Voltage Deviation Improvement in Active Distribution Network Using Battery Energy Storage System Optimal Voltage Droop Control

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ABSTRACT

This work proposes the implementation of battery energy storage system (BESS) management for voltage regulation in the active distribution network (ADN). The primary goal is to minimize the overall voltage deviation of all buses in the power system. Adaptive droop control is employed to regulate BESS and optimize the efficiency of battery operation. In order to enhance the performance of the battery energy storage system, the study employs particle swarm optimization (PSO) to identify the most effective control parameters. To validate the efficacy of the proposed methodology, its performance is examined utilizing an IEEE 33-bus distribution system by testing scenarios both with and without renewable energy sources such as photovoltaic panels and wind turbines. The results demonstrate that the approach extensively decreases the voltage deviation in three scenarios, including with/without BESS. The optimization of BESS management can effectively confine the voltage within the established range of 0.95 – 1.05 and minimize the voltage deviation of all buses to a minimum of 0.0385 p.u. Consequently, this leads to an enhancement in the voltage profile, power quality, and system dependability.

1. INTRODUCTION

Voltage stability in the electrical system is extremely important and must be prioritized. In modern distribution network (DN), renewable energy is currently increasing rapidly, due to the increase in photovoltaic (PV) and wind power. Therefore, many DNs have been transformed into active distribution network (ADNs). The main issue with renewable energy is the discontinuity of the energy that can be generated [1]. These are the challenges that make ADN voltage control more difficult. One of the key indices for voltage stability is voltage deviation (VD). It measures the difference of voltage value from the nominal value. If it exceeds the specified standard, it may have an impact on system efficiency or even cause damage to electrical equipment [2-4]. As a result, many tools have been developed over time to help maintain voltage stability, including transformer load tap changes, shunt capacitor banks, and STATCOM [5]. These tools help to enhance the stability of the electrical system. For example, Sarithumu et al. [6] developed a strategy to regulate voltage in networks with a high level of renewable energy penetration, making the use of traditional tools or methods ineffective, Thus, a technique utilizing on-load tap changer voltage regulation was devised for voltage control. According to Abedini et al. [7], shunt capacitor banks can give a good solution for voltage profile problems in power systems by delivering reactive power to the system, but they still have the problem of transient signals, which might impact sensitive devices. According to Gurav and Mittal [8], STATCOM can supply fast reactive power, but it is not always effective due to the trial-and-error control strategy in controller configuration. Similarly, Xu and Li [9] claimed that classical STATCOM control should not be used in engineering or the real world, despite the fact that it has the advantage of providing fast reactive power.

As mentioned, most conventional devices still have several limitations compared to battery energy storage system (BESS), such as fast response, which can bring more benefits than just voltage regulation. As a result, the usage of BESS is intriguing and has great promise for controlling voltage in power systems and resolving VD issues [10]. BESS has several operating functions, for example, energy arbitrage that provides lowering electricity cost, peak shaving for reducing the peak demand, and even store the excess energy for utilizing in the shortage period [11]. In addition, BESS can also regulate the system frequency and voltage [12]. However, for batteries to function optimally, they must be properly managed or controlled. Several research studies have explored battery management strategies. Mohammed et al. [13] focus on improving the sizing of a stand-alone hybrid energy system that consists of three components: PV, diesel generator, and BESS. Saini

