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Energy Savings in Renewable Integrated Distribution Network and Impact of Storage Devices

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Abstract
The high penetration of wind and solar became the primary task for the optimal size of energy storage to support the power mismatch. Energy loss reduction is a significant issue for Renewable energy planning in the Distribution system. In the present work, energy savings have been obtained in a renewable integrated distribution system. The impact of the energy storage device has also been evaluated. The main contribution of this paper is: (i) Optimal location of DGs and battery are obtained by solving single and multi-objective functions. (ii) determination of DG and battery size for loss savings. (iii) Impact of battery energy storage device on loss profile and total cost of the system. The simulation results of the test system have been compared with other existing results.

Keywords: *Radial distribution system, Battery energy storage device, Energy Loss minimisation, optimal sizing and siting, Renewable Energy sources.*

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I. Introduction

Many of the utilities have been used to compensate for the loss in the distribution network. Therefore, the location and sizing of DGs is the major issue in the distribution network. The co-ordination of energy saving with the overall cost of the system is another issue in the system.

A lot of literature is available for optimal placement of DGs to minimize the power loss and voltage deviations in a network. Authors in [1] presented the annual energy loss minimization with the integration of DGs in the network. The optimal DG placement using Stud Krill herd Algorithm (SKHA) for the radial distribution system in [2]. The population-based Gbest-guided Artificial Bee Colony (GABC) optimization algorithm has used to minimize the power loss and determine the impact of shunt capacitor with DG placement [3]. Many of the literature is based on the nature-inspired algorithm. In this way, the optimal location of DG has been obtained by using Dragonfly algorithm [4]. An improved partical swarm optimization has been used for the installation of DG in Microgrid (MG) system [5]. The analytical representation are used to obtain the size of DG at various locations for total loss minimisation. The loss saving equations was also represented in [6]. The different types of voltage-dependent loads and a separate line X/R ratios have taken into account to study the distribution load flow [7]. Murty et al. [8] have considered the multi-objective based optimization problem for the uncertainty nature of renewable power generation. The reactive power support has also been done using the instllation of DG location in [9]. The optimal power factor has considered for the position of DG to minimize the power loss using PSO algorithm by Kansal et al.[10]. The Mixed Integer Non-Linear Programming (MINLP) formulation has introduced in [11] for loss minimization. The DG location has been obtained by combined power loss sensitivity (CPLS) approach; however, the battery storage was not considered. The clearness index of probability density function (pdf) has been used along with Monte Carlo simulation (MCS) to model the solar irradiance [12]; however, the battery energy support has not considered. MG with four different types of DG has obtained to minimize power loss and to regulate the bus voltage also. In the literature [1-11] the power loss scenario-based optimal location of DGs was obtained. Yet, battery storage has not been found in the literature [1-11].

The combined dispatch strategy for battery along with PV-Diesel system has been implemented in the HOGA (Hybrid Optimisation by Genetic Algorithms) program [13]. The wind-based Distribution generation (DG) has not considered. The multi-source based hybrid generation with battery storage using PSO algorithm has been taken into account to minimize the total power loss [14]. The battery size determination has reviewed in [15] with various indicators likewise, financial, technical and hybrid indicators. (i) In the Financial index, the local currency has become the decision making for the benefit and overall cost of the battery in renewable energy sources (RES). The net present value (NPV) of the battery energy storage system (BESS) [16] has represented to achieve the sizing and placement of ESS. An optimal scheduling analysis for the vanadium redox battery (VRB) has described based on cost-benefit review for MG application [17]. In the technical index, the ESS has to support the dynamic and steady-state behaviour of RES in the MG system. The risk-informed decision-making process has introduced to obtain the size of battery storage by using the probabilistic approach [18]. In the composite index, the battery size has been obtained by considering both financial and technical indicators. The size of battery storage has been determined by considering the electricity market for the wind power plant [19]. The battery storage has also been emphasized the operation and economics of the wind power intermittency. The analysis has been carried out to obtain the daily energy savings with DGs and the impact of battery energy device on the savings.

II. Problem formulation and Mathematical Model

The main objective of the paper is; to obtain optimal location and size of DG along with battery storage devices for minimization of the Daily energy loss of the network. The single and multi objectives have been considered for the analysis.

The single objective problem has formulated as:

- Minimize the Daily energy loss with DGs and battery storage devices.

