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Impact of Load Uncertainty on Optimum Placement and Sizing of Battery Energy Storage in Distribution System

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Abstract: The problem of Optimum Placement and Sizing of Battery Energy Storage (OPSBES) is complex to address in view of better system performance with acceptable reliability and economics. The reasons lie in the matching of uncontrollable Renewable Energy Sources (RES) like solar photovoltaics (PV), uncertain load demands, and associated Battery Energy Storage (BES) behaviour due to its inherent charging and discharging properties. Literature has mainly addressed the problem of resource uncertainty, whereas the effect of uncertainty in electrical load demand is less attended. The impact of load uncertainty on the OPSBES in grid-connected PV-BES Radial Distribution System (RDS) needs to be appropriately investigated. In this paper, this impact is analysed using Improved Grey Wolf Optimization technique. Two strategies namely simultaneous and sequential BES placements are implemented on modified IEEE 33 bus RDS. The effect of load uncertainty with these two strategies is tested with aggregated and distributed BES placements in RDS. This work also emphasizes uncertainty associated with load profiles using a probabilistic approach for various scenarios.

Keywords: *Battery Energy Storage, Distribution System, Load Uncertainty, Optimum Placement, Sizing*

1. Introduction

Solar photovoltaics (PV) integration is increasing in Radial Distribution Systems (RDSs) to reduce the reliance on fossil fuels and to meet the exponentially rising load demands. The nature of PV is irregular and uncontrollable, causing voltage and power instability in the system. These instability issues can be resolved by Optimum Placement and Sizing of Battery Energy Storage (OPSBES). OPSBES has been addressed for various objective functions and tested on several IEEE standard RDSs [1], [2], [3] using different optimization techniques [1], [4], [5], [6], [7], [8]. The BES importance is increasing with the level of PV penetration in RDSs. The role of BES is significant for various services like distribution, ancillary, and energy management [9], [10] in RDSs. To avail these services effectively, the determination of OPSBES is very vital. The improper placement and non-optimum size of BES may lead to increased system losses, system cost, and reduced system reliability.

The OPSBES problem can be solved using single objective functions like improving system voltage [7], congestion management [2], [8], reducing system losses [1], [9], and frequency st ability [11]. There is less research using multi-objectives such as voltage deviations with power losses [4], [12], and voltage improvement with congestion management [4], [8]. Along with such objective functions, some research has also taken into consideration resource uncertainty [4], [12], [13].

It is observed from the literature that researchers have solved the problem of OPSBES in RDSs with a deterministic approach for load demand. However, uncertainty in load demand for OPSBES has rarely been worked on. Load uncertainty is crucial in many planning applications of power systems such as deciding the need for storage units as well as other regulatory actions like load shedding, running a day-ahead market to maximize profitability, etc. The load uncertainty depends on meteorological conditions (temperature, humidity, wind speed, air brightness) and load consumption patterns (holidays, non-holidays, day length, and different seasons of the year) [14]. There are multiple ways to account for load uncertainty [15] by probabilistic approach such as Monte Carlo Simulation [16], Normal/Gaussian Distribution [17], [18], Lognormal Probability Density Function (PDF) [14], etc. In this work, the load uncertainty is accounted for OPSBES using a probabilistic approach. Using EasyFit 5.5 software, it is found that Johnson S_B PDF reflects the practical system behaviour and is the most suitable for the given load data set for five years [19].

In this study, the OPSBES is determined in view of load uncertainty with multiple objectives - the minimization of Active Power Losses (APL), minimization of Power Stability Index (PSI), and maximization of Voltage Stability Index (VSI). These objectives are used as the integration of PV and BES in RDSs affects power losses, voltage stability, and power stability of that system. The simultaneous optimization of these objectives under load uncertainty is found less in the literature so far. In this work, the Weighted

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Sum Method (WSM) is used to prioritise these objectives for OPSBES in grid-connected PV-BES RDS. The improved Grey Wolf Optimization (IGWO) technique is used for the simultaneous optimization of the three objectives. The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) is used to find the exact solution to this optimization problem. This OPSBES is placed simultaneously and sequentially on Modified IEEE 33 Bus Radial Distribution System (MBRDS) using Johnson S_B PDF (probabilistic) as well as a deterministic approach, accounting for load uncertainty.

The importance and contributions of this study are:

- Proposing methodology to account for the load uncertainty using a probabilistic approach (Johnson S_B PDF) with Multi-Objective Functions (MOF) for OPSBES.
- Analyzing options of simultaneous and sequential distributed BES placement considering load uncertainty. for a better perception of the system's behaviour.
- Studying the variations in APL, PSI, VSI, voltage profile, and power profile of the system given load uncertainty.

The paper is arranged in five sections. Section II describes the mathematical modelling of the PV-BES grid-connected system under consideration. The proposed optimization methodology for OPSBES is explained in Section III. The results are discussed in Section IV and Section V concludes the paper.

II. A. Mathematical Modelling of Grid Connected PV-BES System

The schematic of the Modified IEEE 33 Bus Radial Distribution System (MBRDS) under study consists of Solar PV, Utility Grid, Battery Energy Storage System, Inverter, and Load is shown in Figure 1.