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and Gidwani [14] use BESS as an alternative load for charging and discharging. The objective is to minimize yearly energy losses, alleviate reverse power flow, and resolve overvoltage challenges in an IEEE 69-bus system integrated with PV. Tamrakar et al. [15] suggest employing BESS to replace outdated equipment like on-load tap changer capacitor banks. To improve system dependability, Zhang et al. [16] presents a multi-agent system-based control approach for energy storage and PV inverters. Alam et al. [17] presents a novel charge and discharge control scheme that takes into account the status of the charging current. Considering the impact of solar cells in the system in terms of energy efficiency, the storage is utilized to catch the extra energy produced by PV during the PV peak and store it for peak load support. Tandon et al. [18] discovered the optimal allocation of BESS to increase system performance while taking into account load volatility, renewable energy sources, and network constraints. Alzahrani et al. [19] used BESS in a system with high PV deployment to explore system loss and power quality issues, employing a genetic algorithm-based placement methodology. Wang et al. [20] proposed employing BESS to address voltage instability issues in low-voltage grids with high rooftop PV penetration, considering the state of charge (SoC). Rouzbehi et al. [21] proposed a generalized voltage droop (GVD) control approach to address the voltage rise issue. GVD operates in three modes: fixed voltage control, fixed active power control, and traditional voltage droop control (VDC), all of which can be changed using the GVD characteristic of a voltage regulation inverter. Zeraati et al. [22] employed BESS to handle various voltage difficulties, such as voltage rise, and presented a collaboration between a local droop-based control approach for battery installation size and a distributed control system to manage SoC performance to prevent battery saturation. Chen et al. [23] suggested a fuzzy logic-based adaptive droop controller to alter the droop coefficient, resulting in a compromise between DC. Jamreon and Sirisukprasert [24] presented a voltage control technique integrating battery energy storage with SoC management. The battery control employs adaptive droop control as a power supply controller, as well as self-learning particle swarm optimization (PSO) to optimize the operational performance of BESS. Jamroen et al. [25] proposed an adaptive droop-based method that takes into account the SoC system to manage the functioning of BESS in a low voltage (LV) system. The objective is to mitigate voltage rise caused by high solar penetration by enhancing voltage regulation and power-sharing efficiency using fuzzy logic.

The literature research revealed that the current instability of renewable energy poses a variety of issues. This study presents a solution to mitigate the impact of renewable energy on VD in ADN. The optimum BESS management is achieved by adopting a VDC approach that employs BESS to charge and discharge energy to the system. The adaptive droop control approach was chosen for BESS management because it allows the droop coefficient to be chosen as desired and appropriate, as well as taking into account the SoC level. In addition, the PSO is used to get the most appropriate droop coefficient value for battery control. The IEEE 33-bus test system was chosen as a test system because it is a distribution system with voltage levels lower than the standard criterion, making it acceptable for testing.

The following sections of this paper are organized as follows: Section 2 presents a mathematical analysis of BESS management. Section 3 provides an explanation of the voltage regulation technique developed with the PSO algorithm. Section 4 details the simulation analysis and results, while Section 5 concisely summarizes the conclusion.

2. BESS WITH ADAPTIVE VOLTAGE DROOP CONTROL

The BESS configuration is shown in Fig. 1, which includes the following main elements: a battery for storing energy, a battery energy management system for controlling BESS operation, and a power converter for energy conversion.

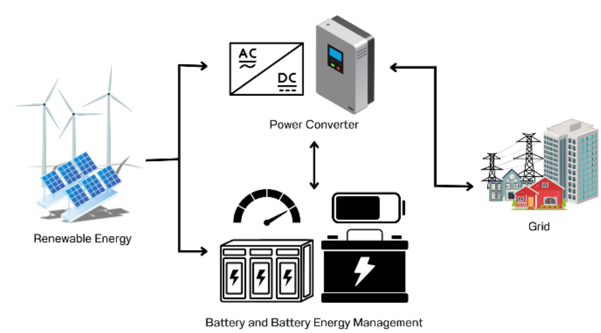

Fig. 1. BESS configuration

In this study, we focus on the battery and its energy management system. This study presents a method for controlling battery operations to resolve the VD issue. The battery can either provide or receive active power from the grid. When the BESS supplies active power to the grid, the voltage level rises, whereas when it absorbs active power from the grid, the voltage level drops. Thus, the BESS's operation can affect the voltage when the active power changes. Therefore, effective BESS operation relies heavily on battery energy management. According to a review, Fig. 2 shows that the VDC has three modes: (1) Mode 1 (Fixed Voltage): Keeps the voltage at a predetermined level and allows the battery power to adjust as needed, (2) Mode 2 (Fixed Power): Keeps the battery's power output constant, (3) Mode 3 (Droop Control): Uses a droop coefficient to determine how much power the battery delivers or consumes depending on the grid voltage.

This study uses the droop control method (Mode 3) to regulate battery operation because it can adjust the droop coefficient, allowing the voltage level to be freely regulated [24], [26]. Fig. 3 illustrates the operating concept as follows:

• 1: If the bus voltage of the battery exceeds the maximum voltage (V_{max}), the battery will charge the maximum power into the system.

• 2: If the bus voltage value of the battery is less than the maximum voltage (V_{max}) but larger than the maximum voltage thresholds ($V_{\text{th}}^{\max}$), the battery will charge power based on VD, which is governed by the droop coefficient.