The problem has been solved in two parts. In the first part: (i) The location of DGs has obtained determining the Daily energy loss minimization using PSO (Particle Swarm Optimization) algorithm. The location of battery storage has been obtained using the combined dispatch strategy in the PSO algorithm.

In the second part: (ii) the size of DGs and battery storage was obtained solving the problem with the MINLP (Mixed Integer Non-Linear Programming) in GAMS.

The multi-objective problem was formulated as:

- Minimisation of the cost of Daily energy loss and the total cost of the system

The total cost of the system consists of the cost of energy loss (CEL), the fuel cost of diesel generator, operation and maintenance cost, replacement cost, and initial installation cost of DG, PV, battery, regulator, invertors etc.

2.1 Mathematical Model and formulation

Single objective function:

(i) minimization of Daily energy loss as:

$$OF1 = \sum_{k=1}^{T}\left(\sum_{j=1}^{nl} PL_{ij}\right) \cdot \Delta k \quad (1)$$

where, PL_{ij} is the total active power loss in the line respectively. Δk is the time duration in hrs.

Multi-objective function:

(ii) Minimization of cost of energy loss and the cost of the DGs as:

$$OF2 = min\left\{C_e.TE_{Loss}^{i} + \sum_{k=1}^{T} NPV_{Batt} + \sum_{k=1}^{T}\left(NPV_{DG}^{Ren} + NPV_{DG}^{Diesel}\right)\right\} \quad (2)$$

where,

$$TE_{Loss}^{i} = 365 \times \sum_{k=1}^{T}\left(\sum_{j=1}^{nl} PL_{ij}\right) \cdot k$$

$$NPV_{Batt} = \sum_{i=1}^{nb}(N_{inv}(i) \cdot NPV_{inv} + N_{batt}(i) \cdot NPV_{batt})$$

$$NPV_{DG}^{Diesel} = Pr_{fuel} \cdot \left(\sum_{i}^{nb} fuel_{consumed}\right) \cdot T$$

$$NPV_{DG}^{Ren} = \sum_{i}^{nb} \left(N_{PV}(i) \cdot NPV_{PV} + N_{wind}(i) \cdot NPV_{wind} + N_{reg}(i) \cdot NPV_{reg}\right) \quad (3)$$

The net present value for all components are given as:

$$NPV = Cost_{Aqu} + Cost_{O\&M} + Cost_{Rep} \quad (4)$$

$Cost_{Aqu}$, is the acquisition cost, C_e is cost of the energy loss, $Cost_{O\&M}$ is the operation and maintenance cost, $Cost_{Rep}$ is the replacement cost. N_{PV}, N_{wind} , N_{batt}, N_{reg}, N_{inv} is the number of PV panel, wind turbine, battery, regulator, invertors respectively. NPV_{PV}, NPV_{wind}, NPV_{batt}, NPV_{reg}, NPV_{inv} is the net present value for PV, wind , battery, regulator, and inverter respectively. $fuel_{consumed}$ is fuel consumed by the DEGs, Pr_{fuel} is the fuel price (litter/kWh), and T is the total time period of operation.

The equality and inequality constraints are:

a. The power balance equations are as;

$P_i^k = \left(Pg_i^k - Pd_i^k\right) = V_i^k \sum_{j=1}^{n} V_j^k \ \left(G_{ij}^k \cos\left(\delta_i^k - \delta_j^k\right) + B_{ij}^k \sin\left(\delta_i^k - \delta_j^k\right)\right)$
(5)
$Q_i^k = \left(Qg_i^k - Qd_i^k\right) = V_i^k \sum_{j=1}^{n} V_j^k \ \left(G_{ij}^k \sin\left(\delta_i^k - \delta_j^k\right) - B_{ij}^k \cos\left(\delta_i^k - \delta_j^k\right)\right)$
(6)
$\forall\, i \in S_B \ \&\ k \in S_T$
where ∀i = 1,2 …. nb , ∀j = 1,2 …. nl , nb is a number of buses and nl is the total number of line. S_B is the set of buses, and S_T is the set of Time k. Pd_i^k and Qd_i^k are the active and reactive power demand for i[th] bus at k[th] time period.

b. Power generation constraints:

$$Pg_i^k = P_{deg_i}^{\ k} + N_{wind}(i) \cdot P_{wind_i}^{\ k} + N_{PV}(i) \cdot P_{PV_i}^{\ k} + N_{batt}(i) \cdot \left(P_{ch_i}^{\ k} - P_{dis_i}^{\ k}\right) \quad (7)$$

$$Qg_i^k = Q_{deg_i}^{\ k} + N_{wind}(i) \cdot Q_{wind_i}^{\ k} \quad (8)$$

where, $P_{deg_i}^{\ k}$ and $Q_{deg_i}^{\ k}$ are the active and reactive power supplied by diesel generator for i[th] bus at k[th] time period.

