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Optimal Placement of Second-Life Battery Storage in Transmission Grids: A PSO-Based OPF and Carbon Footprint Analysis

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Abstract

With the growing adoption of electric vehicles, second-life applications of batteries that have completed their service in EVs are gaining importance. This study aims to enhance power quality and reduce losses in the grid by integrating a 2 MWh energy storage system (ESS) composed of second-use batteries. The IEEE 30-bus test system was employed to examine the effects of second-life ESS integration on active power losses and voltage profiles. ESS units were tested at multiple bus locations, and Optimal Power Flow (OPF) analyses were performed to identify the bus providing the lowest losses. The optimal placement was determined using the Particle Swarm Optimization (PSO) algorithm. Additionally, the environmental impact was evaluated, showing that second-use battery integration supports both technical efficiency and sustainability. The results indicate that reusing EV batteries in grid applications is a promising solution to reduce network losses and carbon emissions while aligning with circular economy principles.

Key words: Second-use battery, grid enhancement, optimal power flow, sustainability, optimal battery placement

1. Introduction

The rapid integration of renewable energy sources into power grids, alongside the widespread adoption of electric vehicles (EVs), has introduced new dynamics that demand advanced solutions for enhancing flexibility and resilience in modern power systems. The variable nature of renewable generation, coupled with the growing demand for EV charging, imposes substantial stress on existing grid infrastructure [1]. In order to meet decarbonization and electrification targets, energy storage systems (ESS) play a critical role in ensuring grid stability by providing load balancing, frequency regulation, and voltage profile enhancement functions [2]. Second-use battery systems, repurposed from EV battery modules that have reached the end of their primary life cycle, offer a cost-effective and environmentally sustainable alternative to conventional ESS technologies [3]. Extending the life cycle of these batteries also contributes to reducing the environmental impact associated with new battery production, supporting circular economy principles [4]. In particular, the integration of second-use batteries into power grids is considered an effective solution for minimizing active and reactive power losses, improving voltage profiles, and facilitating renewable energy integration [5]. Recent studies have highlighted the technical and environmental benefits of second-use battery systems. For instance, Chen et al. (2023) demonstrated that integrating second-life batteries into distribution grids could reduce network losses by up to 15% while also lowering CO_2 emissions [6]. Similarly, Martínez-Lao et al. (2023) showed that second-use batteries

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significantly enhance voltage stability, particularly in weak grid conditions [7]. However, determining the optimal placement of such systems within the network is a complex and nonlinear optimization problem. In this context, metaheuristic algorithms such as Particle Swarm Optimization (PSO) are widely employed to address such challenges [8]. In this study, a second-use battery energy storage system (BESS), composed of reclaimed EV battery modules, is integrated into the IEEE 30-bus test system to evaluate its potential in reducing active power losses and improving voltage profiles. Using an OPF-based PSO approach, the most suitable placement of the ESS within the grid is determined, and both technical performance and environmental impacts, including carbon footprint reduction, are assessed. The study presents a comprehensive framework that simultaneously addresses sustainability and performance objectives in modern power systems.

2. System Modelling and Methodology

The integration of second-use battery energy storage systems (BESS), repurposed from electric vehicles (EVs), into distribution grids requires comprehensive modeling that considers the dynamic characteristics of these batteries and their interaction with power systems. Given their cost-effectiveness and environmental benefits, second-use BESS are increasingly being investigated as a viable solution for grid modernization and flexibility enhancement [9]. In this study, the IEEE 30-bus test system is selected as a representative distribution network model to evaluate the effects of second-use BESS integration on power losses and voltage profiles. An Optimal Power Flow (OPF) problem is formulated to minimize active power losses, and a Particle Swarm Optimization (PSO)-based approach is employed to determine the optimal placement of the BESS units within the grid. This section presents a detailed framework for modeling the characteristics of second-use BESS, the formulation of the OPF problem, and the metaheuristic optimization strategy adopted in the study.

