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Sizing of Energy Storage with Network Constraints Economic Dispatch of Fuel Cell Micro-Turbine and Renewable Energy Sources

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Abstract*: Micro-Grid is the appropriate solution to various problems in the power system. Different types of energy sources, likewise Fuel cell (FC), Micro-Turbine (MT) and renewable energy sources can be integrated with micro-grids (MG). The battery energy storage has played a crucial role to support the power mismatch of on-grid or off-grid MG. Therefore the optimal size of battery energy storage along with the optimal cost-based calculation has become an essential part for the micro-grid operator. The piecewise linear cost method is used for the cost based analysis. The main contribution of this paper is: (i) the optimal size of battery energy storage has been determined with a Fuel cell (FC) and Micro-Turbine (MT) based distribution generation (DG). (ii) The impact of battery storage with DG and renewable energy sources (RES) has been considered. (iii) The total benefit and market benefit has been maximised. (iv) The unit-commitment cost of FC and MT with spinning reserve, piecewise linear cost function, ramp rate, minimum up and downtime constraints has been considered for the sizing of battery storage. (v) The network constrained has been found to obtain minimum daily energy loss for the optimal size of battery storage. (vi) The state of charge (SOC) of battery, the power output of DG's and RES, power loss, battery cost per day, operating cost of generation, etc. have been determined. The optimal sizing of battery energy storage determination is helpful for the both Microgrid operators as well as designers. The IEEE-33 bus test system with ZIP load has been carried out for analysis and result validation. The general algebraic modeling system (GAMS) is used to solve the deterministic optimisation problem.

Keywords: Battery Energy Storage Device (BES), Energy Loss, Market Benefit, Unit Commitment, Piecewise linear function, Renewable Energy Sources.

I. INTRODUCTION

In recent years, renewable energy has been intermittent with micro-grid (MG) in a large scale. The intermittency of renewable and distributed generation (DG) has become an essential need for storage in MG. The optimum sizing of storage devices has become an essential task for MG operators. Although the size of energy storage is varying in nature from the type to type of DG's. The sizing of battery storage must be considered with market benefit in MG with various energy sources along with the network constraints.

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The optimal size of BES has studied not only the total benefit of energy sales but also to reduce the energy loss of the distribution network.

The power loss saving is another issue for MG operators. The energy-saving capacity with renewable PV power generation using the rooftop installation of PV has represented in [1]. A potential game model has described in [2] for battery energy storage scheduling with renewable sources. The loss saving has been discussed with the installation of a photovoltaic (PV) system in the network [3]. In recent years, the power loss minimisation and energy-saving problem based on random search methods have been published. The metaheuristic Ant Lion Optimization (ALO) algorithm had used to determine the optimal DG size for loss minimisation [4]. The sizing of battery energy storage based literature has considered in MG for cost based objectives. Chen, S. X et al. [5], has determined the size of battery storage with cost-benefit based unit commitment problem but the minimum up and downtime constraints did not consider. The FC and MT have been taken into account for the unit commitment (UC) problem without network constraints also.

Bahmani-Firouzi et al. [6] the bat algorithm has been implemented for determining the size of battery storage. The piecewise linear cost function, minimum up and downtime constraints did not consider in[6]. To minimises the power losses and expected operational cost of the microgrid with the stochastic problem had been represented in [7]. The nonlinear constraints multi-objective has been solved using Adaptive Modified Particle Swarm Optimization algorithm (AMPSO) is presented for MG dispatch with FC, MT and battery storage as a back-up [8]. The battery model was solved using Runge–Kutta method for standalone hybrid PV-battery system [9]. The conditional depreciation balancing strategy had used for hybrid energy storage and virtual battery model and compared with the state of charge method also [10]. The automatic segmentation method and the segmentation method are proposed to obtain the capacity of the battery energy storage system [11]. The formal mathematical model combined with power network topology has been represented for FC and MT integrated MG system [12]. V.V.S.N. Murty et al. [13] has represented Fuzzy logic based energy storage system scheduling for optimal energy dispatch strategy and energy saving.

The unit commitment was not considered in [13]. The probabilistic approach has been represented in [14] for the sizing of battery storage with Wind Turbine power fluctuations. The dispatching methodology with the cost-based rule has represented using Monte Carlo simulation (MCS) for micro-grids [15]. The solar radiation model using MCS as described in [16], but the battery storage has not considered.

