity allocation of the aforementioned system based on an optimal EMS framework. The primary focal point of this investigation is the minimization of total power losses. Validation of our proposition is conducted on the IEEE 14-bus standard system, incorporating the particle swarm optimization (PSO) algorithm. Simulation outcomes incontrovertibly affirm the efficacy and robustness of the proposed EMS, yielding substantive reductions in power losses and noteworthy enhancements in voltage profile integrity. Notably, the implementation of EMS leads to a remarkable 31% reduction in total power losses as compared to the initial scenario, prior to the amalgamation of PVDG-BES components. In sum, this study epitomizes a comprehensive strategy for fortifying power grid efficiency by orchestrating the symbiotic interplay of distribution generators and battery energy storage systems through an adept energy management paradigm.

1. Introduction

The deployment of PV distribution generation (PVDG) in the electrical network becomes the top cruciality of the current energy balance, due to its advantages in terms of pollution reduction and electrical energy generation. In fact, the penetration of DG unit in the electrical grid changes the power flow direction from unidirectional (from the source to consumption points) to bidirectional (from the source to consumption points and vice versa) which consequently led to the reverse power flow presence (Abdul Kadir et al., 2014; Majeed and Nwulu, 2022). This phenomenon engenders an escalation in both frequency and voltage fluctuations, as well as heightened power losses, among other consequences. The rectification of this issue mandates the incorporation of an energy storage system (ESS), exemplified by battery energy storage (BES) units. This challenge has elicited the attention of numerous researchers, as its resolution is pivotal in ensuring the robust stability of the electrical grid. The pivotal role of the aforementioned system lies in its capacity to curtail grid interventions by

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mitigating the net power exchange with the grid. Consequently, this serves to ameliorate the extent of reverse power flow.

However, the judicious determination of the optimal siting and dimensions of PV-BES systems necessitates meticulous consideration. This is imperative for enhancing and elevating the overall power grid quality and safety. A nuanced comprehension of this imperative involves the strategic identification of the paramount location and magnitude of these systems, primarily contingent on their demonstrated capability to diminish active power losses and enhance the grid's voltage profile.

Consequently, the mitigation of power losses at the point of interconnection mandates the meticulous orchestration and optimization of power flows among all components within the grid-connected PVDG-BES system. This strategic alignment aims to fulfill the designated objectives. Consequently, the deployment of an optimal strategy to systematically manage the power flow within the system assumes crucial significance. This pivotal facet is comprehensively expounded upon and meticulously explored within the context of this study.

In the literature, many endeavors have been realized and made by researchers to investigate power losses and voltage profile issues and to discuss several optimization methods, in order to obtain the optimal allocation and capacity of PVDG system (Khenissi et al., 2021b). These research studies are classified into three main objectives.

Most researchers investigate the allocation and size optimization of only the PVDG system in the distribution network and aim to demonstrate the effect of this integration on grid power quality and safety. In fact, Yang et al. (2021) have proposed a multi-objective function based on power losses, DG costs, pollution emissions, and system voltage profile to find the optimal size and position of a PV system in the standard IEEE 33 and 69 bus distribution systems. In addition, Dulău et al. (2016) have proposed an optimization approach to find the optimal placement of a 2.3 MW distributed generator (DG) in the IEEE 14 bus test system, with the aim of reducing power losses. To reach this target, the Newton-Raphson extended technique has been used in this study. Janamala (2021) used a novel meta-heuristic Pathfinder algorithm (PFA) to minimize power losses of the standard IEEE 33- and 69-bus systems after finding the optimal position of only the PV system. Added to that, a quantum particle swarm algorithm (QPSO) has been proposed by Guan et al. (2017) to reduce power losses and to improve voltage stability of the IEEE 33 nodes radial distribution network after obtaining the optimal allocation and capacity of (PV-Wind) system integrated to the aforementioned test system.

However, other studies provide the sizing of only the Storage Energy system and discuss its adding effect on electrical network security. Chedid and Sawwas (2019) proposed a novel approach to study the effects of integrating a battery energy storage system (BESS) into the IEEE 13-bus distribution network with the aim of reducing power losses based on the resolution of a multi-objective function using the Genetic Algorithm (GA). However, in Farsadi et al. (2015) an optimal position of battery energy storage (BES) is determined using the genetic algorithm, in order to minimize the net present value (NPV) under different load percentage levels and specific electricity prices.

The last category of research studies aims to optimally size, allocate and integrate (PV-BES) systems in the distribution network. Alzahrani et al. (2019) investigated the grid total losses issue with the aim of obtaining the optimal PV-BESS size and location in the standard IEEE 33 nodes test feeder using the GA as an optimization method. A new bi-level multi-objective function is used by Wankhede et al. (2022) to plan (PV-BES) systems' optimal size and allocation based on four parameters which are, life cycle cost, unused energy, integration level, and finally social welfare, and using the butterfly-PSO (BF-PSO) technique. In the same case, Radosavljević et al. (2020) have presented a hybrid meta-heuristic algorithm defined as the combination of the phasor PSO algorithm and the Gravitational Search technique, tested on the IEEE 69-bus distribution network and aims to reduce grid power losses and maximize the renewable distribution generator (RDG) owner profit after obtaining the best capacity and position of a (PV-BES) systems.

According to the mentioned literature review, the majority of research papers have focused on obtaining the optimal size and position of only the DG system such as PV or wind turbine (WT), and on analyzing the effect of this integration on grid quality and security. Further, other researchers have provided several studies to correctly size and install only the energy storage system.