• 3: If the battery's bus voltage value falls within the range of the minimum voltage thresholds ($V_{\text{th}}^{\min}$) and the maximum voltage thresholds ($V_{\text{th}}^{\max}$) or the deadband range, the battery will not charge or discharge at all.

• 4: If the bus voltage value of the battery is larger than the minimum voltage ($V_{\min}$) but less than the minimum voltage thresholds ($V_{\text{th}}^{\min}$), the battery will discharge the power based on VD, which is governed by the droop coefficient.

• 5: If the battery's bus voltage value is less than the minimum voltage (V_{min}), it will discharge the maximum power back.

It can be represented mathematically as an equation given below:

$$P_{BES} = \begin{cases} -P_{BES}^{\max} & \text{if } V_i \geq V^{\max} \\ k_{BES,c(SoC)}\Delta V & \text{if } V_{\text{th}}^{\max} < V_i < V^{\max} \\ 0 & \text{if } V_{\text{th}}^{\min} \leq V_i \leq V_{\text{th}}^{\max} \\ k_{BES,d(SoC)}\Delta V & \text{if } V^{\min} < V_i < V_{\text{th}}^{\min} \\ P_{BES}^{\max} & \text{if } V_i \leq V^{\min} \end{cases} \quad (1)$$

$$\Delta V = V_i - V_0 \quad (2)$$

Since the battery may be saturated, it cannot be utilized further, causing the system to have a VD value that exceeds the required limit. As a result of the investigation, the SoC level was examined, as shown in the equation below.

$$k_{BES,d} = \begin{cases} 0 & \text{if } 0 < \text{SoC} \leq \text{SoC}_{\min} \\ \dfrac{K_{\max}K_{\min}e^{n_d(SoC-SoC_{\min})}}{K_{\max}+K_{\min}e^{n_d(SoC-SoC_{\min})}-1} & \text{if } \text{SoC}_{\min} < \text{SoC} \leq 1 \end{cases} \quad (3)$$

$$k_{BES,c} = \begin{cases} 0 & \text{if } \text{SoC}_{\max} \leq \text{SoC} < 1 \\ \dfrac{K_{\max}K_{\min}e^{n_c(SoC_{\max}-SoC)}}{K_{\max}+K_{\min}e^{n_c(SoC_{\max}-SoC)}-1} & \text{if } 0 < \text{SoC} < \text{SoC}_{\max} \end{cases} \quad (4)$$

$$SoC(t) = SoC(t-1) - \frac{1}{E}\int P_{BES}(t)dt \quad (5)$$

$$k_{droop} = \begin{cases} k_{BES,c}, & \text{charging} \\ k_{BES,d}, & \text{discharging} \end{cases} \quad (6)$$

$$n = \begin{cases} n_c, & \text{charging} \\ n_d, & \text{discharging} \end{cases} \quad (7)$$

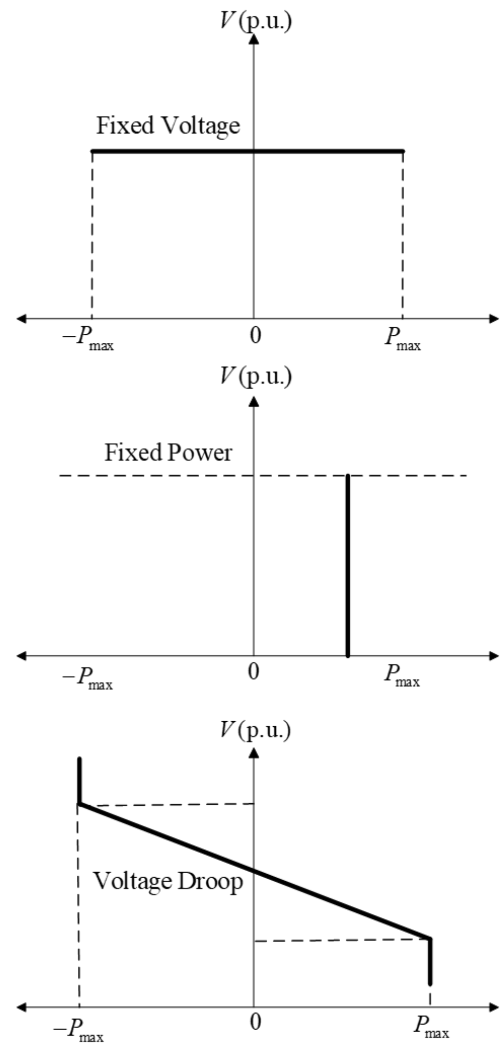

Fig. 2. VDC strategies.