G.Ma et al.[17] has considered the simplified unit commitment (UC) of generating units along with a one-hour time scale for energy storage with renewable Wind turbines and solar. The priority-based UC problem has been solved with demand-side biding of controllable loads in paper [18]. The UC of the diesel plant has been considered using the mixed-integer formulation for the rating of the energy storage system along with isolated Wind Turbine-diesel. The marketable reduction in cost has been concluded utilising the combination of the energy storage system (ESS) and diesel generator in paper [19]. The total generation cost for the unit commitment problem using the gravitational search algorithm gives the batter results, computation time and precision for the energy storage system in MG application in [20]. A piecewise linear approximation and integer algebra have been implemented for linear expression of nonlinearities with the renewable energy sources in paper [21]. The piecewise linear approximation constraints have also been used for computation of power loss in low voltage grid-connected battery storage system [22]. The battery storage has been considered with residential PV system in [23]. The energy saving issue has also been considered with influence of storage and PV system in literature [24]-[25].

In the above literature from [1] to [26] the various algorithm and techniques have been used for energy loss minimisation using renewable energy sources along with the BES. The multiple algorithm used for determining the size of BES with the installation of FC, MT, Wind Turbine (WT) and PV has been discussed in the literature [6] to [12]. The UC problem with spinning reserve has been considered for the sizing of BES in [17] to [22].

In this paperwork, the size of battery storage has been determined by considering the Fuel cell (FC), and Micro-Turbine (MT) based DG's along with Wind Turbine and solar-based renewable energy sources. The sizing of battery energy storage has been obtained, considering the impact of renewable-based energy sources also.

II. PROBLEM FORMULATION AND MATHEMATICAL MODEL

In this paperwork, the optimal size of battery energy storage has been obtained. The size of BES has been determine considering the multi-objective function. The multi-objective function have been considered as follows;

(i) To maximise the total benefit, including the cost of power sale/ punches from the grid.
(ii) To minimise the daily energy loss profile.

In this paper, the objective function has consisted of the outer layer and inner layer optimisation problem.

a. In the outer layer optimisation problem, an iterative algorithm has been solved. The BES has been obtained at each iteration. The total benefit, market benefit, cost of UC and daily energy loss curve have been obtained at each size of BES. Based on the result of the outer layer optimisation problem, the best size of BES has been obtained. The battery size has been obtained at that iteration having the minimum daily energy loss value and maximum market benefit.
b. In the inner layer optimisation problem, the obtained size of BES from outer layer optimisation has been analysed as follows;
   1) The UC problem, spinning reserve, the total hourly spinning reserve has been solved.
   2) The piecewise linear cost function has been solved for determining the fuel cost of FC and MT units.
   3) The start-up and shut-down cost of generators have been determined with up-time and down-time constraints.
   4) The total power output of FC, MT, PV and WT have been determined.
   5) The state of charge SOC, charging and discharging power of BES has been obtained.

The outer layer optimisation has been solved using MATLAB simulation, whereas the inner layer optimisation problem has been solved using MINLP technique in GAMS software.

The algorithm has been solved for various case study. The unit commitment with spinning reserve has been considered for dispatch-able sources; likewise, Fuel cell and micro-turbine (MT). The renewable-based Wind Turbine and PV energy sources have been considered in this scenario.

In this paperwork, the IEEE 33 bus test system has been carried out. The time-varying ZIP load has been taken into account for the analysis. The impact of battery energy storage with and without renewable energy sources has also been analysed. The unit commitment problem has been formulated, including piecewise cost segment, ramp rate, minimum uptime and downtime constraints. The problem is solved by MINLP solver in GAMS. The data interpretation has been done with the interfacing of MATLAB and GAMS software.

A. Mathematical Modelling

In this section the mathematical modelling of Solar, Wind Turbine, Fuel Cell, Micro-Turbine and battery storage has been represented as follows;

1) PV Panel modeling

The PV generator is the renewable source which provides the DC at 48 V. The Monte Carlo Simulation (MCS) has been taken for the exact modelling of solar power output. In this scenario, 1000 numbers of the sample have been chosen for simulation [23].

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The solar PV model is;

$$P_{solar}(I_\beta) = N_{PV} \cdot P_{rated}^{PV} \frac{G}{G0} \cdot \{1 - T_c(T_A - 25)\} \cdot \eta_{inv}\eta_{rl} \quad (1)$$

where, P_{solar} is the output power, P_{rated}^{PV} rated power of PV, and N_{PV} is the total number of solar panel [16]. $G$and$G0$ are solar irradiation and slandered solar irradiation in $(\frac{watt}{m^2})$.The Fig.1 shows solar PV output for 24 hours. T_A is the ambient temperature and Tc is the temperature coefficient of the maximum power of PV. $\square_{inv}$ and $\square_{rl}$ represent the efficiency of the inverter and the relative efficiency of the PV modules respectively.