However, the determination of the best place and capacity of a PVDG system including an ESS under daily energy demand and changeable weather conditions was not deeply explained and considered. Added to that, limited details have been presented to discuss and investigate the utility of an optimal energy management strategy (EMS) on the best setting of the PV-BES systems in the electrical network.

The primary objective of this research endeavor is to discern the optimal site and dimensions of a PVDG system combined with a battery storage system, guided by a meticulous energy scheduling optimization strategy. This strategic framework offers inherent advantages, yielding superior outcomes in terms of the mitigation of power losses and the augmentation of the voltage profile. It is unequivocal that the adept management of power flow interactions among all constituents within the system underpins the reduction of grid interventions and consequent prevention of reverse power flow. In contrast to the methods expounded upon in the preceding literature review, this study introduces distinctive contributions characterized as follows:

1. Introduction of a novel approach to ascertain the most advantageous placement and capacity of (PV-BES) systems predicated on an energy management strategy. Within this optimization strategy, the optimal location and capacity of the PVDG-BES ensemble are ascertained through the application of an objective function geared towards the curtailment of cumulative active power losses and the enhancement of the voltage profile. Addressing the power flow intricacies, the Newton-Raphson method is employed as a salient tool in this investigation.
2. Incorporation of an energy storage apparatus into the framework to systematically scrutinize the ramifications of this integration on grid security and quality.
3. Rigorous assessment of the robustness and credibility of the proposed approach is undertaken. This evaluation transpires within the context of the modified IEEE 14-bus system, encompassing scenarios of both steady and intermittent load demands, and its performance is juxtaposed against the outcomes of parallel research endeavors.

The ensuing sections of this paper are organized as follows: Section 2 delineates the contextual exposition of the problem at hand. The suite of optimization methodologies is unveiled in Section 3. Subsequently, Section 4 elaborates on the devised method, and, ultimately, Section 5 is dedicated to the comprehensive presentation and analysis of simulation results and ensuing discussions.

2. Problem explanation

The main goal and objective of this paper is to suggest a novel method to find the optimal site and size of (PV-BES) systems of the modified IEEE 14 bus distribution network, under fixed and intermittent PV power production and load consumption profile. In fact, this method is based on introducing an optimal power flow management strategy to optimally manage the energy flow between all system components and subsequently reduce grid power losses. To reach these goals, PV and BES systems should be integrated on the same point of connection to prevent power losses in case of the BES discharge and charge state (Raihani et al., 2019). To get a better understanding, a simple two buses example is taken and shown in Fig. 1. Where, in Fig. 1, V_i, V_j represent the voltage magnitude of the node i and j. R and X represent the resistance and the reactance of the line (i, j), P_{dg_i}, P_{load_i} are the power produced by the PV system and that consumed by loads. P_{bat_char} is the power stored in the energy storage unit during the charge state and $P_{bat\_dischar}$, represents the power taken from it during the discharge state. P_{loss_i} represents the power losses of the line (i, j).

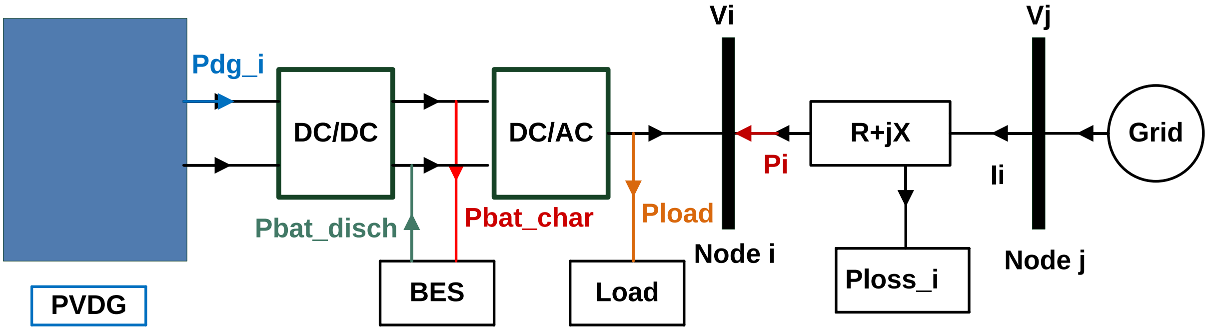

Fig. 1: Simplified diagram of the PVDG-BES systems connected to the grid

2.1. Objective function

The objective function used in this research paper is formulated as follows (Devabalaji et al., 2015):

$$\mathcal{F} = \min(P_{losses}) \tag{1}$$

$$P_{losses} = \sum_{i=1}^{M} P_{loss_i} = \sum_{i=1}^{M} R \times I_i^2 \tag{2}$$

where, M represents the line number, and R is the line resistance. However I_i represents the current of the line 'i.'