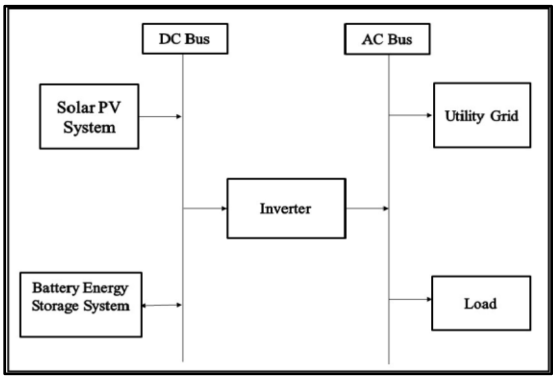

Figure 1: Grid Connected PV-BES System

The mathematical modelling of system components, shown in Figure 1, is described in detail as 1, 2, and 3.

1. Solar Photovoltaic System:

This work has assumed the placement of six PV panels based on loss minimization and voltage improvement criteria at those buses [1]. The profile of solar irradiance for a PV-BES system for one day is considered for a specific location [20] in W/m^2. The output power of a single PV panel can be calculated using equation (1) [21] by considering solar radiations falling on PV panels at that location.

$$p_{PV-Each} = \begin{cases} P_{Rs}\left(\frac{r^2}{R_{SRS}R_{CR}}\right) & if\ 0 \leq r \leq R_{CR} \\ P_{Rs}\left(\frac{r}{R_{SRS}}\right) & if\ R_{CR} \leq r \leq R_{SRS} \\ P_{Rs} & if\ R_{SRS} \leq r \end{cases} \quad (1)$$

The total power from six PV systems can be found depending upon the number of PV panels in the system using equation (2) [21] and plotted against 24 hours as shown in Figure 2.

$$P_{pv}(t) = p_{pv-Each}(t) \times N_{pv}(t) \quad (2)$$

Where -

$\boldsymbol{P_{Rs}}$= Rated PV power in watt,

$\boldsymbol{r}$ = Solar irradiance in W/m^2,

$\boldsymbol{R_{CR}}$ = Certain solar irradiance point (150 W/m^2),

$\boldsymbol{N_{pv}}$=Number of PV panels,

$\boldsymbol{R_{SRS}}$= Solar irradiance in the standard environment is 1000 W/m^2,

$\boldsymbol{p_{pv-Each}}$ = Power output of each PV panel in watt,

$\boldsymbol{P_{pv}}$=Total power output combining of all installed PV panels in watt

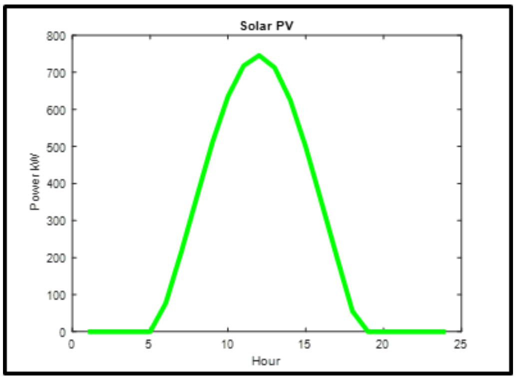

Figure 2: Power Output of Solar PV System

2. Load:

Load uncertainty is considered a crucial factor in planning applications of power systems to decide the need for BES units or load shedding [14]. In this work, the load uncertainty is accounted for OPSBES using a probabilistic approach (Johnson S_B PDF) to reflect the behaviour of a real system. For the deterministic approach, the real data of load (kW) for a particular site is considered for one day as depicted in Figure 5 (blue curve) [19].

For the probabilistic approach, the load data is collected for five years [19] and the best suitable Johnson S_B PDF for the given load pattern is found using EasyFit 5.5. The PDF predicts the probability of load values as 'Z' (on the X axis in kW) and Johnson S_B PDF (on the Y axis) for a particular hour. The shape parameters (γ and δ), load demand (Z), and the best-fitted load data curves using Johnson S_B PDF are found for 24 hours using equation (3). The best-fitted predicted load curves for 24 hours are obtained, but for simplicity, predicted load curves for two specific hours are shown by Figure 3 (12th Hour) and by Figure 4 (at 21st Hour). All parameters (Gamma, Delta, Lambda, and X) for Johnson S_B PDF are calculated using equation (3) and presented in Table 1. The load obtained for 24 hours is presented by a curve in Figure 5 (orange curve). If X is a random variable, then the predicted load variable (Z) in kW can be found by Johnson S_B distribution using equation (3) [22] as

$$Z = \gamma + \delta log\left[\frac{(X-\theta)}{(\theta+\lambda-X)}\right] \quad (3)$$

Table 1: Parameters (Gamma, Delta, Lambda and Xi) of Load for Johnson S_B PDF

Time (Hour)	Shape Parameter (Gamma-(γ))	Shape Parameter (Delta (δ))	Scale Parameter (Lambda-(λ))	X	Load (Z) kW
1	-0.34076	0.84889	2542.8	4689.7	2646.459
2	-0.34022	0.78879	2395.2	4676.1	2607.583
3	-0.39138	0.72934	2285.8	4680.4	2596.59
4	-0.38118	0.74446	2333.8	4684.9	2609.385
5	-0.41181	0.67209	2229.8	4844.2	2659.822
6	-0.4405	0.80285	2665.4	5082.4	2875.345
7	0.04521	0.87069	3269.8	5765.1	3170.105
8	0.02639	0.7947	3330.7	5856.1	3226.45
9	0.06425	0.77834	3787	5749.2	3252.478
10	0.04764	0.77306	3948.4	5521.5	3202.527
11	-0.06243	0.77198	3882.8	5165	3073.339
12	-0.21982	0.78038	3863.1	4756.1	2966.372
13	-0.26341	0.77127	3845	4593.1	2899.297
14	-0.35543	0.76368	3842.6	4412	2864.02
15	-0.40062	0.75997	3706.2	4428.5	2851.934
16	-0.31298	0.78231	3867.5	4498.5	2886.526
17	-0.24057	0.7717	3985.3	4723.8	2984.373
18	-0.15018	0.75495	4010.3	5069	3106.063
19	-0.21124	0.67887	3761.9	5705.3	3350.335
20	-0.10864	0.72538	3340.8	6297.5	3457.072
21	-0.20404	0.80906	3312.5	5970.6	3346.962
22	-0.16641	0.71456	2934.1	5797	3175.78
23	-0.34792	0.81684	2563.8	5304.9	2914.398
24	-0.36325	0.85412	2654.3	4813.6	2728.839