(iv). Power Loss equation

$$\left|P_{ij}^k\right| = \left|V_i^k V_j^k \left(G_{ij}^k \cos\left(\delta_i^k - \delta_i^k\right) + B_{ij}^k \cos\left(\delta_i^k - \delta_i^k\right)\right) - (V_i^k)^2 G_{ij}^k\right| \le Pl_{max}^k \quad (9)$$

where, Pl_{max}^k is the maximum apperent power flow through the line at kth hrs. $l \in S_L$ is the set of line.

Inequality constraints:

(v). Constraints for Transmission line

$$P_{fsmin_j}^{\ k} \le P_{fs_j} \le P_{fsmax_j}^{\ k},\ i \in S_{fs}$$
$$Q_{fsmin_i}^{\ k} \le Q_{fs_j} \le Q_{fsmax_j}^{\ k},\ i \in fs\ r$$
$$P_{frmin_j}^{\ k} \le P_{fr_j} \le P_{frmax_j}^{\ k},\quad i \in S_{fr}$$
$$Q_{frmin_i}^{\ k} \le Q_{fr_j} \le Q_{frmax_j}^{\ k},\ i \in S_{fr} \quad (10)$$

(vi). Capacity Limits of the distribution generation system

$$P_{Gi}^{min} \le Pg_i \le P_{gi}^{max},\ i \in S_G \quad (11)$$

$$Q_{gi}^{min} \le Qg_i \le Q_{gi}^{max},\ i \in S_G \quad (12)$$

(vii). Voltage and angle limits

$$V_i^{min} \le V_i \le V_i^{max},\ i \in S_B \quad (13)$$

$$\delta_{min_j}^{\ k} \le \delta_i \le \delta_{max_j}^{\ k},\ \forall i = 1,2 \ldots . nb \quad (14)$$

(viii). Power factor limits

$$pf_i^{lo} \le pf_i \le pf_i^{up},\ i \in S_B \quad (15)$$

2.2 Mathematical modelling of energy sources

In this section, the mathematical modelling of renewable-based DGs, diesel generator based DG and battery energy storage are given.

2.2.1. Modelling of wind power generation

The quadratic model of wind power generation has been taken for analysis. The wind turbine model is as:

$$P_{wind} = \begin{cases} P_{rated} \cdot \left({(v_{rated} - v_{in})^2}/{(v_r - v_{in})^2} \right); & v_{in} \le v_{rated} \le v_r \\ P_{rated}\,; & v_r \le v_{rated} \le v_{out} \\ 0 \quad ; & v_{rated} > v_{out}\ and\ v_{rated} < v_{cut} \end{cases} \quad (16)$$

where, P_{wind} is the wind power output, P_{rated} is the rated wind power, v_{in} is cut in the velocity of wind, v_{out} is cut out wind velocity. The Fig.1 shows the wind turbine output vs wind velocity curve. The cut in the velocity of the wind v_{in} is 3 (m/s), cut out v_{out} is 20 (m/s) and rated velocity v_{rated} is 13 (m/s) carried out for analysis.

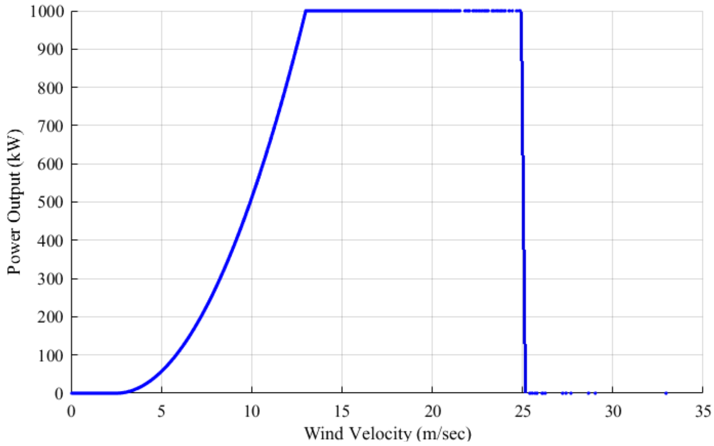

Fig 1 Wind turbine power output curve

2.2.2. Modelling of PV- based DG

The renewable source of energy, PV generator provides the DC current at 48 V. The PV generator output has been obtained using the Monte Carlo Simulation (MCS).