To solve this objective function, a number of constraints should be satisfied and taken into consideration such as:

- Power flow constraints: The power flow constraints during the discharge and the charge of the BES system can be given in Eqs. 3 and 4 respectively (Khenissi et al., 2021a):

$$P_i + P_{dg\_i} + P_{bat\_dischar} = P_{loss\_i} + P_{load\_i} \tag{3}$$

$$P_i + P_{dg\_i} = P_{loss\_i} + P_{load\_i} + P_{bat\_char} \tag{4}$$

- Voltage Bus V_i constraints (Ammous et al., 2015):

$$V_{i,min} \le V_i \le V_{i,max}, \quad |V_i| \le 1 \pm 0.1 \text{ pu} \tag{5}$$

- PVDG power P_{dg} constraints:

$$P_{dg,min} \le P_{dg} \le P_{dg,max} \tag{6}$$

$$P_{dg,min} = 1\text{MW}, P_{dg,max} = 5\text{MW}$$

- BES power P_{BES} constraints:

$$P_{BES,min} \le P_{BES} \le P_{BES,max} \tag{7}$$

$$P_{BES,min} = 1\text{MW}, P_{BES,max} = 4\text{MW}$$

3. System under study and optimization technique

3.1. Test system

Due to the availability of its data, the modified IEEE 14-Bus standard system is proposed and used in this paper. Its single-line diagram is shown in Fig. 2, where the initial total active and reactive power losses are 13.5 MW and 56.9 Kvar, respectively system (Khenissi et al., 2021b). This studied test system is composed of 9 loads, 3 synchronous condensers, and 2 generators.

3.2. Optimization technique

The particle swarm optimization algorithm is implemented in this work to determine the optimal position and capacity of both the PVDG system and BES unit, due to its simplicity and ease of implementation (Kumari et al., 2017). Moreover, it is considered the most powerful algorithm and technique that deals with discrete and continuous optimization problems (Nazaripouya et al., 2015). This optimization algorithm was discovered and proposed by the sociologist Doctor “James Kennedy” (Sayed et al., 2021) and is based on and inspired by the natural behavior of birds or animals. In PSO, the velocity and position of each particle j are updated at each iteration k, as follows (Sayed et al., 2021).

$$V_j^{k+1} = w \times V_j^{k} + C_1 \times rand \times \left(P_{best_j} - X_j^{k}\right) + C_2 rand \times \left(g_{best}^{k} - X_j^{k}\right) \quad (8)$$

$$X_j^{k+1} = X_j^{k} + V_j^{k+1}, j=1, 2, \ldots, m \quad (9)$$

where, m is the number of particles. w represents the inertia weight factor that should be less than 1. g_{best}^{k} and P_{best_j} are the best solution in the entire population and the best solution of the j th particle at iteration k, respectively. C_1 and C_2 represent the acceleration constants, where $C_1 + C_2 > 4$ (Sayed et al., 2021).

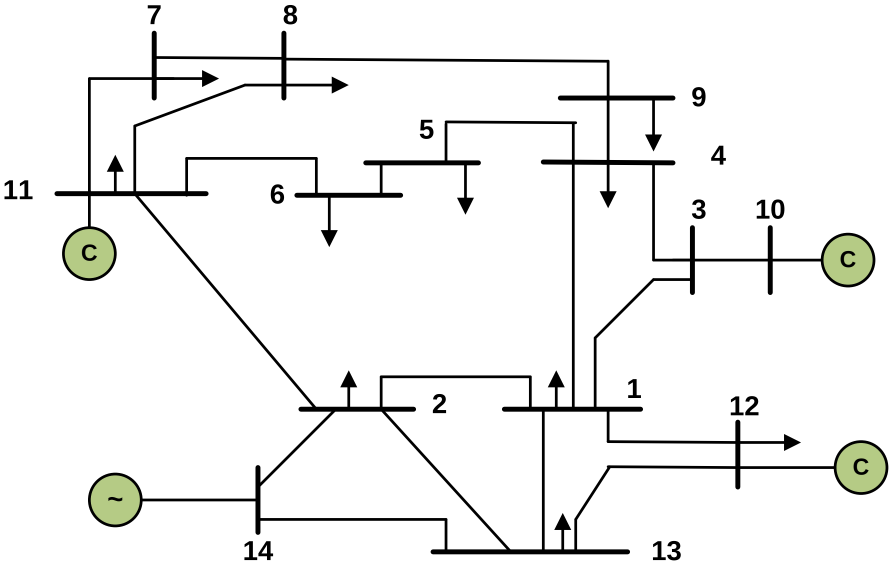

Fig. 2: System under study

3.3. The proposed method

As it is cited before, the main objective of this research paper is to determine the best size and allocation of a PVDG system and the BES unit of the IEEE 14 Bus distribution network after minimizing the total power losses. The determination of these losses depends on the location where the PVDG-BES systems are integrated and especially the size of each system. In fact, the reverse power flow presence is the principal cause of grid power losses. For this reason, an optimal strategy should be used to correctly manage the power flow between the grid, loads, the PV system, and the energy storage unit. This section elucidates the importance of using EMS for grid loss reduction, voltage profile amelioration, and load satisfaction. To get a better understanding, when the energy production is higher than the load demand at bus i, BES will be charged. However, if the energy production cannot cover all load needs, BES will provide power to these points of consumption. The principle of this strategy is presented and explained in Fig. 3. Hence, P_{bat_char} and $P_{bat\_dischar}$ willbe calculated and obtained to satisfy the constraints presented in 3 and 4. Subsequently, the best setting and capacity of the PV-BES will be determined. The different steps of the proposed strategy applied for the determination of the best size and allocation of a PVDG-BES unit are described in Fig. 4.