When evaluating k_{droop}, it is discovered that this value is related to the determination of $K_{\max}$, $K_{\min}$, SoC, and n As a result, while examining (1), (3), and (4), it can be represented in Fig. 4 and 5. From Fig. 4, it has been discovered that as the SoC of the battery increase, the $k_{BES,d}$ value gradually increases, the $k_{BES,c}$ value gradually decrease. This is because adaptive droop management is intended to protect the battery's functionality, which increases the *SoC* range, resulting in less charging and discharging. On the other hand, a low *SoC* level in the battery causes it to charge more and discharge less. The aforementioned relationship leads to the design of K_{max}, K_{min} and n values, demonstrating that K_{max} and K_{min} will have a relationship with the desired power output, and n will be the factor determining the battery's power distribution, which is related to SoC, as shown in Fig. 5.

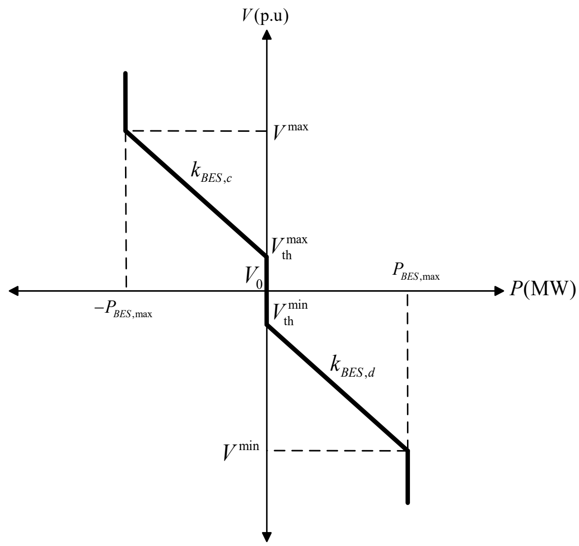

Fig. 3. Adaptive VDC strategy.

3. PSO BESED VOLTAGE DEVIATION IMPROVEMENT

PSO is a well-known metaheuristic method that mimics bird group's foraging activity. It accomplishes this by altering the locations of particles in search space, directing them toward the best solution discovered, similar to birds following the individual closest to a food source until the food is reached. Consequently, PSO is adept at determining optimal settings by iteratively updating particle positions.

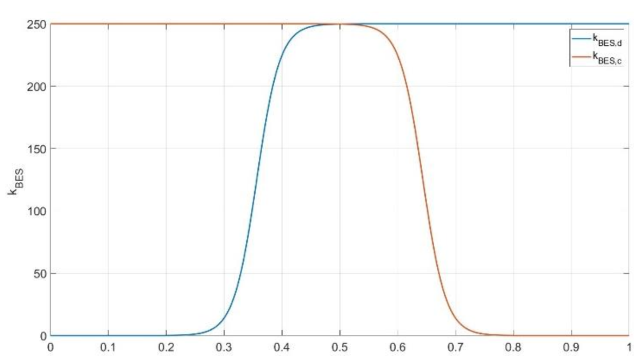

Fig. 4. The Relationship between *SoC* and k_{BES} with the *SoC* is within the range of SoC_{min} and SoC_{max}

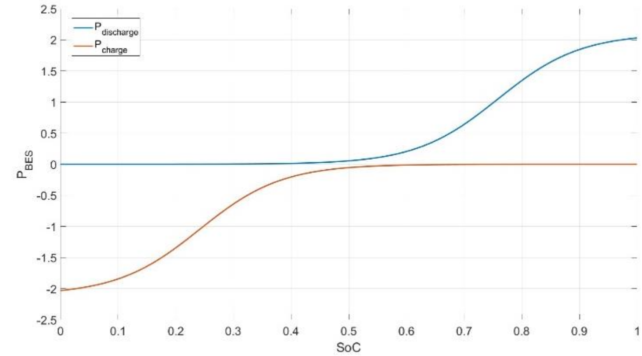

Fig. 5. The Relationship between *SoC* and *n* with the *SoC* is within the range of SoC_{min} and SoC_{max}.