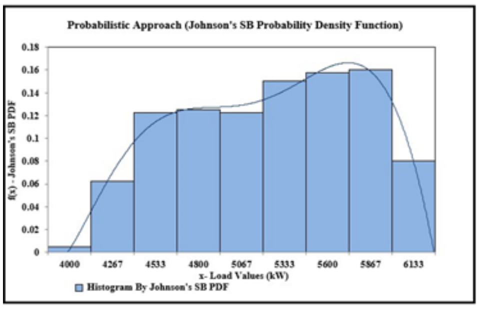

Fig 3: Load at 12th Hour by Johnson S_B PDF

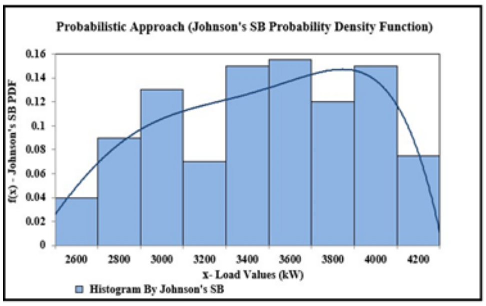

Fig 4: Load at 21st Hour by Johnson S_B PDF

The load for both approaches (deterministic- blue curve and probabilistic-Johnson S_B distribution-orange curve) are plotted for 24 hours as shown in Figure 5. The OPSBESS can be found after solving MOF along with constraints for all load conditions.

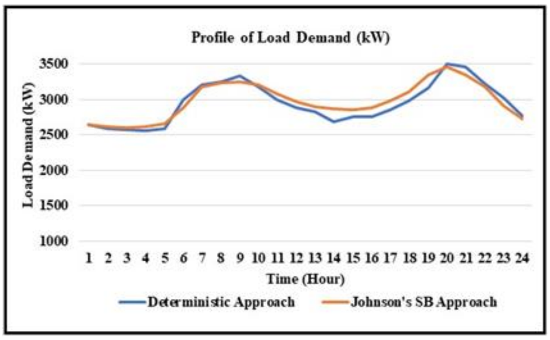

Fig 5: Profile of Load Demand

3. Battery Energy Storage System (BESS):

The BESS is integrated to absorb excess energy (charging) from the installed solar PV during the day at low load and inject energy (discharging) into the system during the night. The charging and discharging energies of the BESS at time 't' can be calculated by finding the difference between energy generated from six PV systems at time 't' and load at the same time 't'. The energies are calculated for both deterministic and probabilistic approaches (Johnson S_B PDF). These charging and discharging modes are presented by the equations - (4) and (5) [21] and energy (EBESS) is determined for 24 hours.

Charging Mode:-

$$E_{BESS}(t) = E_{BESS}(t-1) \times (1-\sigma) + \left[E_{pv}(t) - \frac{E_{load}(t)}{\eta_{inv}}\right] \times \eta_{BESS} \quad (4)$$

Discharging Mode:-

$$E_{BESS}(t) = E_{BESS}(t-1) \times (1-\sigma) - \left[\frac{E_{load}(t)}{\eta_{inv}} - E_{pv}(t)\right] \times \eta_{BESS} \quad (5)$$

Where-

$E_{PV}(t)$ = Energy generated by solar PV in kWh at instant t,

$E_{BESS}(t)$ = Energy stored in BESS in kWh at instant t,

$E_{load}(t)$ = Energy supplied to load in kWh at instant t,

σ = Self-discharge rate of BESS,

η_{inv} = Efficiency of Inverter, η_{BESS} = Efficiency of BESS

B. Multi-objective Problem Formulation and Constraints:

The power flow, power losses, voltage stability, and power stability of RDSs change due to the integration of BES, its placement, and sizing in the power system. So, these should be incorporated for finding OPSBES. In this work, the objectives related to active power losses, voltage stability, and power stability of the system such as minimization of APL, minimization of PSI, and maximization of VSI are considered. These parameters are optimized simultaneously for OPSBES considering load uncertainty. The strategy of simultaneous and sequential distributed BES placement with their optimum sizes is applied with deterministic and probabilistic approaches for grid-connected PV-BES system as shown in Figure 1.