4. Simulation results and discussion

This section is divided into two main steps in order to analyze the integration level effect of PV-BES systems and the unsteady power demand on the total power losses and voltage profile. These two steps are presented as follows with the aim of finding the best allocation and capacity of a PV-BES system:

- Step 1: The number of the PV-BES system integrated into the electrical network changes from one to three PVDGs and the power demand of each node is the same and constant during 24h.
- Step 2: In this part, the number of the PV-BES system integrated into the electrical network is fixed. However, the power consumed by each load as well as the atmospheric conditions, are variable during 24 hours.

Technique optimization parameters as well as PV-BES characteristics are presented in Table 1.

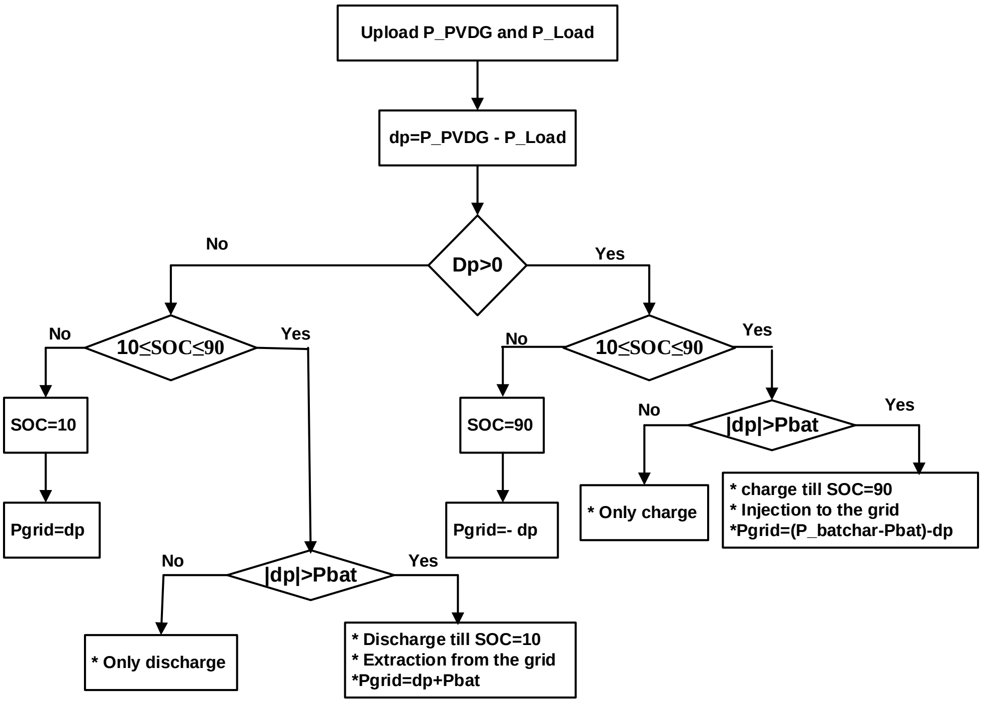

Fig. 3: Proposed power flow management strategy

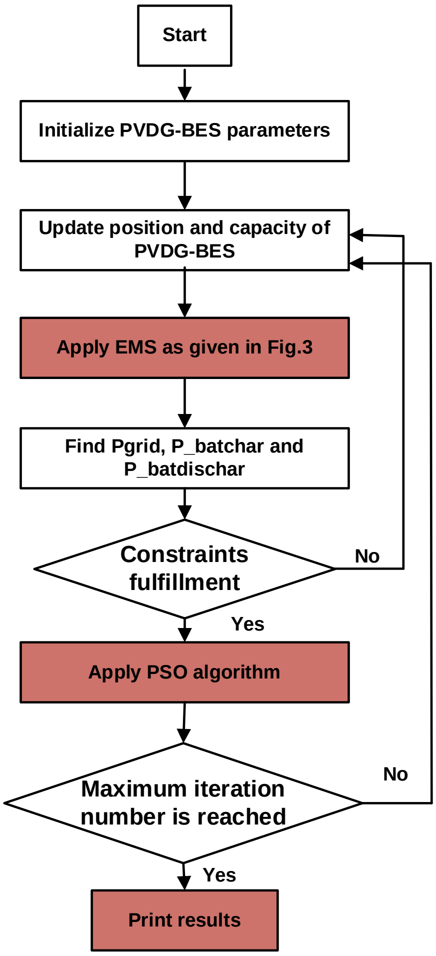

Fig. 4: Proposed method flowchart

4.1. First case: Variable PV penetration level with steady PV-generated power and load demand

Fig. 5 presents the convergence characteristic of the objective function F after the integration of three PV system levels using the PSO optimization algorithm.

Table 1: PSO parameters

PSO parameters	Maximum number of iterations	Population number	w	C_1=C_2
Value	50	100	0.9	0.73

As delineated in Fig. 5, it becomes evident that the PSO algorithm attains convergence towards the optimal solution with remarkable rapidity, reaching the optimized state within 2 iterations for 'case a,' 8 iterations for 'case b,' and 4 iterations for 'case c.' This compellingly underscores the efficacy of this approach in terms of expeditious convergence to the optimal solution. Furthermore, a discernible trend emerges from the data: the aggregate power losses are notably curtailed to 0.12981 p.u, 0.1165 p.u, and 0.109 p.u following the sequential incorporation of a solitary PVDG, two PVDGs, and three PVDGs, respectively.

In summation, a pivotal inference can be drawn; as the count of grid-interconnected PVDG systems escalates, a concomitant reduction in total power losses is evidenced. This empirically verifies the influence of varying levels of Photovoltaic (PV) integration on the amelioration of grid power losses.