Each parameter or particle updates its position iteratively until reaching the optimal value. The highest-performing value identified within the swarm is termed the global best, or $gBest$, while the best value found by an individual particle is known as the personal best, or $pBest_i$ [27]. This study uses PSO to change the adjustment exponent and calculate the droop efficient value, which is connected to battery operation, leading to the most efficient procedure based on the defined objective function.

This study aims to minimize the system's total voltage deviation (TVD) through the objective function. By reducing the TVD, the stability of the power system can be greatly enhanced. The objective function employed in this study is shown in the following equation.

$$\text{minimize } TVD = \sum_{i=1}^{N} (|V_i - V_0|) \tag{8}$$

and the constraints are defined as follows:

$$P_k^{gen} - P_k^{load} - \sum_{j=1}^{N} [V_k V_j (G_{kj} \cos\theta_{kj} + B_{kj} \sin\theta_{kj})] = 0 \tag{9}$$

$$Q_k^{gen} - Q_k^{load} - \sum_{j=1}^{N} [V_k V_j (G_{kj} \sin\theta_{kj} - B_{kj} \cos\theta_{kj})] = 0 \tag{10}$$

$$V_{\min} \le V_i \le V_{\max} \tag{11}$$

$$SoC_{\min} \le SoC \le SoC_{\max} \tag{12}$$

$$P_{BES,\min} \le P_{BES} \le P_{BES,\max} \tag{13}$$

$$k_{BES,d}^{\min} \le k_{BES,d} \le k_{BES,d}^{\max} \tag{14}$$

$$k_{BES,c}^{\min} \le k_{BES,c} \le k_{BES,c}^{\max} \tag{15}$$

The working equation of PSO is as follows:

$$v_i^{t+1} = wv_i^t + c_1 r_1 (pBest_i^t - x_i^t) + c_2 r_2 (gBest^t - x_i^t) \tag{16}$$

$$x_i^{t+1} = x_i^t + v_i^t \quad (17)$$

where, x_i is the population of particles that represent the adjust exponent of $k_{BES,d}$ and $k_{BES,c}$, which are n_d and n_c, respectively. The proposed PSO-based VD improvement computational procedure is illustrated in Fig. 6.

4. RESULTS AND DISCUSSION

The test was conducted on the IEEE 33-bus system, which includes one generator bus and 32 load buses, where bus 1 is designated as the slack bus. The system's voltage restrictions range from 0.9 to 1.1 p.u. The system contains 3.715 MW of real power load and 2.3 MVar of reactive power load. The substation's nominal voltage is configured at 13.8 kV, with the transformer at bus 1 having a capacity of 3 MW. [28], [29]. In the simulation, the experiment is conducted as a single fixed-load test.

Table 1 also provides the study's parameters, which were evaluated and adjusted as needed, mostly through trial and error. The battery size was selected by using trial-and-error to adjust parameters, so they suit the operation of the IEEE 33-bus power system under both non-renewable and renewable energy conditions. From these trials, it was found that a 2 MWh size is appropriate for this system. The variable *n* specifies how quickly the battery can charge or discharge. A larger *n* allows faster charging or discharging when the BESS SoC is near its maximum or minimum, whereas a smaller *n* slows charging or discharging when the BESS SoC is near the nominal level. Therefore, we conducted trials to adjust these ranges, as illustrated in Fig 5.

The test is divided into three scenarios, as follows:

- Case I: base case,
- Case II: modified IEEE 33-bus with PV and wind power penetration, and
- Case III: modified IEEE 33-bus with PV and wind power penetration and BESS with optimal VDC.

The system with renewable energy and BESS is shown on Fig. 7.

4.1 IEEE 33-bus base case

An initial test was conducted on an IEEE 33-bus distribution system. The voltage of each bus in the system ranges from 0.9038 p.u. to 1.0000 p.u., and the TVD is 1.8047 p.u., This significant deviation indicates that the bus voltages are not within the typical standard range of 0.95 p.u. to 1.05 p.u. The bus with the lowest value is Bus 18. Consequently, the lower-voltage bus should be prioritized to prevent power system instability, which could potentially lead to blackouts.