The mathematical formulations of these objective functions - APL, PSI, and VSI are expressed as follows:

1. a) Minimization of Active Power Loss (APL) (F1): In electrical power systems, huge power losses occur during power transfer reducing the annual profits of the utility in RDSs. So, minimization of power losses with deterministic and probabilistic load is considered as one of the objectives, which is presented by equation (6) and referred from [10]-

$$F1 = Minimization\ of \sum_{i=1}^{N}\sum_{j=1}^{N} \alpha ij(PiPj + QiQj) + \beta ij(QiPj - PiQj) \quad (6)$$

where –

$\alpha_{ij} = [r_{ij} \cos(\delta_i - \delta_j)/V_iV_j]$ and $\beta_{ij} = [r_{ij} \sin(\delta_i - \delta_j)/V_iV_j]$

N= Total number of buses in the system,

P_i and Q_i = Real and Reactive power injections at the i^{th} bus in watt and VAr respectively,

r_{ij} = Resistance of branch between buses i and j in ohm,

V_i and δ_i = Voltage magnitude (volts) and the angle (radians) at the i^{th} bus respectively,

V_j and δ_j = Voltage magnitude (volts) and the angle (radians) at the j^{th} bus, respectively

1. b) Minimization of Power Stability Index (PSI) (F2): The PSI decides the line voltage stability. A value closer to zero (PSI ≤ 0), offers better line voltage stability of the system. PSI locates the weakest bus in the system, leading to line voltage instability in the future due to increased load. It is as important as APL and VSI for better line voltage stability. The PSI values for all buses are calculated without BES and organized in a descending order and the bus with the highest PSI value is the most appropriate bus for BES placement. For a stable voltage operation of a 2-bus system, the PSI is presented by equation (7) [23]-

$$PSI = \frac{[4rij(PL - PG)]}{[|Vi|cos(\theta - \delta)]^2} \leq 1$$

$$F2 = Minimization\ of \frac{[4rij(PL - PG)]}{[|Vi|cos(\theta - \delta)]^2} \leq 1 \quad (7)$$

Where -

r_{ij} = Line resistance of the branch connecting buses i and j in ohm,

P_L= Real power at the load bus in watt,

P_G = Generated real power of the system in watt,

Θ = Line impedance angle in radians,

δ = Phase angle in radians

1.c) Maximization of Voltage Stability Index (VSI) (F3): The VSI reflects line voltage stability. The higher the VSI, the better the line voltage stability. The VSI of a branch is calculated using equation (8) and needs to be improved as per the constraint given by equation (17). If VSI is less than one, the system is stable and if VSI is more than one, the system is unstable. Equation (8) expresses the proposed objective function for the maximization of VSI. The VSI of a branch connecting nodes i and j in a power system can be written as a quadratic equation (8) and calculated under load uncertainty [10], [24] as -

$VSI_{ij} = V_j^{\,4} - 4(P_i r_{ij} + Q_i x_{ij})V_j^{\,2} - 4(P_i x_{ij} - Q_i r_{ij})^2$ (8)

Where -

r_{ij} and x_{ij} = Resistance and Reactance of the branch connecting nodes i and j in ohm,

P_i and P_j = Active power at the sending and receiving end in watt (W),

Q_i and Q_j = Reactive power at the sending and receiving end in voltampere reactive (VAR),

V_i and δ_i = Voltage magnitude (volts) and the angle (radians) at the i^{th} bus, respectively,

V_j and δ_j = Voltage magnitude (volts) and the angle (radians) at the j^{th} bus, respectively

The bus having the lowest VSI is the most appropriate bus for BES placement to achieve better stability of the system. So, VSI is inversely stated as shown in equation (9). Thus, the third objective function becomes -

F3 = Maximization of VSI= Maximization of VSI_{ij} $\forall$ i, j (9)

Hence by combining, equation (6) to equation (9), the minimum of MOF can be formulated. OPSBES is calculated for a particular load uncertainty after satisfying all constraints mentioned below-

Multi-objective Problem Formulation: OPSBES for better system performance with acceptable reliability and economics is a challenge. Reasons include matching intermittent solar PV generation, and uncertain load with associated unpredictable charging and discharging BES behaviour. This problem of OPSBESS needs to be carefully handled as the worldwide deployment of BES is exponentially increasing. A small change in sizing and locations of BES may affect the sizing and losses of the system with tremendous monetary change. In this work, OPSBES is tackled by considering the Multi-Objective Function (MOF) in view of load uncertainty. Two Multi Criteria Decision Making (MCDM) methods are applied as Weighted Sum Method (WSM) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [25]. The WSM prioritised the objectives, while TOPSIS along with IGWO algorithm optimized the results under load uncertainty (deterministic and probabilistic approach).

The MOF is framed as given by equations (10) to (13). The weights W1, W2, and W3 are set as per the objective function. The values of these weights are changed from zero to one in increments of 0.1. It is observed that APL changes are sensitive to slight variations in BES size than PSI and VSI. So, APL is given the highest priority over PSI and VSI, with final values of W1, W2, and W3 as 0.4, 0.3, and 0.3 respectively for finding OPSBESS. This MOF decides the best solution for OPSBESS which is mathematically expressed by equation (13). Thus, the bus with the lowest value of MOF is an appropriate option for the BES placement.

$$\sum_{i=1}^{n}(W_i) = \sum_{i=1}^{3}(W_i) = 1 \quad (10)$$

Where- W1, W2, W3: Weight factors for three objective functions as-

(W1+W2+W3) = (0.4 +0.3 + 0.3) =1 (11)

Minimization of MOF = Min[(W1×F1) + (W2×F2) + (W3 F3)] (12)

Where F1 is the Minimization of Active Power Loss (APL), F2 is the Minimization of Power Stability Index (PSI) and F3 is the Maximization of Voltage Stability Index (VSI).

So, using equations (11) and (12), MOF can be written as-

Minimization of MOF = Minimization of [(0.4×APL) + (0.3×PSI) + (0.3/VSI)] (13)

The equation (13) finds the optimized solution of OPSBESS.