The solar PV model is:

$$P_{solar}(I_\beta) = N_{PV} \cdot FF \cdot V \cdot I \tag{17}$$

where, 1000 number of sampels are taken for MCS, P_{solar} is the output power, FF is the fill factor, V is the rated DC voltage, I is the DC current output, and N_{PV} is the total number of solar panel [12]. The PV generator power output over 24 hrs is shown in Fig.2.

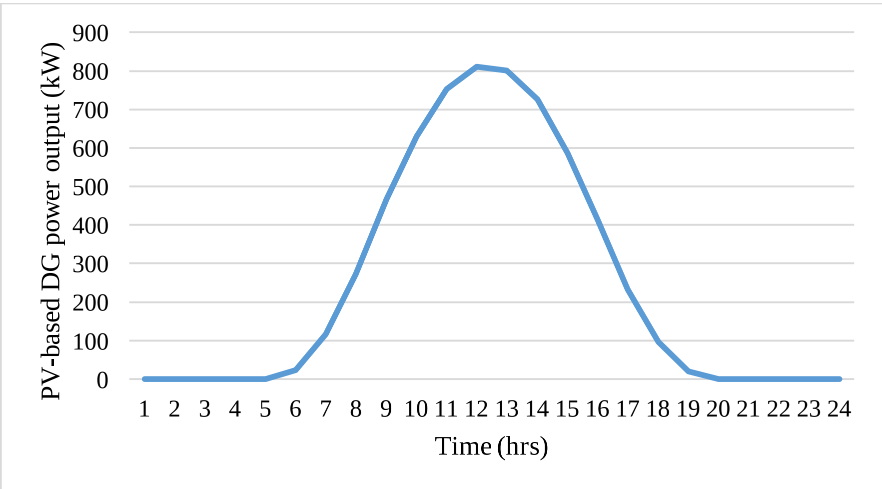

Fig 2 Solar power output curve for 24 hrs

2.2.3 Diesel generator

The diesel generator-based DG has been considered to backup for system power requirement. The diesel generator can charge the battery and supply the load demand for a short period according to the dispatch strategy. The linear model of fuel consumption for diesel generator has been considered for analysis [13]. The fuel consumption can be represented as:

$$fuel_{consumed} = B_{fuel}.P_{NGen} + A_{fuel}.P_{Gen}.\frac{1}{h} \tag{18}$$

where, P_{NGen} is Diesel Generator (DEG) rated power in kW, P_{Gen} is the output power A and B are the fuel curve coefficient. The value of A_{fuel} is 0.246 $\left(\frac{1}{kWh}\right)$ and B_{fuel} is 0.08415 [14].

2.2.4 Radial Distribution system

The radial distribution system network of 100 kVA, 12.66 kV, IEEE 33-buss system has considered as a test system. The radial distribution system has 33 buses and 32 branches [7].

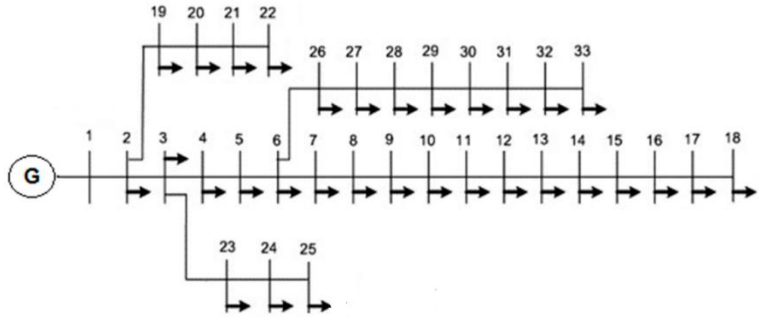

Fig.3 Equivalent circuit model of Radial Distribution system

The single line diagram of IEEE 33 bus radial distribution system is shown in Fig.3.

III. Algorithm

In this section, the various steps have explained to solve the optimization problem using MINLP solver in GAMS. The MATLAB and GAMS interfacing has also been described in this algorithm for solving the hybrid optimization algorithm.

3.1. The hybrid PSO and GAMS algorithm

In the proposed hybrid optimization algorithm from step 1 to 4; the PSO algorithm has used. Whereas in step 5 to step 8, the MINLP solver in GAMS has used for obtaining the size of DGs and battery storage.