Fig. 6 presents the convergence characteristics of the same objective function after the BES inclusion. The aim of this part is to explain the importance of using the storage element and to highlight the effect of this integration on power loss reduction.

According to Fig. 6, it is clear that the PSO algorithm converges to the best solution at the 3rd iteration, 18th iteration, and also at 18th iteration for cases a, b, and c, respectively. It can be seen also that power losses are reduced from 0.12981 pu to 0.12679 pu, 0.1152 p.u, and 0.1081 pu after integration of 1(PVDG+BAT), 2(PVDG+BAT) and 3(PVDG+BAT), respectively. That explains the important role of the BES system in the electrical network quality amelioration enhancement, in terms of power losses reduction. All the obtained results are presented in Table 2 and Table 3.

Fig. 7 shows the voltage profile of all test system buses after the integration of only the PVDG 1 and PV-BES systems as presented in (a) and (b), respectively. According to Fig. 7, it is clear that the voltage profile of the test system is ameliorated for the two cases (a) and (b). In fact, this enhancement is considered only in PQ nodes, where loads are connected to these buses. In addition, the voltage magnitude at all system nodes is within the permissible limits (1±10%). Added to that, it can be noted that, the more the number of the PV system or PV-BES systems increase the more the voltage buses amelioration increase. Then, as shown in (b), when the storage element is added to the grid-connected PV system, the voltage profile of all nodes is more ameliorated compared to (a). Taking for example the fifth node, the voltage magnitude of this node is increased from 1.0268 pu to 1.031 pu after integrating 1 PVDG system, then, it is ameliorated to 1.034 pu when 1(PVDG+BES) system is connected to the optimal placement. In conclusion, adding batteries to the electrical network can also ameliorate its voltage profile.

4.2. Second case: Changeable atmospheric conditions and variable daily load demand

In this step, atmospheric conditions such as the temperature and the irradiation are variable during 24h and are given in Fig. 8 and Fig. 9, respectively. Added to that, the energy consumption profile, of all loads, changes during the 24h. It can be noted that the aim of this subsection is to highlight and explain the effect of variable weather conditions and changeable energy consumption profiles on obtaining the best sitting and capacity of the PV-BES systems. To reach this target, the proposed strategy presented in Fig. 3 is employed and used to correctly manage the energy flow between all system components and thus to find the aforementioned optimal solutions. Fig. 10 represents the convergence characteristic of the objective function using the PSO algorithm and after integrating only 1 PVDG-BES system under variable atmospheric conditions and intermittent loads consumption profile.

According to Fig. 10, the PSO algorithm converges to the optimal solution at iteration 4, added to that, the optimal position of the PVDG-BES is bus number 1 and the best capacity is 5MW for the PV system and 4 MW for the BES unit. According to this allocation and size, the minimum of total power losses is equal to 0.0931 pu. In fact, these results are compared with other research outcomings (Khenissi et al., 2023) wherein the genetic algorithm (GA) is used as an optimization technique. According to these results, the proposed method applied in this research paper presents better performance compared to the GA in terms of power loss reduction. That proves the efficiency and robustness of this method.

Table 4 explains the effect of using variable weather conditions as well as variable loads demand on power losses, optimal site, and size of the PV-BES systems.

From Table 4, it is clear that grid power losses, the best site, and size determination of the DG depend on weather conditions and particularly the load consumption profile.

Fig. 11 represents the voltage profile of all system buses after using the fixed (Red curve) and the specific load consumption profile (Green curve). In fact, the aim of this step is to explain and analyze the effect of using variable atmospheric conditions and intermittent load demand on the grid voltage profile.

As shown in Fig. 11, it is clear that the voltage profile is enhanced after the integration of the PVDG-

BES system, especially when intermittent load demand and variable climatic conditions are used. Taking for example the fifth node, it is much more improved using the variable conditions compared to fixed load and atmospheric conditions profiles. However, it is always still in the acceptable interval, which is ±10%. That proves the positive effect of the PVDG-BES systems integration on the voltage profile amelioration.