Constraints: The MOF presented in equation (13) is subjected to the following constraints:

The active and reactive power balance at i^{th} bus is represented by equations (26) and (27).

$$P_i = Vi \sum_{j=1}^{N} VjYij\cos(\theta ij + \delta j - \delta i) \quad \forall i \quad (14)$$

$$Q_i = -Vi \sum_{j=1}^{N} VjYij\sin(\theta ij + \delta j - \delta i) \quad \forall i \quad (15)$$

Where -

V_i and δ_i = Voltage magnitude (volts) and the angle (radians) at the i^{th} bus,

V_j and δ_j = Voltage magnitude (volts) and the angle (radians) at the j^{th} bus,

Y_{ij} and θ_{ij} = Elements of Y-bus matrix and impedance angles

The maximum installation size of a single BESS at i^{th} bus should be less than a certain maximum limit, which is shown by equation (16) so as to avoid overloading of the i^{th} bus.

$S_{BESSi} \leq S_{BESSmax}$ $\forall$ i (16)

The RDSs integrated with solar PV and BES may lead to voltage rise at buses due to the reverse flow of inrush current and power. Hence, the voltage magnitude at each bus should be verified for the minimum and maximum limits for simultaneous and sequential BES placements with IGWO algorithm. These limits are given as:

$$V_{i(min)} \leq V_i \leq V_{i(max)} \qquad \forall\, i \qquad (17)$$

Where V_i denotes the magnitude of the voltage at i^{th} bus. Any power system equipment is designed to operate within the acceptable tolerance of ± 5 % of rated voltage. Therefore, in this case, minimum ($V_{i(min)}$) and maximum ($V_{i(max)}$) voltage levels are 0.95 pu and 1.05 pu respectively.

Thus, after satisfying all the constraints, equation (13) is solved using optimization algorithm to find OPSBES to be placed at the highest value of MOF. The multi-objective optimization algorithm in view of load uncertainty is explained in Section III.

III. Methodology for OPSBES Optimization Algorithm

In this work, the problem of OPSBES is determined for multiple objectives such as APL minimization, PSI minimization, and VSI maximization with their different weights using Modified IEEE 33 Bus RDS (MBRDS) in view of load uncertainty (deterministic and probabilistic approach). To solve this multi-objective problem, the load flow is run with MOF and their constraints many times, which is quite time-consuming and complicated. Hence, the use of the optimization technique is essential.

There are various optimization techniques reported in the literature for addressing the OPSBESS as GA [1], [6], COA [7], IEHO [10], etc. An IGWO method is chosen being suitable for the said problem in the power system [26]. In this work, the priorities of objective functions are decided by WSM method and TOPSIS is combined with IGWO (WSM-TOPSIS-IGWO) to find out optimized solution under load uncertainty.

The IGWO is applied to solve OPSBESS to satisfy MOF along with the constraints using MBRDS under load uncertainty (deterministic and probabilistic approach). The results of optimization for simultaneous and sequential (aggregated and distributed) BES placements are discussed in section IV.

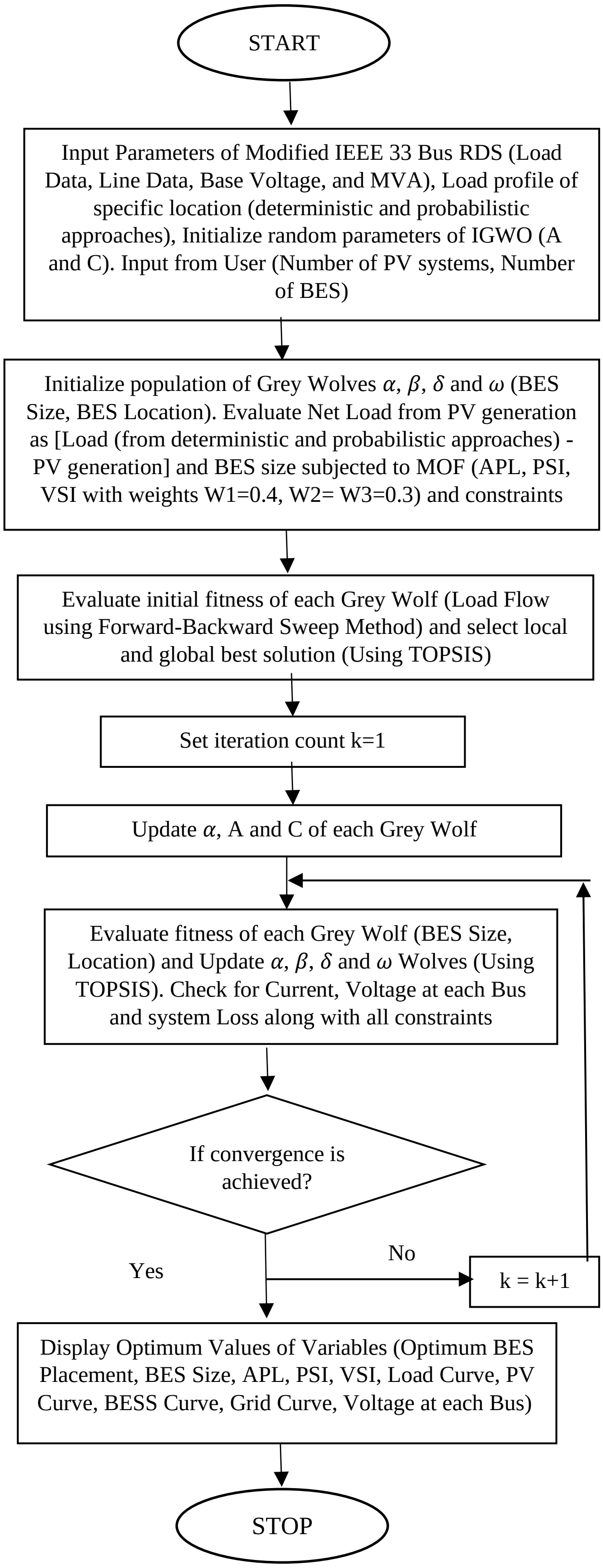

Fig 6: Flow Chart of IGWO Methodology for OPSBES

IV. Results and Discussion

The OPSBESS is solved for MOF along with the constraints using WSM-IGWO-TOPSIS methods. Two criteria namely simultaneous and sequential BES placements are analysed with six different cases (Case I to Case VI) considering the optimum BES size on a MBRDS. The results for aggregated and distributed BES placements for MBRDS are tabulated and graphically presented for six cases in view of load uncertainty (deterministic and probabilistic approach-Johnson S_B PDF) in this section.