Step 1

(a) Initialize the random population for PSO algorithm.

(b) Solve the equation for wind and solar power calculation.

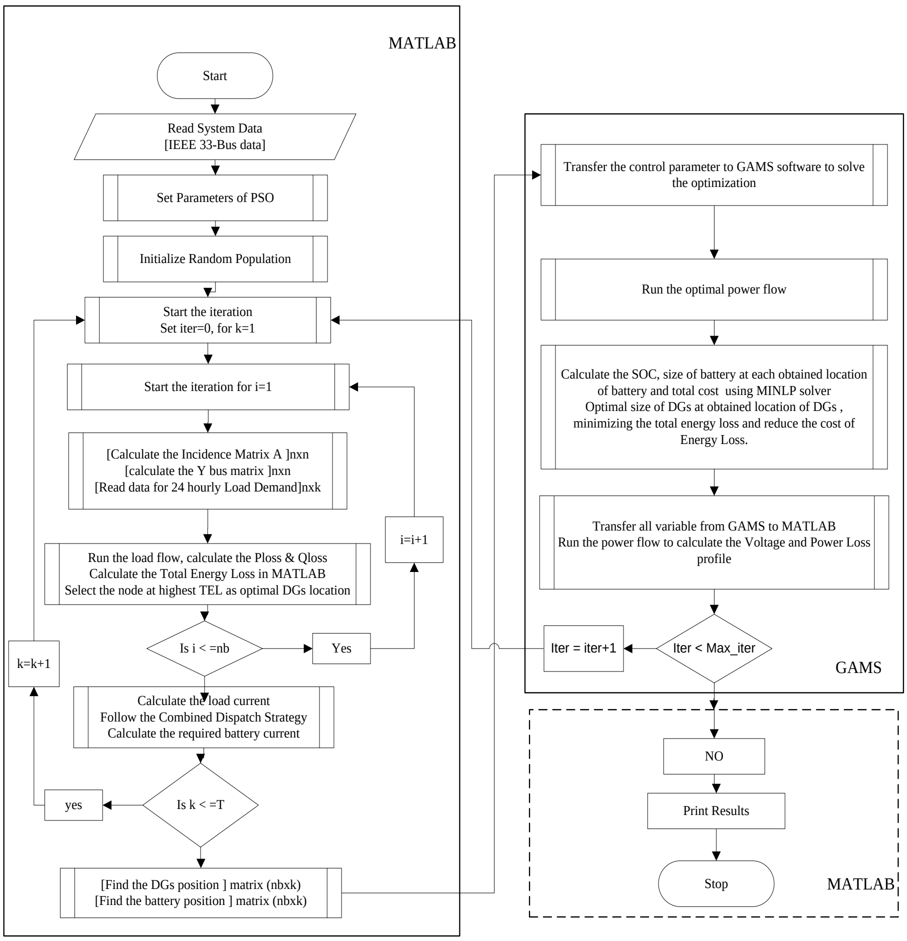

Fig.4. Flow chart for hybrid GAMS and PSO optimization

Step 2
(a) Run the load flow program for 24-hrs and obtain the base Case Daily energy loss using PSO algorithm.
(b) Select the candidate node having the highest energy loss for DG location. Save the place for DGs.
Step 3 Solve the combined dispatch strategy for each buses i=1to nb and k=1 to 24 hrs.
(a) Obtain the position of batteries at each node determining the net load current from step 2(a).
(b) The iteration for i^{th} bus and k^{th} time solve up to $i \leftarrow i+1; k \leftarrow k+1$. If $i < nb$ and k< T; go for step 2 otherwise go to next step.
Step 4. After obtaining the location of the candidate node, the size of DGs, along with battery storage, has determined. Transfer the all control parameter from MATLAB to GAMS.
(a) Solve the objective function.
(b) Obtain the size of the battery, SOC, charging and discharging of the cell.
(c) Obtain the size of DG.
Step 6 Transfer the objective variables form GAMS to MATLAB.
(a) Get the results
Step 7 Print the results.
The flow chart of the proposed hybrid algorithm is shown in Fig.4.

IV. RESULTS AND DISCUSSIONS

The results are obtained for the IEEE 33 bus radial distribution system having DGs along with the storage devices.
In objective (i) two Cases have been considered as;

- Base Case: Without DGs and Battery storage devices.
- Case 1: Single DG with Battery Storage Devices.
- Case 2: Two DGs with Battery Storage Devices.