Table 1. IEEE 30 Bus Technical Parameters

Parameters	Value	Description
Total Bus Number	30	Total number of bus in the system
Toplam Branch Number	41	Total transmission line in the network
Toplam Production Units	6	Main generators (G1-G6)
Load Bus Nmber	24	Load-bearing bus, excluding production bus
Toplam System Load	283.4 MW / 126.2 MVAr	Total active and reactive load in the system
System Voltage Level	132 kV nominal voltage	Voltage base value of the network
Minimum Bus Voltage	0.95 p.u.	Minimum bus voltage after OPF

Max Bus Voltage	1.05 p.u.	Maximum bus voltage after OPF

2.1. Second Use Battery Grid Applications

Second-use battery energy storage systems (BESS) play a strategic role in enhancing the flexibility and reliability of distribution and transmission networks. Battery modules retired from electric vehicles are increasingly utilized in energy storage systems due to their remaining capacity and cost-effectiveness. These batteries are most commonly employed in grid applications such as peak shaving, frequency regulation, voltage support, and loss minimization [10]. Additionally, second-life battery systems contribute effectively to balancing fluctuations and providing short-term energy support in the integration of renewable energy sources (such as wind and solar) into the grid. One of the most critical issues in second-use BESS applications in distribution systems is their placement within the network. Improper placement of battery systems can result in undesirable effects on power flow and increase line losses. Therefore, determining the optimal locations for second-use batteries within the grid is of vital importance for both technical performance and economic efficiency [11]. Many studies in the literature have shown that integrating second-use battery systems into distribution networks offers a low-cost and sustainable energy storage solution. These systems enhance grid power quality, provide active and reactive power support, and minimize total system losses. Furthermore, under the principles of the circular economy, repurposing end-of-life batteries significantly reduces environmental impacts.

2.2. System's Mathematical Modeling

The Optimal Power Flow (OPF) problem is defined as an optimization task that aims to determine the optimal settings of generator outputs and other control variables to ensure economical and reliable operation of electrical power systems. In the literature, OPF is widely applied in the context of loss minimization, voltage stability enhancement, and economic load dispatch [12]. In this study, an OPF problem focused on minimizing active power losses is formulated using the MATPOWER simulation environment to model the integration of second-use battery energy storage systems (BESS) into the IEEE 30-bus test system.

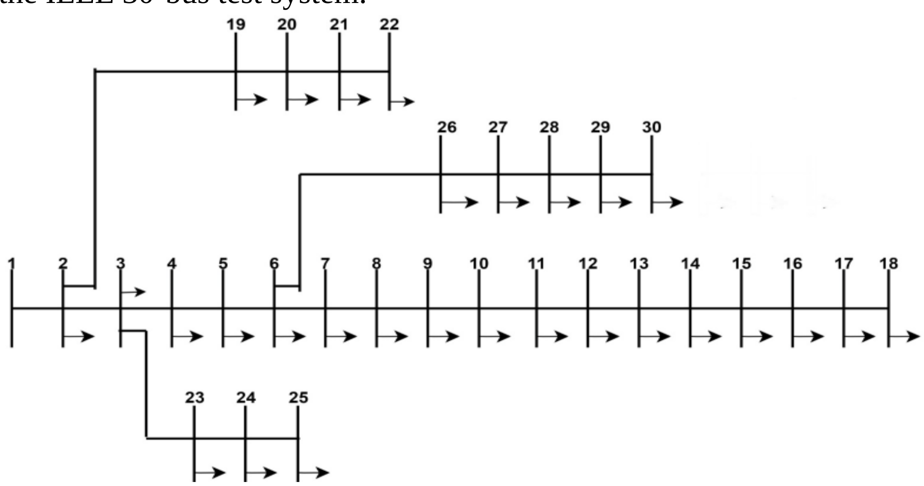

Figure 1. IEEE 30 Bus Power System single line diagram

Objective Function

In this study, the objective function is defined as the minimization of the total active power losses in the system, and it is expressed as follows:

$$min \sum_{i=1}^{n} Ploss, i \quad (1)$$

Here, *Ploss*, *i* P*loss*, i represents the active power loss (in MW) in branch i i. The total system losses are calculated based on the squared current losses reported in the branch flow results of MATPOWER. Such loss-minimization-based OPF models are widely adopted in the literature, especially for determining the optimal placement of energy storage systems [13].