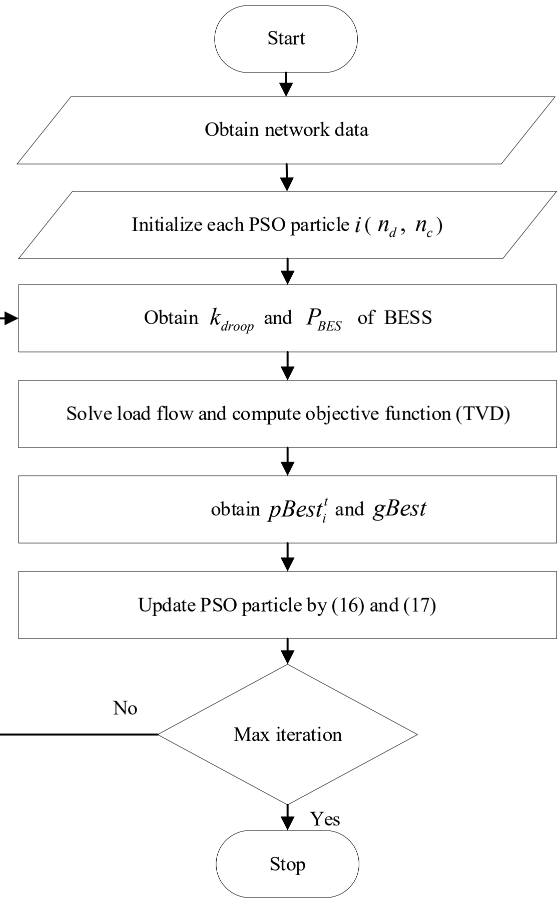

Fig. 6. The PSO based BESS optimal VDC computation procedure.

Table 1. Specification of the BESS

Parameter	Specification
Range of the adjust exponent (n_d, n_c)	-100 to 100
The maximum power of battery ($P_{BES}^{\max}$)	2 MW
The maximum droop coefficient ($K_{\max}$)	250
The minimum droop coefficient ($K_{\min}$)	0.1
Nominal Voltage (V_0)	1.00 p.u.
Battery capacity (E)	2 MWh
The maximum voltage (V_{max})	1.10 p.u.
The minimum voltage (V_{min})	0.90 p.u.
Maximum state of charge (SoC_{max})	0.8 p.u.
Minimum state of charge (SoC_{min})	0.2 p.u.

4.2 Modified IEEE 33-bus with PV and wind power penetration

In this study, PV and wind power, as renewable energy sources, were integrated into an IEEE 33-bus distribution network. Two 1 MW wind turbine generators were installed at buses 18 and 24. Additionally, three 1 MW PV systems were deployed at buses 5, 21, and 31, while four 500 kW PV systems were positioned at buses 8, 12, 28, and 33 [30]. As a result of these renewable energy installations, the system's real power increased to 10.715 MW. It was observed that the system voltage ranged from 1.0000 p.u. to 1.0534 p.u. and that TVD was 0.6879 p.u. These findings indicate that high levels of renewable energy penetration impact the power system, causing over voltages and significant voltage fluctuations that negatively affect the electrical network. Therefore, appropriate energy management strategies should be implemented.

4.3 Modified IEEE 33-bus with PV and wind power penetration and BESS with optimal VDC

In case III, the proposed method incorporates a battery into the system and employs PSO to optimize the system to obtain the best value that minimizes TVD. The PSO parameters are configured as follows w ranges from 0.1 to 1.1, both c_1 and c_2 are set to 1.49 and the maximum iterations is 100, which was selected through multiple trial runs. It was observed that the values generally start to converge around iterations 20-50, so this value was set accordingly. A 2 MWh battery has been installed on buses 18, 21, 24, and 32. The results show that the voltage levels on all buses in the system are within the prescribed range, with TVD being 0.0385 p.u. This adjustment was made using the variables presented in Table 2, specifically the values of the adjust exponent (n), droop coefficient (k_{droop}) and regulating power (P_{BES}) for each battery. The sign of P_{BES} for each value indicates whether the battery is charging or discharging. Specifically, a negative sign denotes that the BESS is charging, whereas a positive sign signifies that it is discharging.