4.1 Results for Single Objective Function

The results are obtained for IEEE-33 bus test system. The total demand for the test system is $3715 + j2300$ kVA.

1.1.1 Results for Base Case

The load data is shown in Fig.5. The Daily energy demand for 24 hrs load variation is 73.9285 MWh. The minimum voltage found is 0.9037 pu at bus number 18. The Daily energy loss for a day obtained is 2031.45 kWh. The annual cost of energy loss (CEL) obtained is 88,712.8 (€). The results are also compared with the base Case and other existing methods and techniques.

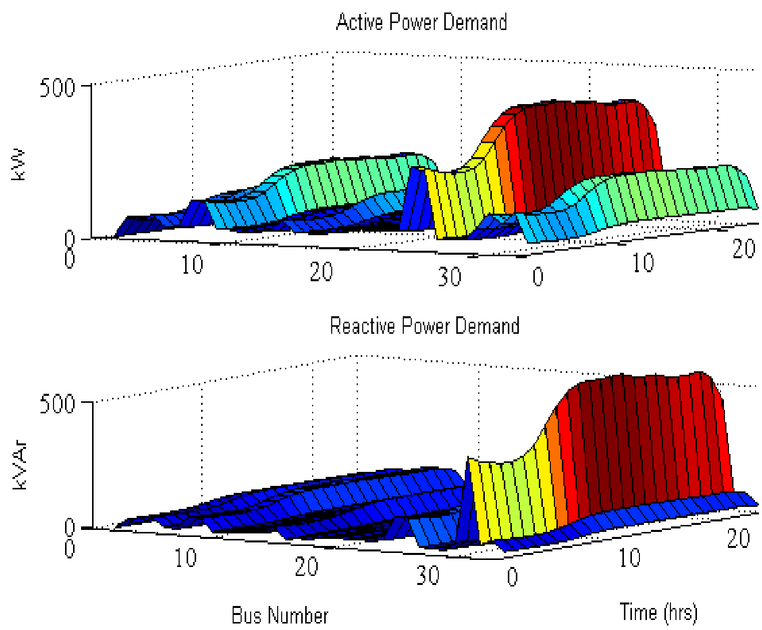

Fig.5 Load Demand for 24 hrs.

1.1.2 Case 1. Result for Single DG

The Daily energy loss profile for single DG without battery storage device is shown in Fig.6.

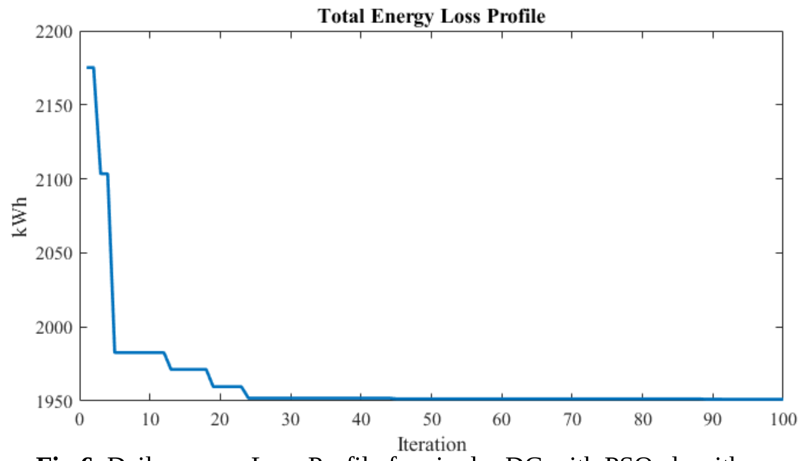

Fig.6. Daily energy Loss Profile for single- DG with PSO algorithm

The Daily energy loss obtained without battery storage is 1950 kWh for 24 hrs load variation. The daily energy loss profile without battery is shown in Fig. 6.

The daily energy loss obtained with battery storage and single DG is 1062.2 kWh for 24 hrs load variation. The size and location of DGs along with battery storage is shown in Fig. 7. The size of single DG obtained is 1355.7 kW at bus number 6^{th}. The maximum size of battery obtained is 116.736 kWh at bus number 26^{th}. The optimal location of battery storage is selected using combined dispatch strategy. The maximum and minimum numbers of battery cell obtained are 8 and 4, respectively.