Equality Constraints

In the OPF problem, the power balance equation constitutes the fundamental equality constraint of the system. For each bus, both active and reactive power balance must be satisfied:

$$PGi - PDi = \sum_{j=1}^{n} ViVj(Gijcos\theta ij + Bijsin\theta ij) \quad \forall i \quad (2)$$

$$QGi - QDi = \sum_{j=1}^{n} ViVj(Gijsin\theta ij + Bijcos\theta ij) \quad \forall i \quad (3)$$

In these equations, Pgi P G i and Qgi represent the active and reactive power generation at bus i, while Pdi and Qdi i denote the active and reactive load at the same bus. Vi and Vj are the voltage magnitudes at buses i and j, respectively. *Gij* and *Bij* are the conductance and susceptance elements of the network admittance matrix.

Inequality Constraints

The operational constraints for each bus and component are defined as follows:

Voltage Magnitude Limits:

$$V_{i}^{min} \leq Vi \leq V_{i}^{max} \quad \forall i \quad (4)$$

Generator Active Power Limits:

$$\mathrm{P}_{\mathrm{gi}}^{\mathrm{min}} \leq \mathrm{Pgi} \leq \mathrm{P}_{\mathrm{gi}}^{\mathrm{max}} \quad \forall \mathrm{I} \quad (5)$$

Generator Reactive Power Limits:

$$\mathrm{Q}_{\mathrm{gi}}^{\mathrm{min}} \leq \mathrm{Qgi} \leq \mathrm{Q}_{\mathrm{gi}}^{\mathrm{max}} \quad \forall \mathrm{I} \quad (6)$$

ESS Specific Constraints

For second-use battery systems, charge and discharge limits are defined as additional constraints:

$$P_{ESS}^{min} \leq PESS \leq P_{ESS}^{max} \quad (7)$$

In this formulation, P_{ESS}^{min} represents the discharging limit of the ESS, while P_{ESS}^{max} denotes the charging limit. In this study, the ESS is modeled as a unit with a storage capacity of 2 MWh. Power balance constraints and operational limits are defined in accordance with the IEEE 30-bus system specifications. Voltage magnitude limits and generator operating boundaries serve as critical components of the OPF formulation to ensure system stability and minimize losses [14].

- Power Balance Equation: Ensures that total power generation matches total consumption plus losses.

$$\sum_{i=1}^{N} Pgi - \sum_{j=1}^{N} Pdj - PLoss = 0 \quad (8)$$

where is the power generation at bus, is the power demand at bus, and P_{LOSS} represents the total system losses.

- Voltage Stability Constraints: Maintains voltages within prescribed operational limits to prevent instability.

$$V_{\dot{}\,min} \leq Vi \leq V_{\dot{}\,max} \quad \forall i \in N \quad (9)$$

where is the voltage magnitude at bus, and define the lower and upper voltage limits.

- Objective Function: Minimizes the total system losses while maximizing battery utilization efficiency.

$$min \sum_{i=1}^{N}(PLossi) + \Delta \sum_{k=1}^{M} PBk = 0 \quad (10)$$

where P B,k represents the power contribution of the second-life battery at bus k, and Δ is a weighting factor to balance battery utilization and system losses. The OPF model incorporates time-series data to assess the effect of battery integration under varying load and generation conditions.

2.2. Optimization Approach: Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a population-based optimization technique in which a group of particles (solution candidates) with randomly initialized positions collectively search for the global optimum within the problem space [15]. PSO has been widely applied to solve nonlinear and constrained problems such as Optimal Power Flow (OPF), due to its simplicity, flexibility, and convergence capabilities [16].