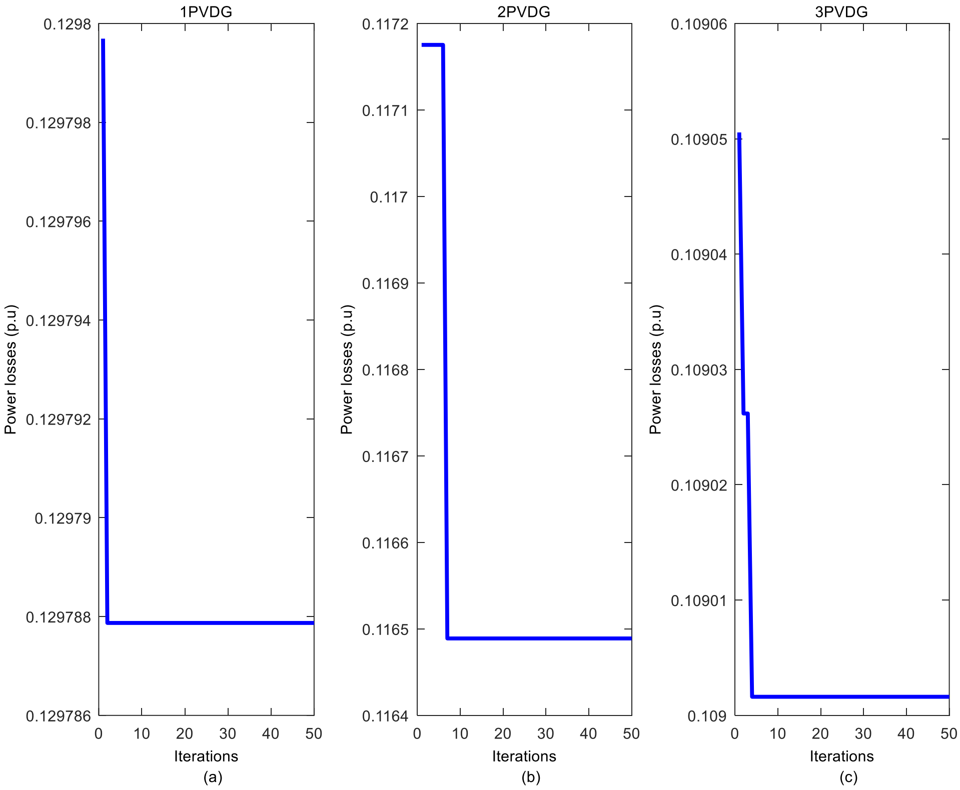

Fig. 5: Convergence characteristic of the objective function using only the (a) 1PV, (b) 2PV, and (c) 3PV systems

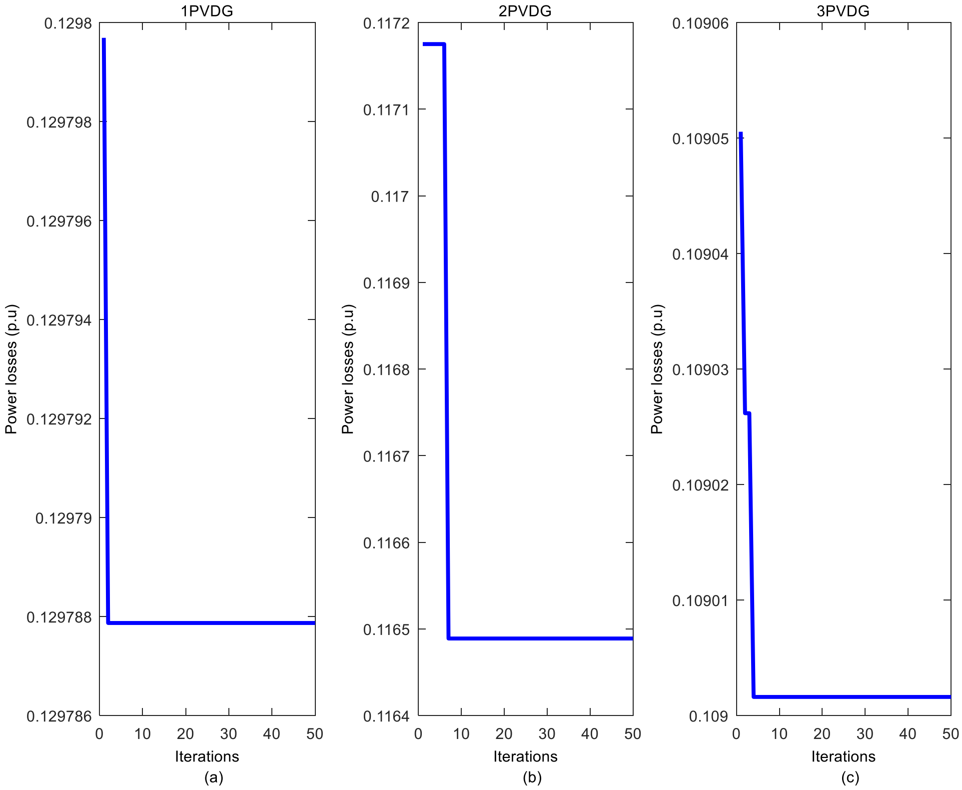

Fig. 6: Convergence characteristic of the objective function using (a) 1(PV-BES), (b) 2(PV-BES), and (c) 3(PV-BES) systems

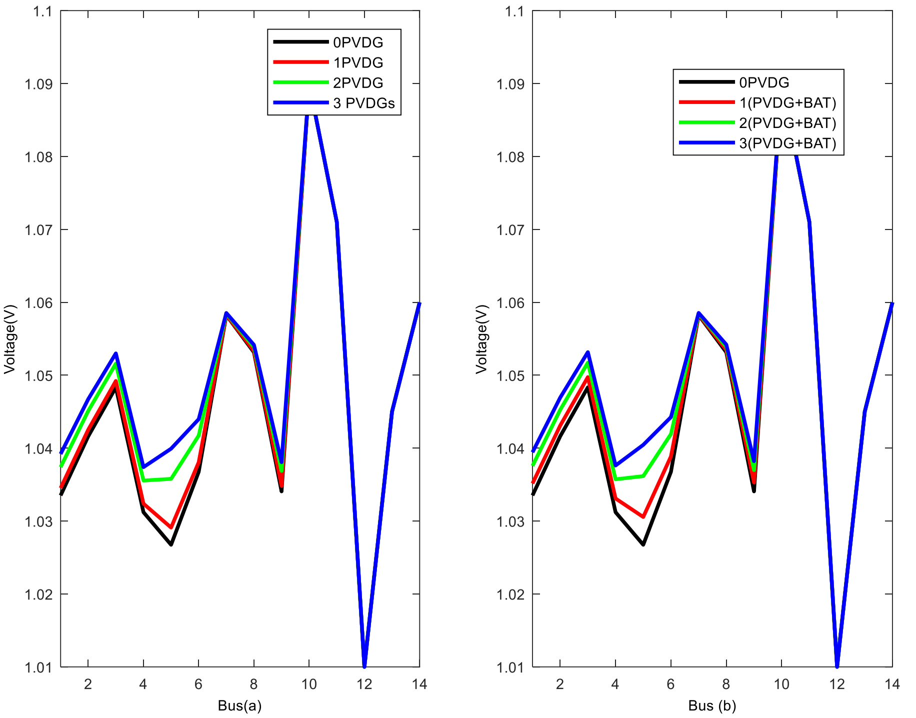

Fig. 7: Grid voltage profile after integrating only (a) PV and (b) PV-BES systems