In this scenario, the Daily energy loss has been reduced from the of 1950 kWh to 1062.2 kWh with using both the DGs and the battery energy storage. The percentage of energy loss reduction obtained using the DG with battery storage is 45.52% compared with the single DG only.

1.1.3 Case 2. Result for Two DGs.

The Daily energy loss profile for two DGs without battery storage device is shown in Fig.7. The energy loss has been reduced from 2150 kWh to 1750.56 kWh by using DG without battery storage. The PSO algorithm is conversed up to 50 iterations beyond it the energy loss curve is flat.

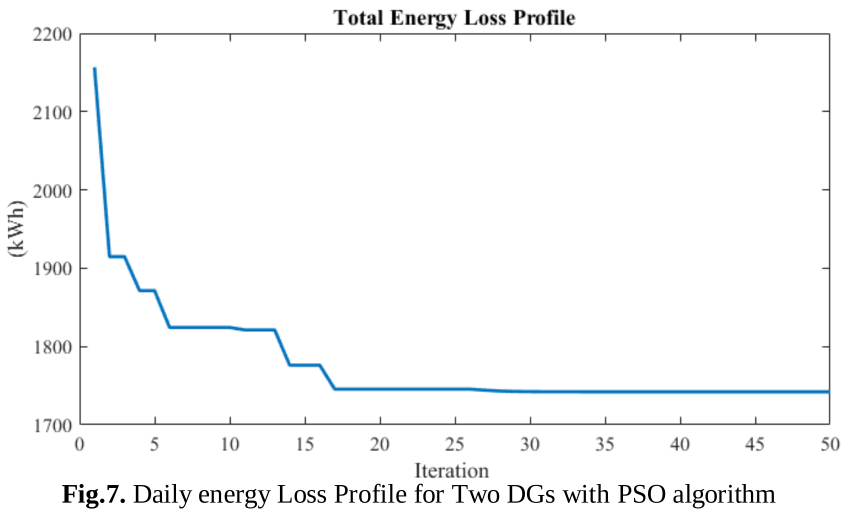

Fig.7. Daily energy Loss Profile for Two DGs with PSO algorithm

The size of renewable-based DGs obtained are 655.74, 901.6394 at 13^{th} and 30^{th} bus respectively. The total size of diesel generator obtained is 120 kW and the maximum size of battery storage is 58.368 kWh at 26^{th} bus.
The energy loss has been reduced from base case of 2031.5 kWh to 821.84 kWh by using battery energy storage and DGs. The percentage of energy loss reduction obtained is 59.547% with the base Case.
The daily energy loss obtained is 1750.56 kWh using two DGs only, whereas daily energy loss obtained is 821.84 kWh using two DGs and battery storage. Therefore the percentage of energy loss reduction obtained is 45.528% compared with two DGs without battery storage.

4.2 Voltage Profile and Power Loss

The proposed algorithm has been used to obtain the voltage regulation also. The minimum voltage of Case 1 and Case 2 for 24 hrs load variation is shown in Fig.8. The minimum voltage obtained is 0.9635 pu across 18th bus at 12th hours for Case-1. The minimum voltage obtained is 0.9766 pu across 33rd bus at12th hrs for Case-2.

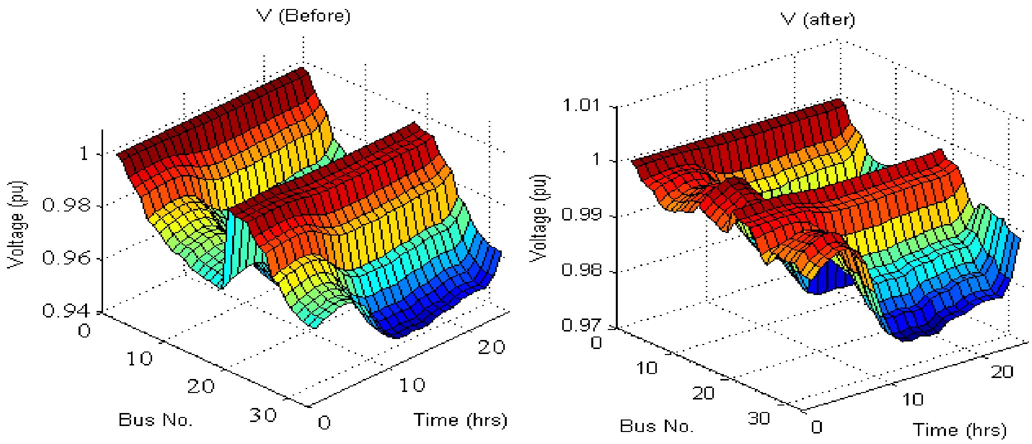

Fig.8. Voltage profile for 24 hrs load variation for IEEE 33-bus system

In Fig.9, the minimum voltage profile for 33 bus systems, is considered for 24 hrs load variation. The voltage profile has enhanced for Case-2 and Case-1 as compare with the base Case.