Case I. Modified IEEE 33 Bus Radial Distribution System (MBRDS): In this study, the OPSBESS problem is formulated and solved using an MBRDS. It is a 12.66 kV system with real and reactive power demands of 3.5 MW and 2.1 MVAr respectively. The active and reactive power losses are 20.144 MW and 17.51MVAR.

Case II. MBRDS - Without BES: In this case, considering the voltage improvement and loss reduction criteria, six PV systems are placed at specific six locations like at bus numbers - 3, 8, 14, 25, 30, and 31 of the MBRDS.

Case III. MBRDS with Aggregated BES (Single BES Unit of 100% of Optimum Size): After placing six PV systems, load flow is run to find the optimum size and candidate bus that will satisfy MOF along with the constraints. This candidate bus (bus 30) is the highest priority bus for the placement of single BESS (aggregated BESS) which minimized APL and PSI, and maximised VSI with the optimum size. This case is shown in Figure 7. The changes in the system losses, PSI, VSI, voltage profiles, and system power flow for this aggregated BESS are shown in Figures 10 - 15. The other cases with distributed BES placements are not shown for simplicity.

Case IV. MBRDS with Distributed BES (Two BES Units), **Case V.** MBRDS with Distributed BES (Three BES Units) **Case VI.** MBRDS with Distributed BES (Four BES Units): For the next three cases (Case IV to Case VI), the logic of simultaneous and sequential BES placements is applied to MBRDS. For case IV to case VI, the optimum size of aggregated BES unit is distributed into two (60% and 40%-initial guess), three (60%, 20%, and 20%), and four (60%, 20%, 10%, and 10%) suitable sizes, depending upon the number of BES units required to be installed in that system. The highest size of BES (60% of the optimum size-) is placed at the first location and the remaining BES units are placed simultaneously in one approach and sequentially in another approach in the system depending upon the number of BES units to be installed. These six cases (Case I to Case VI) are presented for the deterministic approach and probabilistic (Johnson S_B) approach in Result Table 2.

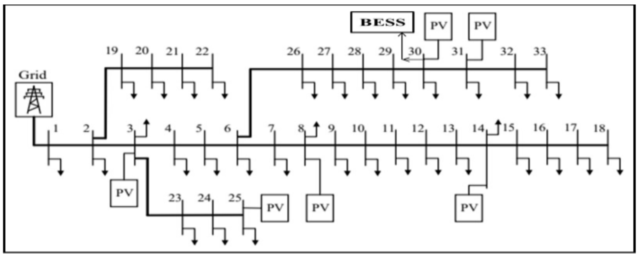

Fig 7: Modified IEEE 33 Bus RDS with 6 PV and Aggregated BESS Placements - Depicting Case III

In simultaneous BES placement, depending upon the number of BES units to be installed in the system, the load flow is run once to find out APL, PSI, and VSI values. For example, for the placement of two BES units (60% and 40%), after running the first load flow with the placement of six PV systems, two bus locations are identified. The first BES unit (60% of the optimum size of BES) is placed at the weakest bus (Bus 30) and the second BES unit (40% of the optimum size of BES) is placed at the second weak bus (Bus 7) to improve performance of the system. This process is followed for deterministic and probabilistic (load uncertainty) approaches. The optimum BES size required for deterministic and probabilistic (Johnson S_B) approaches are 0.72MW and 0.822MW respectively. This optimum BES size is simultaneously distributed as per the number of BES units required to be installed in the system.

In sequential BES placement, depending upon the number of BES to be installed in the system, the load flow is run for those many times. For example, for the placement of two BES units (60% and 40%), the first BES unit (60% of the optimum size of BES) is placed at the weakest bus (Bus 30) after running the first load flow with the placement of six PV systems. Once the first BES unit of 60% of optimum size is placed, the load flow is run again to find out the next weakest bus (Bus 26). The second BES unit (40% of the optimum size of BES) is placed on that bus. This process is followed for deterministic and probabilistic (load uncertainty) approaches. The optimum BES size required for deterministic and probabilistic (Johnson S_B) approaches are 0.72MW and 0.822MW respectively. This optimum BES size is sequentially distributed as per the number of BES units required to be installed in the system. The number of BES units required to be installed in the system is taken as input from the user and used in IGWO program for optimizing the MOF with constraints. Case I to Case VI are presented with simultaneous and sequential OPSBES considering deterministic and probabilistic approaches in Result Table 2.