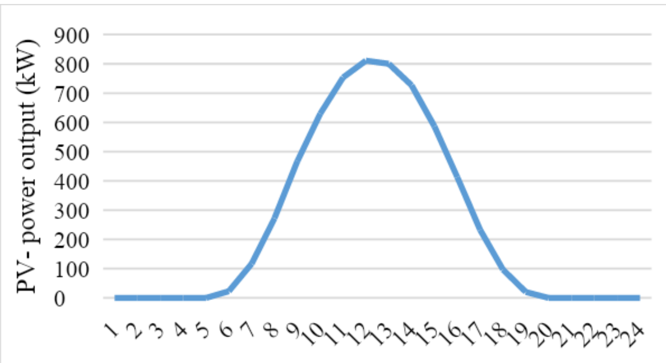

Fig. 1 Solar power output curve for 24 hrs

2) Wind Turbine Power Model

In this paper, the quadratic model of Wind Turbine has been taken. The wind turbine output is shown in Fig 2. The Wind Turbine model is as:

$$P_{wind} = \{P_{rated}\left(\frac{(v-v_{in})^2}{(v_r-v_{in})^2}\right) \; ; \; v_{in} \le v \le v_r \quad P_{rated} \; ; \quad v_r \le v \le v_{out} \quad 0 \quad ; \quad v > v_{out} \text{ and } v < v_{cut} \quad (2)$$

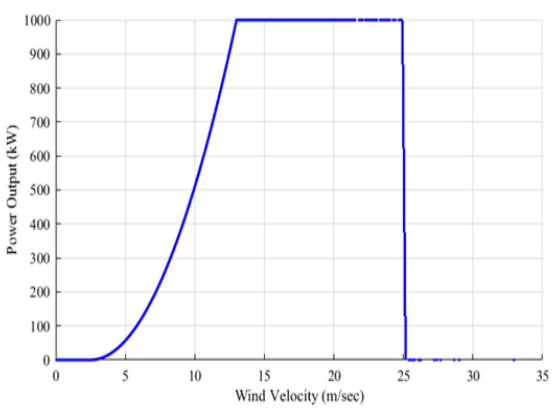

Fig. 2 Wind Turbine power output curve

where, P_{rated} is the rated Wind Turbine power, P_{wind} is the Wind-Turbine power output v_{in} is cut in the velocity of Wind Turbine, v_{out} is cut out Wind Turbine velocity.

3) Battery Storage Model

The battery storage works as back-up storage. The discharging and charging power limits of battery are the control parameters. The maximum value depends on the nominal capacity, while the minimum value depends on its Depth of Discharge (DOD).

$$SOC_{min} = N_{bat}Batt_{size}(1 - DOD_{max\ \_bat}) \quad (3)$$

$$SOC_{max} = N_{bat}Batt_{size} \quad (4)$$

$$SOC(i, k + \Delta k) = SOC(i, k).(1 - \delta) + \left(P_{ch_i}^{\ k}.\eta_{ch} - Pdisik.1\eta dis.\Delta k \right. \quad (5)$$

Eq.(3) and (4) are represent the minimum and maximum value of BES, whereas Eq.(5) is represent the state of charge (SOC) calculation for battery storage device.

where, k is time in hrs 1,2,….24 and Δk is the time step. $DOD_{max\ \_bat}$ is the maximum depth of discharge, $Batt_{size}$is the nominal capacity (kWh), N_{bat} total number of battery, SOC is a state of charge, P_{ch} charging power, P_{dis} is discharging power, $\square_{ch}$and $\square_{dis}$ are the charging and discharging efficiency of the battery.

The discharging schedule depends on the SOC of battery also. Once the peak energy-saving is stabilized the discharging of battery is as follows;

$$E_{dis_{i,k}}^{\ min} = \int_k^T \left(Pd_{Load,i}^k - (Pgrid_i^k) - max\,(P_{gen_i}^{\ k}) \right) \Delta t \quad \text{if } Pd_{Load,i}^k \ge (Pgrid_i^k) \quad (6)$$

where, $P_{gen_i}^{\ k}$ is the generator output at each i[th] bus for k[th] time, $Pgrid_i^k$is grid power, $Pd_{Load,i}^k$ load demand. $\forall\, i = 1,2 \ldots nb$ and . $\forall\, k = 1,2 \ldots T$, T is total time .i.e 24 hrs.