Table 2: Various integration levels of PVDGs results

	1 PV	2 PV		3 PV		
		1st PV	2nd PV	1st PV	2nd PV	3rd PV
Best position	5	5	8	5	6	4
Best size (MW)	4	4	3	4	1.37	3.64
P_{losses}(p.u)	12.98	11.65		10.9		
Reduction (%)	3.8	13.7		19.25		

Table 3: Various integration levels of PVDG-BES systems results

	1 PV-BES		2 (PV-BES)				3 (PV-BES)					
	PV	BES	1st PV	1st BES	2nd PV	2nd BES	1st PV	1st BES	2nd PV	2nd BES	3rd PV	3rd BES
Best position	5		5		4		5		7		2	
Best size (MW)	4	3.5	3.22	3.49	1.43	3.93	3.96	3.34	3.96	3.71	1.53	3
P_{losses}(p.u)	12.679		11.52				10.81					
Reduction (%)	6.08		14.66				19.392					

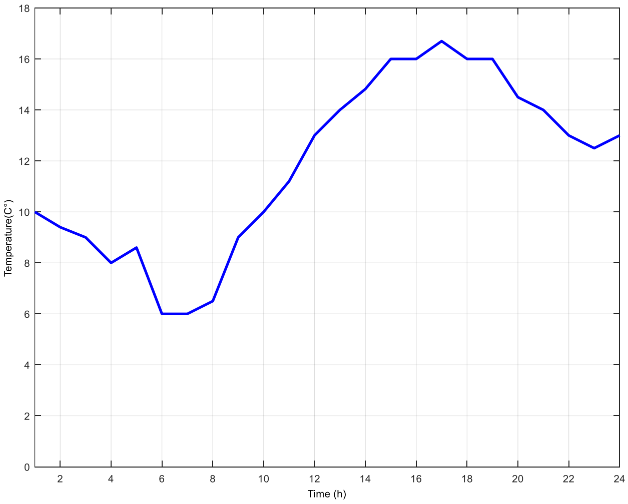

Fig. 8: The daily temperature profile

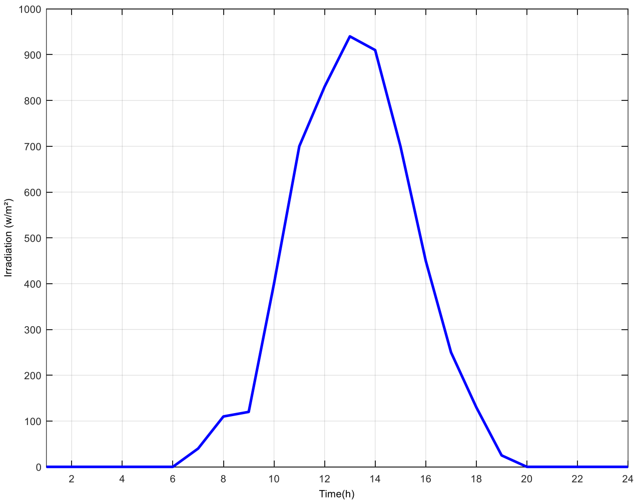

Fig. 9: The daily irradiation profile

Table 4: PVDG-BES systems integration results

1 (PVDG+BES)	P_{losses}(p.u)	Best position	Best size(MW)		Reduction (%)
			PV	BES	
PSO	9.31	1	5	4	31
GA (Khenissi et al., 2023)	9.53	4	1.5	1.5	29.3

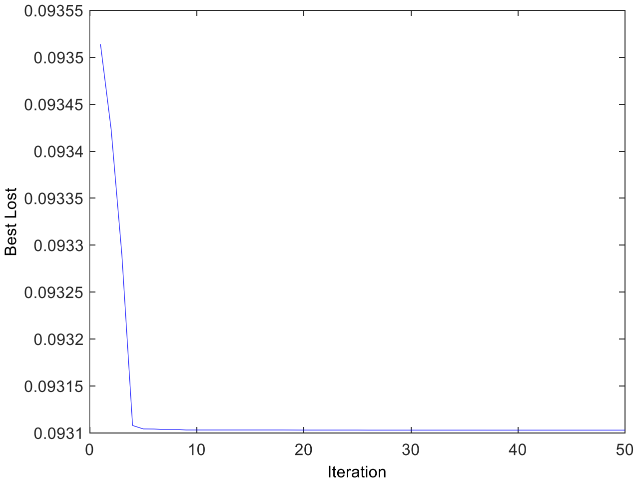

Fig. 10: Convergence characteristics of the objective function using 1 (PV-BES) systems