From Result Table 2, it is observed that the optimum BES size required for deterministic and probabilistic (Johnson S_B) approaches are 0.72MW and 0.822MW respectively. The aggregated BES size with the probabilistic approach (0.822 MW) is higher than the deterministic approach (0.72 MW) due to consideration of uncertain parameters in load demand. Therefore, the overall loss reduction due to sequential BES placement is more significant in probabilistic (Johnson S_B) approach than that of deterministic approach. It is seen that as compared to simultaneous BES placement, loss reduction in sequential BES placement is noteworthy in both approaches and can be graphically presented using Figure 8 and Figure 9. In both these figures, only four cases (Case III to Case VI) are presented to clearly show the loss reduction due to distributed BES with their simultaneous and sequential placements. By comparing both figures, it is observed that losses reduced with sequential BES placement are considerable than simultaneous BES placement though the BES capacity is small (less than 1 MW). In practice, when BES capacity is more than a few MW, then loss reduction will be substantial to improve the system performance to a greater extent and thus signifies the study.

Result Table 2: Simultaneous and Sequential OPSBES with Deterministic and Probabilistic Approaches

Case Number	***Deterministic Approach***				***Probabilistic Approach***			
	Aggregated BESS Size =0.72 MW				***Aggregated BESS Size =0.822 MW***			
	Simultaneous OPSBES		***Sequential OPSBES***		***Simultaneous OPSBES***		***Sequential OPSBES***	
	Location & Size (MW) of BES	***System Losses (MWh)***	***Location & Size (MW) of BES***	***System Losses (MWh)***	***Location & Size (MW) of BES***	***System Losses (MWh)***	***Location & Size (MW) of BES***	***System Losses (MWh)***
Case I -MBRDS (Zero PV and Zero BES)	-	20.144	-	20.144	-	20.144	-	20.144
Case II (6 PV systems of total 0.750 MW)	-	14.047	-	14.047	-	14.047	-	14.047
Case III (1 BES unit of optimum size-Aggregated 100 %)	30 (0.72)	3.434	30 (0.72)	3.32	30 (0.822)	3.26	30 (0.822)	3.024
Case IV (2 BES units as 60% & 40% of optimum size)	30 (0.432), 7 (0.288)	3.248	30 (0.432), 26 (0.288)	3.12	30 (0.493), 7 (0.3288)	3.035	30 (0.493), 26 (0.328)	2.841
Case V (3 BES units as 60%, 20% & 20% of optimum size)	30 (0.432), 7 (0.144), 14 (0.144)	3.042	30 (0.432), 26 (0.144), 14 (0.144)	2.791	30 (0.493), 7 (0.164), 14 (0.164)	2.8427	30 (0.493), 26 (0.164), 14 (0.164)	2.634
Case VI (4 BES units as 60%, 20%, 10% & 10% of optimum size)	30 (0.448), 7 (0.144), 14 (0.072), 31 (0.072)	2.793	26 (0.448), 30 (0.144), 14 (0.072), 25 0.072)	2.541	30 (0.493), 7 (0.164), 14 (0.082), 31 (0.082)	2.658	30 (0.493), 26 (0.164), 14 (0.082), 25 (0.082)	2.4314

From Result Table 2, the aggregated BES size with the probabilistic approach (0.822 MW) is higher than the deterministic approach (0.72 MW) due to consideration of uncertain parameters in load demand. Therefore, the overall loss reduction due to sequential BES placement is more significant in the probabilistic (Johnson S_B) approach than that of the deterministic approach. It is seen that as compared to simultaneous BES placement, loss reduction in sequential BES placement is significant in both approaches and can be graphically presented using Figure 8 and Figure 9. In both these figures, only four cases (Case III to Case VI) are presented to clearly show the loss reduction due to distributed BES with their simultaneous and sequential placements. By comparing both figures, it is observed that losses with sequential BES placement are considerably less than simultaneous BES placement though the BES capacity is small (less than 1 MW). In practice, when BES capacity is more than a few MW, then loss reduction will significantly improve the system performance to a greater extent and thus signifies the study.

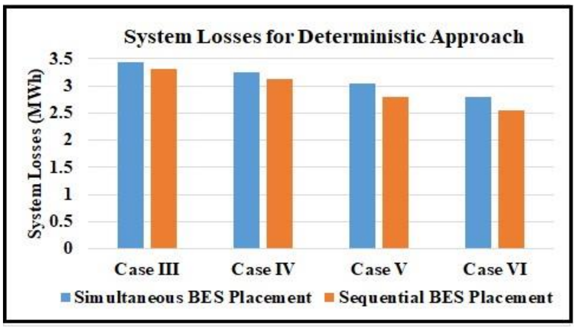

Fig 8: System Losses for Deterministic Approach

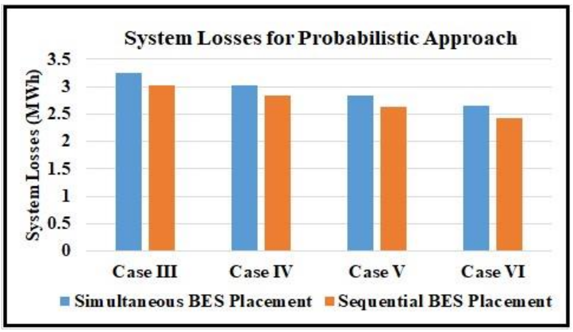

Fig 9: System Losses for Probabilistic Approach

Results of Aggregated OPSBES (Case III) for Probabilistic Approach:

In this work, multiple objectives such as APL minimization, PSI minimization, and VSI maximization with their different weights for OPSBESS are studied for MBRDS. The uncertainties in load demand are accounted for using the probabilistic (Johnson S_B PDF) approach and compared with the deterministic approach. The results of system losses, PSI, VSI, voltage profile and convergence curve of IGWO are determined for Case III with the logic of simultaneous and sequential BES placements. Only the results for aggregated OPSBESS for Johnson S_B PDF are shown to avoid repetition. A sample case of variations in system losses (Figure 10), PSI (Figure 11), VSI (Figure 12), voltage profile (Figure 13), system profile (Figure 14), and convergence curve of IGWO (Figure 15) for probabilistic approach are shown for aggregated BES. These figures are presented for three conditions as - MBRDS, with placements of 6 PV (MBRDS+6 PV) and Aggregated BESS (MBRDS+ Aggregated Battery Case- Case III).