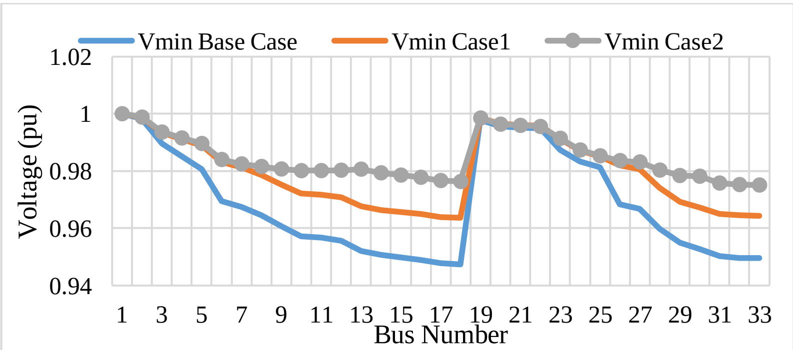

Fig. 9. Minimum voltage profile for varous case study

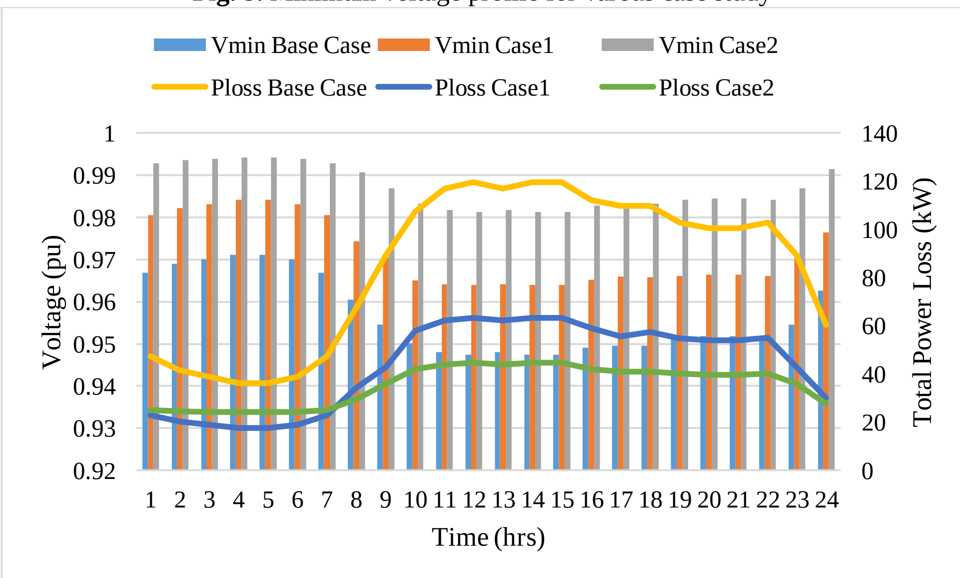

Fig.10. The Power loss and voltage profile for 24 hrs load variation

The total power loss and improved voltage profile have been shown in Fig.10 for 24 hrs load variation. The highest voltage at 5th hrs and lowest at 12th hrs have been obtained for each Case. The total power loss has been reduced by increasing the numbers of DGs. Therefore, in Case2; the total power loss and voltage profile have superior results with other Cases. The minimum power loss has obtained with Case-2 at 4th hrs, whereas the highest power loss obtained at 15th hrs.

V. CONCLUSION

This paper represents the hybrid PSO and GAMS optimization using MATLAB and GAMS interfacing to solve the multi-objective problem. This study provides the optimal sizing and siting of battery storage with the integration of renewable sources to minimize the Daily energy loss and cost of the system also. The proposed hybrid algorithm has solved in two parts. (i) In the first part, the PSO algorithm, along with a combined dispatch strategy, has been addressed to obtain the location of DGs and battery storage. (ii) The MINLP algorithm in GAMS has been solved to get the size of DGs and battery storage.

The best combination for economical operation and loss minimization obtained is, PV-based, wind-based, diesel-based DG + battery storage.

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