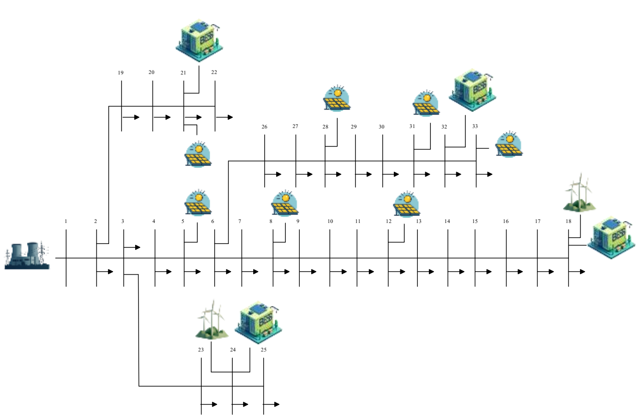

Fig. 7. The modified IEEE 33-bus with PV and wind power penetration and BESS.

Figure 8 illustrates the voltage profile for all three scenarios, showing that the proposed method maintains the voltage profile within the specified range through efficient battery charging and discharging. Table 3. depicts the 3 scenarios of TVD, indicating that the proposed method alsoproduces the best results by reducing VD compared to case 1 and 2. Furthermore, Fig. 9 shows the convergence plot of the proposed PSO-based BESS optimal VDC. it is clear that the value of the objective function progressively converges toward the optimal solution. Fig. 10 presents the results of 30 trials conducted using the proposed method that have the average value is 0.0409, standard deviation value is 0.0052, maximum value is 0.0524 and minimum value is 0.0385. The low standard deviation of the objective function values indicates that they are closely clustered, suggesting that the results obtained from PSO algorithm are reliable. The runtime of the proposed method was evaluated over 30 runs on a computer equipped with an AMD Ryzen 5 6600H CPU (3.30 GHz up to 4.50 GHz) and 16 GB of RAM. On average, the method took 774.45 seconds to complete, with a standard deviation of 178.33 seconds. The minimum runtime observed was 591.81 seconds, while the maximum reached 1490.75 seconds. Thus, although the PSO method typically requires about 774.45 seconds, it can occasionally take as long as 1490.75 seconds, likely due to unfavorable random initializations delaying convergence. These results are illustrated in Figure 11.

Table 2. Adjust exponent, Droop coefficient and BEES regulating power of BESS

Bus with Battery Installed	n	k_{droop}	P_{BES} (MW)
18	9.7258	12.3498	-0.6591
21	13.6507	67.4965	-0.6139
24	10.2878	16.0991	-0.0627
32	10.7010	19.5058	-0.5282

Table 3. Adjust exponent, Droop coefficient and BEES regulating power of BESS

Scenarios	TVD (p.u.)
IEEE 33-bus base case	1.8047
Modified IEEE 33-bus with PV and wind power penetration	0.6879
Modified IEEE 33-bus with PV and wind power penetration and BESS with optimal VDC.	0.0385

5. CONCLUSION

This paper introduces a voltage regulation approach utilizing BESS management, tested on an IEEE 33-bus power distribution system. The primary goal is to determine the power value that will minimize TVD. The BESS management employed in this work is VDC, which is responsible for optimizing battery performance and responding to changes in electrical loads. In addition, the PSO approach is employed to determine the settings for BESS control. The results of this study indicate that the proposed method significantly reduces VD, resulting in a more stable power supply. Reducing voltage variation is critical for sustaining power quality and reliability across the power system.

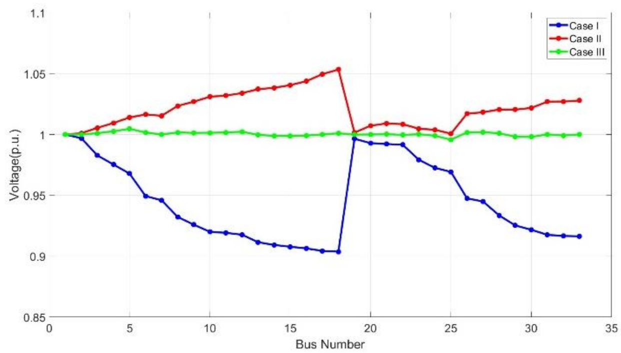

Fig. 8. Comparative Voltage Profile of modified IEEE 33-bus system.