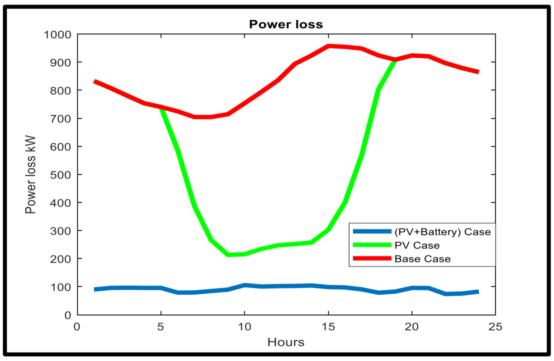

Fig 10: System Losses for Base Case, 6 PV and Aggregated BES Placements

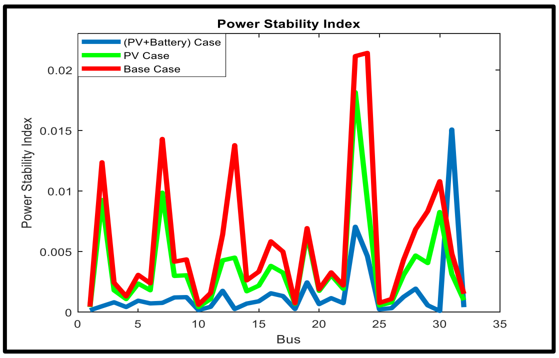

Fig 11: PSI for Base Case, 6 PV and Aggregated BES Placements

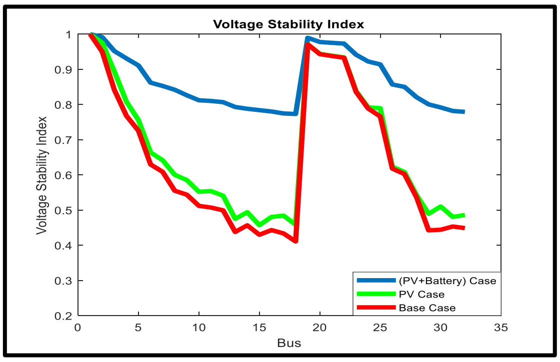

Fig 12: VSI for Base Case, 6 PV and Aggregated BES Placements

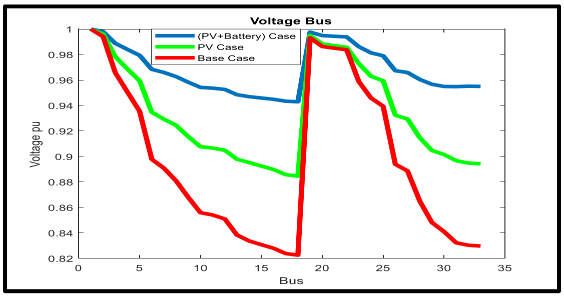

Fig 13: Voltage Profile for Base Case, 6 PV and Aggregated BESS

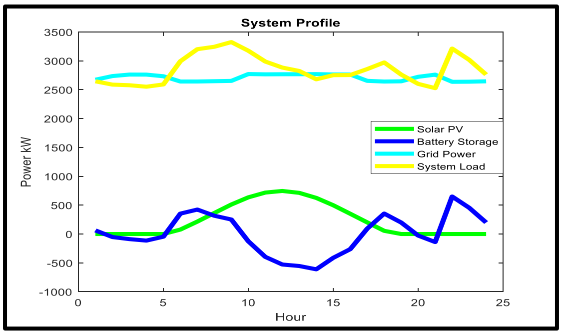

Fig 14: System Profile with Solar PV, BES and Grid Power

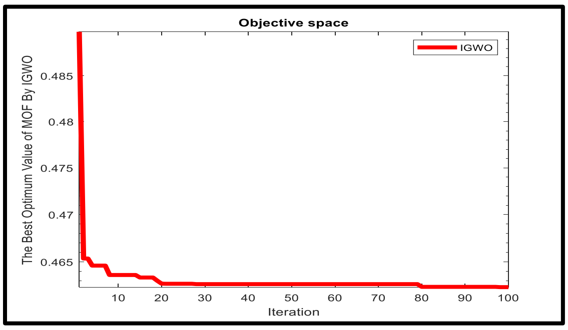

Fig 15: Convergence Curve of IGWO

V. Conclusions

The Optimum Placement and Sizing of Battery Energy Storage (OPSBES) is analysed for multiple objectives using WSM- IGWO-TOPSIS techniques in view of load uncertainty. The randomness in the load is accounted for and its effect on OPSBES is analysed for the probabilistic (Johnson S_B PDF) approach and compared with the deterministic approach. Two criteria, namely simultaneous and sequential optimum-sized BES placements are executed on an MBRDS. The sequentially distributed BES stabilises the system to a greater extent than simultaneously distributed BES, despite its charging mode. As compared to aggregated BES, significant loss reduction is observed with distributed BES placement. This study can be worked out for different energy sources such as PV- wind turbine - fuel cell - BES for RDS.

Author contributions

Gauri Karve: Conceptualization, Methodology, Software, Writing-Original draft preparation, Validation.

Dr Mangesh Thakare and **Dr. Geetanjali Vaidya:** Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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