Velocity and Position Updates:

In the PSO algorithm, the position xi and velocity vi of each particle are updated using the following classical equations [15]:

$$v_i^{k+1} \leq w * v_i^k + c1 * r1 * \left(Pbesti - x_i^k\right) + c2 * r2 * (gbest - x_i^k) \quad (11)$$

In these equations, w denotes the inertia weight, c 1 and c 2 represent the cognitive and social learning coefficients, r 1 and r 2 are random numbers uniformly distributed in the range [0,1], pbest i is the best solution found by the ith particle, and gbest indicates the global best solution obtained among all particles.

In the integration of the OPF problem with the PSO method, each step of the PSO process includes the following:

- The selected bus location is introduced into the MATPOWER environment as a new ESS generation point.
- An OPF solution is executed, and the total active power losses are calculated.
- The PSO algorithm updates the velocity and position vectors to minimize these losses.
- The algorithm continues until it identifies the bus position corresponding to the minimum power losses (the global best, gbest).

This algorithmic structure is widely used in the literature for determining the optimal placement of second-use BESS systems and has proven to be effective [16]. The PSO algorithm offers advantages in solving OPF problems, such as fast convergence, low computational cost in constrained and complex systems, and the ability to approach the global optimum in nonlinear solution spaces [17].

3. Second Use Battery Integration and Carbon Emission Analysis

In this section, second-use battery energy storage systems (BESS) were integrated into the IEEE 30-bus power system. The analyses evaluated the impact of BESS integration on reducing active power losses, improving voltage profiles, and lowering carbon emissions. The base case and the optimized ESS placement scenario were compared, and the results were supported by OPF outputs.

3.1 Base Case: IEEE 30-Bus System Without BESS

A baseline OPF analysis was conducted on the IEEE 30-bus test system without integrating a second-use battery-based energy storage system (BESS). The results revealed the presence of active power losses and noticeable voltage deviations at several buses. These findings indicate that, in the absence of flexible energy resources, distribution networks are prone to increased losses and voltage irregularities [18]. This baseline scenario was used as a reference for comparison with the outcomes obtained after BESS integration, and the corresponding voltage profile is illustrated in the figure below.