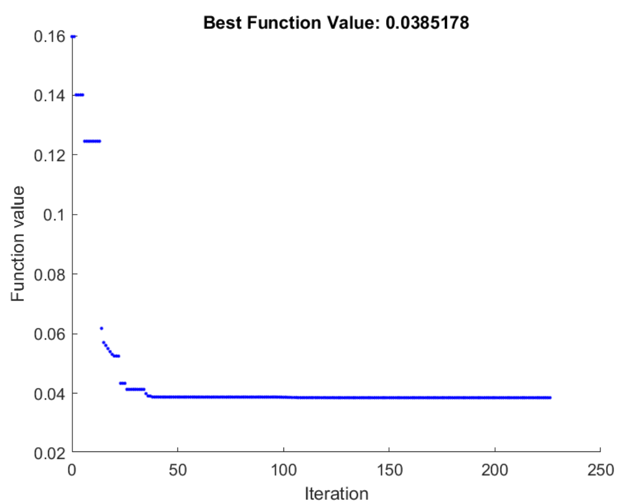

Fig. 9. the convergence plot of the proposed PSO-based BESS optimal VDC.

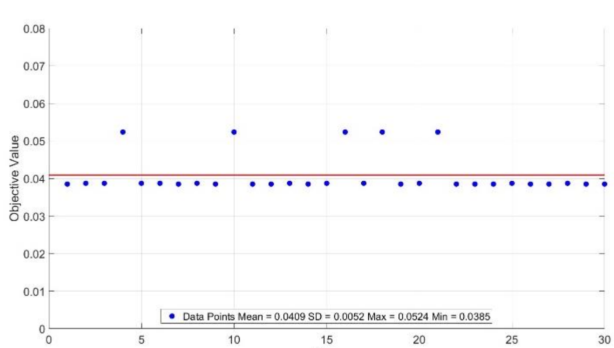

Fig. 10. The result of 30 trials of the proposed method.

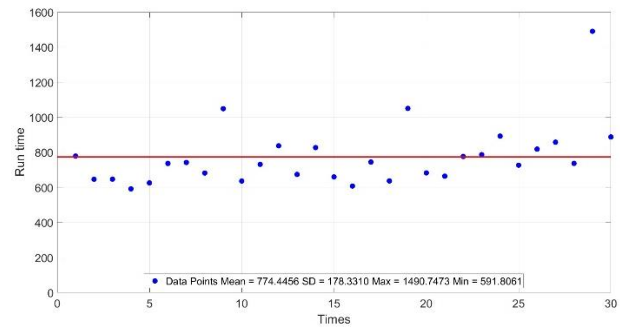

Fig. 11. The result of 30 trials of the computation time

ABBREVIATIONS

P_{BES}	The electrical power that a battery charges or discharges
$P_{BES}^{\max}$	The maximum power that the battery can supply.
k_{droop}	The droop coefficient
$k_{BES,c}$	The droop coefficient controls energy charge.
$k_{BES,d}$	The droop coefficient controls energy discharge.
ΔV	voltage deviation
V_i	Bus voltage
V_0	Nominal voltage
TVD	Total voltage deviation
$V_{\text{th}}^{\max}$	The maximum voltage thresholds
V_{min}	The minimum voltage
V_{miax}	The maximum voltage
K_{max}	The maximum droop coefficient
K_{min}	The minimum droop coefficient
n	The adjust exponent
n_d	The adjust exponent for $k_{BES,d}$
n_c	The adjust exponent for $k_{BES,c}$
$SoC(t)$	state of charge at the current step
$SoC(t\text{-}1)$	state of charge at the previous step
E	Battery capacity
N	Number of buses
SoC	State of charge
SoC_{min}	Minimum state of charge
SoC_{max}	Maximum state of charge

$P_{BES,min}$	The minimum power that the battery can supply
$P_{BES,max}$	The maximum power that the battery can supply
$pBest_i$	The best value of each particle *i*
$gBest$	The best value of all particles
t	The iteration
v_i	The velocity for a particle *i*
c_1 and c_2	Constant numbers
r_1 and r_2	Random parameters
w	Inertial weight
x_i	The population of particles *i*
P_k^{gen}	Active power generated at bus *k*
P_k^{load}	Active power consumed by the load at bus *k*
Q_k^{gen}	Reactive power generated at bus *k*
Q_k^{load}	Reactive power consumed by the load at bus *k*
G_{kj}	Conductance between bus *k* and *j*
B_{kj}	Susceptance between bus *k* and *j*
θ_{kj}	Phase angle difference between bus *k* and *j*

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