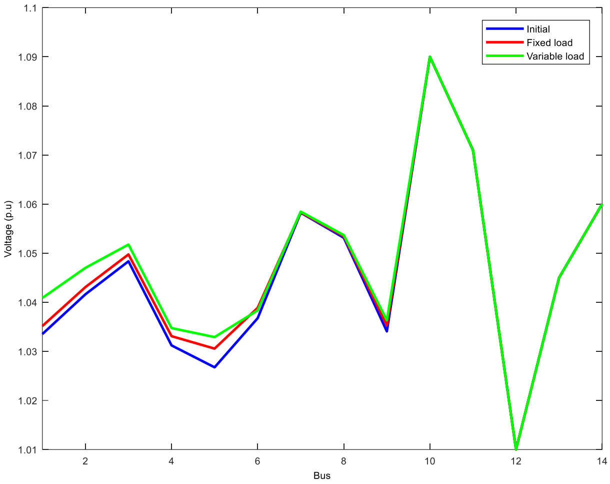

Fig. 11: Grid voltage profile

Fig. 12 presents the variation of grid power losses during 24h with and without a power flow management strategy. It can be noted that the grid power loss profile is reduced after using the optimal power flow management strategy (Green Curve) compared to the initial state (without EMS). That proves the efficiency of this strategy on the total power losses.

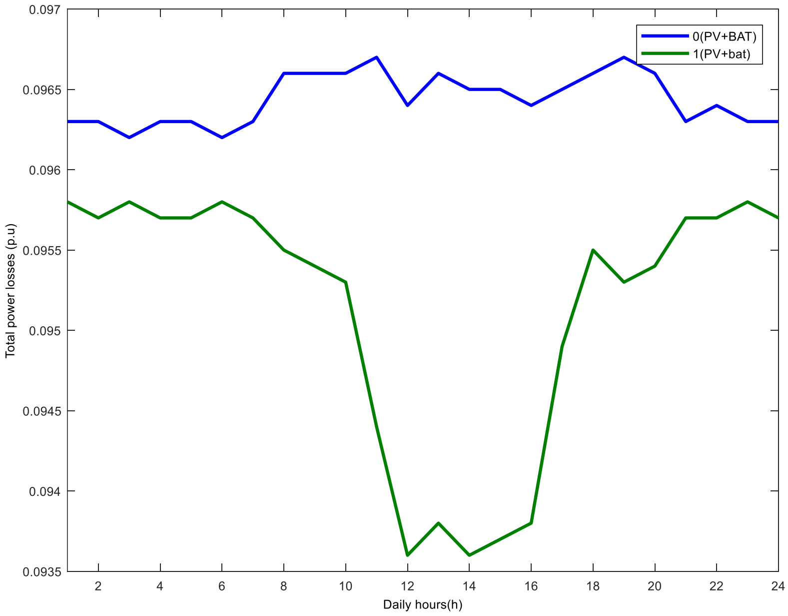

Fig. 12: Grid power losses variation

5. Conclusion

The advancement of scientific knowledge and the rapid expansion of the global population have engendered a substantial augmentation in the demand for power. In light of this, the integration of DG units within the distribution network is viewed as a pivotal stride toward meeting the escalating electricity demand. As such, this paper meticulously deliberates upon the judicious allocation and sizing of PVDG-BES systems. Notably, the introduction of a BES system to a grid-connected PV framework emerges as a key focus, aimed at comprehending and elucidating its profound impact on the reduction of power losses.

An optimal strategy for power flow management is proposed and implemented herein, orchestrating the seamless interaction among all components within the system. This endeavor effectively curbs grid interventions and concomitant power losses. The overarching objectives of this research endeavor encompass the minimization of cumulative power losses and the enhancement of the voltage profile.

To ascertain the resilience and viability of the proposed strategy, comprehensive assessments are conducted across varying conditions encompassing the IEEE 14-bus system, accounting for both stable and fluctuating weather conditions and dynamic load demand profiles. Through rigorous comparison with parallel research initiatives, simulation outcomes corroborate the superiority of the proposed strategy, rooted in an accurate Energy Management Strategy (EMS), in terms of augmenting voltage profiles and mitigating grid power losses.

As future research avenues, the exploration of alternative optimization methodologies is envisaged, aiming to pinpoint the optimal site and dimensions of diverse DG systems, spanning both active and reactive power generators. This endeavor reflects the commitment to an ever-evolving pursuit of advancements in this critical domain.

List of symbols

C	Acceleration constants
g_{best}^{k}	Best solution for the kth iteration
I_i	Current of line 'i'
m	Particle number of PSO algorithm
M	Line number
R	Line resistance
X	Line Reactance
P_{dg_i}	Power produced by PV system
P_{load_i}	Power consumed by loads
P_{bat_char}	Amount of power provided by batteries
$P_{bat\_dischar}$	Amount of power stored in batteries
P_{loss_i}	Power losses in line 'i'
P_i	Power injected in line 'i'
P_{losses}	Total power losses
pu	Per unit
V_i	Voltage magnitude of node 'i'
V_j	Particle velocity of the jth iteration
$V_{i,min}$	Minimum voltage magnitude supported by node 'i'
$V_{i,max}$	Maximum voltage magnitude supported by node 'i'
$P_{dg,min}$	Minimum power produced by PV system
$P_{dg,max}$	Maximum power produced by PV system
$P_{BES,max}$	Maximum power stored in batteries
$P_{BES,min}$	Minimum power stored in batteries
X_j	Particle position of the jth iteration
w	Inertia weight factor
SOC	State of the charge

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Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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