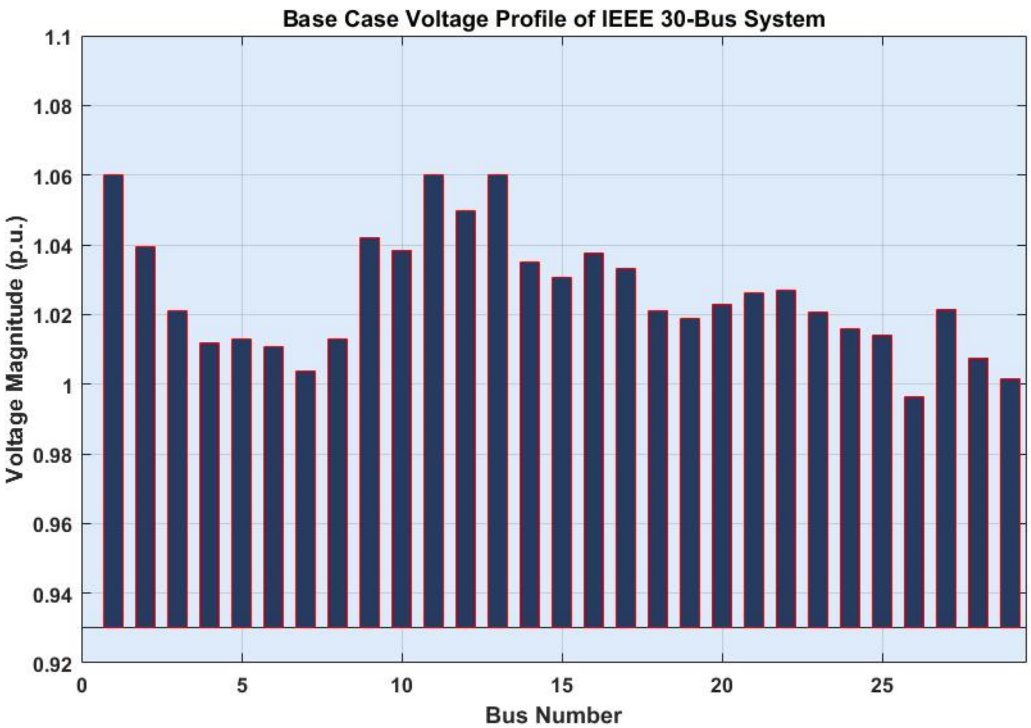

Figure 2. IEEE 30 Bus Voltage Profile

3.2 Optimal Placement of Second-Use BESS Using PSO

At this stage, an energy storage system (BESS) composed of second-use batteries was integrated into the IEEE 30-bus system. In the study, the BESS was placed at candidate buses excluding generation and specific load buses (1, 2, 5, 8, 11, 13), and Optimal Power Flow (OPF) analyses were conducted for each placement scenario. In every scenario, the BESS was modeled as a generator unit in the MATPOWER environment, and total active power losses were calculated following the OPF solution.

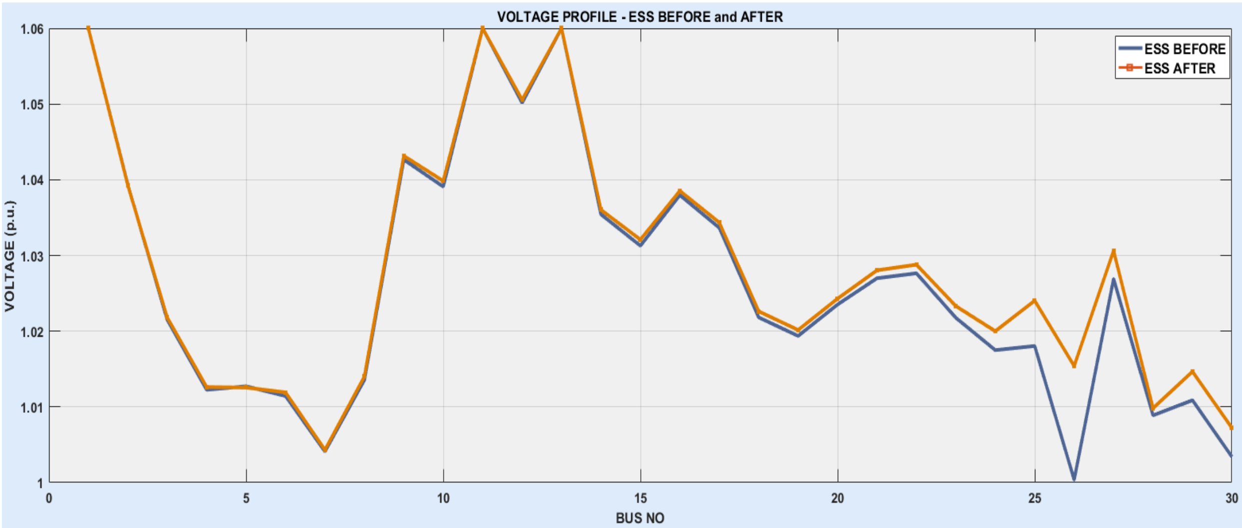

Figure 3. Base case and after-PSO voltage profiles

With the aid of the PSO algorithm, power losses associated with each candidate bus were minimized. According to the results obtained, bus number 19 was identified as the optimal ESS placement location, where the minimum total loss was achieved at approximately 11.36 MW. This technical analysis demonstrates that the integration of second-use BESS significantly reduces network losses and provides an effective strategy in solving the OPF problem.

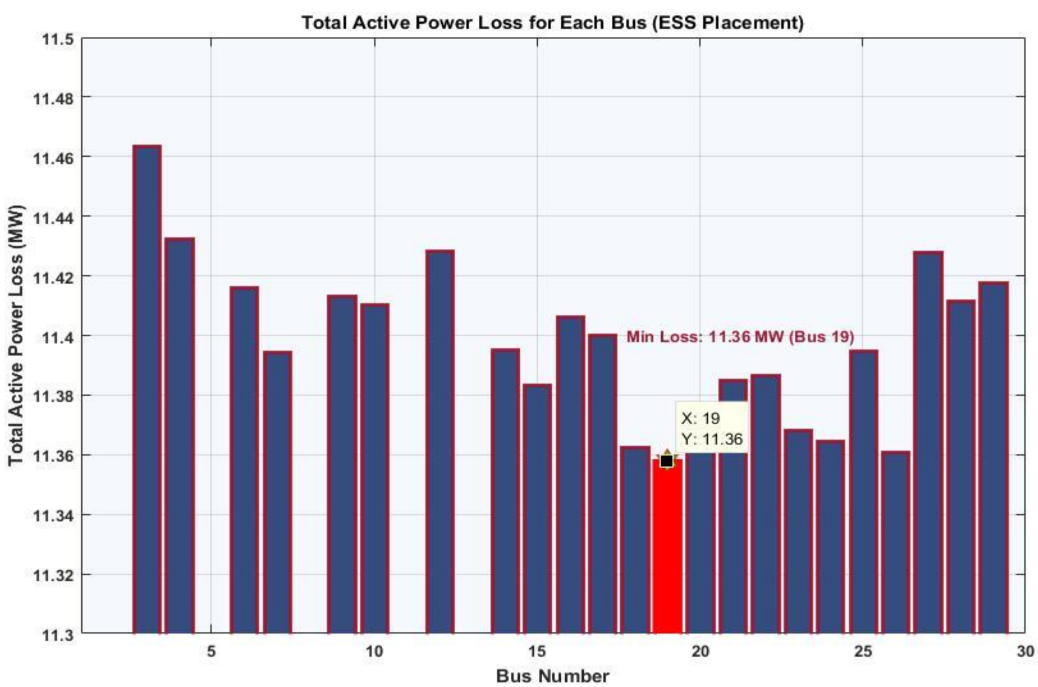

Figure 4. Total active loss after IEEE 30-bus PSO

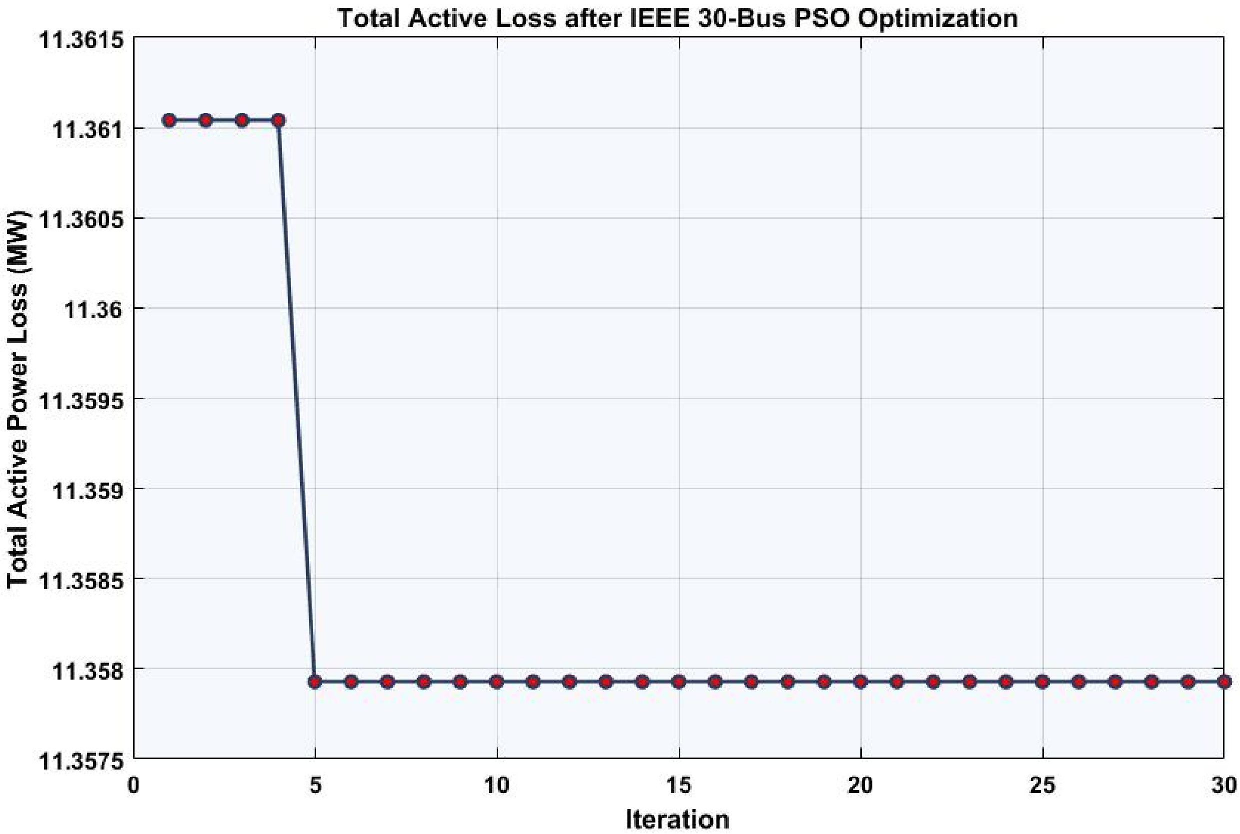

Figure 5. IEEE 30-bus PSO OPF convergence curve

3.3 Sustaniability Analysis of Second-Use BESS Integration

As a result of the OPF and PSO-based analyses conducted in this study, the integration of second-use battery-based energy storage systems led to a reduction of approximately 382 kW in active power losses (from 11.742 MW to 11.36 MW). The reduction in network losses indirectly decreases the demand for electricity generation and contributes to lower carbon emissions. According to the International Energy Agency (IEA), every 1 MWh of electricity lost in distribution systems results in an average of 0.4 tons of CO_2-equivalent greenhouse gas emissions [19]. The 382 kW loss reduction achieved in this study corresponds to an annual prevention of approximately 1,339 tons of CO_2 emissions. This amount is roughly equivalent to the annual carbon emissions of 270–280 passenger vehicles. Moreover, the use of second-life batteries recovered from electric vehicles helps reduce the demand for new battery production, thereby lowering the carbon footprint associated with battery manufacturing processes [20]. Therefore, this approach not only enhances energy efficiency by reducing network losses but also provides an environmentally sustainable solution aligned with circular economy principles. These findings highlight the technical and ecological benefits of second-use battery systems and emphasize the importance of promoting such solutions within future energy transition strategies.

4. Result and Discussion

In this study, the integration of second-use batteries recovered from electric vehicles into electrical grids as battery energy storage systems (BESS) was evaluated. Optimal Power Flow (OPF) analyses were conducted on the IEEE 30-bus test system, and the Particle Swarm Optimization (PSO) algorithm was employed to determine the most suitable placement location for the second-life batteries within the distribution network. As a result of the optimization process, Bus 19 was identified as the optimal location for BESS integration, providing the lowest total active power loss. The integration of the BESS led to a reduction of approximately 382 kW in active power losses (from 11.742 MW to 11.36 MW). This reduction not only improved energy efficiency by decreasing generation demand but also significantly contributed to carbon emission mitigation. According to calculations based on the International Energy Agency (IEA) guidelines, the achieved loss reduction corresponds to the prevention of approximately 1,339 tons of CO_2 emissions annually. This figure is roughly equivalent to the annual carbon emissions of 270–280 passenger vehicles. The findings clearly demonstrate that integrating second-life batteries into the grid yields both technical and environmental sustainability benefits. These systems prove effective in minimizing network losses, enhancing voltage profiles, and reducing the overall carbon footprint. Moreover, the reuse of EV batteries also indirectly reduces the demand for new battery production, thereby supporting circular economy principles. For future implementations, it is recommended to employ multi-objective optimization algorithms that jointly consider energy storage systems and renewable energy sources, while also incorporating the dynamic operational behavior of the power grid.

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