The charging schedule of battery energy storage has scheduled based on peak energy saving. The renewable-based DGs has stabilised to supply the load as well as to supply the battery storage. Once the peak energy is scheduled based on the lower market bid as well as the availability of renewable energy the formulation of charging of battery storage has determined as follows;

$$E_{ch_{i,k}}^{\ min} = \int_k^T \left((Pgrid_i^k) + (P_{gen_i}^{\ k}) - Pd_{Load,i}^k \right) \Delta t \quad \text{if } Pd_{Load,i}^k \le (Pgrid_i^k) \quad (7)$$

where, $E_{ch_{i,k}}^{\ min}$ and $E_{dis_{i,k}}^{\ min}$ are minimum charging and discharging the energy of battery energy storage.

4) Fuel Cell (FC) Model

The fuel cells are considered as a clean energy source because FCs do not need conventional fuel. FC has a higher efficiency than a diesel engine and simple to maintain also. FC has needed the continuous source of fuel and oxygen; therefore, FCs are differed with the battery as per longer operating time. The cost of a fuel cell ($Cost_{FC}$) depends on the FC's efficiency ($\square_{FC}$) and power output ($P_{gen_i}^{\ FC}$) of a fuel cell.

$$Cost_{FC} = \left(\frac{P_{gen_i}^{\ FC}}{\eta_{FC}}\right) Csu_{fuel\_FC} \quad (8)$$

where, Csu_{fuel_FC} is price to supply of fuel ($/kWh).

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5) Micro-Turbine

MT has more benefits as compared to conventional heat engine in terms of the low maintenance cost, small compact size, more substantial reliability, low emission and flexible operation of the fuel. The cost of MT ($Cost_{MT}$) depends on the MT's efficiency (□$_{MT}$) and active power output (${P_{gen}}_i^{MT}$) of MT.

6) Piecewise linear cost model of FC and MT generation

The piecewise linear cost function has been carried out for Fuel cell (FC) and Micro-Turbine (MT) generation. The number of segments is used for piecewise linear cost model[27]. The cost segments have been made for power segments ($\Delta P_{i,k}^{sg}$).

$$0 \le P_{i,k}^{sg} \le \Delta P_{i,k}^{sg} \cdot U_{i,k}^{gen};\ \forall\ sg \in nsg \tag{10}$$

$$\Delta P_{i,k}^{sg} = \frac{\left({P_{gen}}_{i,k}^{max} - {P_{gen}}_{i,k}^{min}\right)}{nsg} \tag{11}$$

$$P_{i,k,ini}^{sg} = (sg-1)\Delta P_{i,k}^{sg} + {P_{gen}}_{i,k}^{min} \tag{12}$$

$$P_{i,k,final}^{sg} = \Delta P_{i,k}^{sg} + P_{i,k,ini}^{sg} \tag{13}$$

$${P_{gen}}_i^{k} = {P_{gen}}_{i,k}^{min} \cdot U_{i,k}^{gen} + \sum_{sg}^{nsg} \left\{\Delta P_{i,k}^{sg}\right\} \tag{14}$$

$${Cost_{gen}}_{i,k,ini}^{sg} = \left\{a_i (P_{i,k,ini}^{sg})^2 + b_i\, P_{i,k,ini}^{sg} + c_i\right\} \tag{15}$$

$${Cost_{gen}}_{i,k,final}^{sg} = \left\{a_i (P_{i,k,final}^{sg})^2 + b_i\, P_{i,k,final}^{sg} + c_i\right\} \tag{16}$$

$$s_i^{sg} = \frac{\left({Cost_{gen}}_{i,k,final}^{sg} - {Cost_{gen}}_{i,k,ini}^{sg}\right)}{\Delta P_{i,k}^{sg}} \tag{17}$$

$$Cost_{fuel}^{gen} = U_{i,k}^{gen}\left\{a_i ({P_{gen}}_i^{k})^2 + b_i {P_{gen}}_i^{k} + c_i\right\} + \sum_{sg}^{nsg} \left\{s_i^{sg} \Delta P_{i,k}^{sg}\right\} \tag{18}$$

$\forall\ gen \in (FC, MT)$

where, nsg is total number of segments, $U_{i,k}^{gen}$ is the on/off status of FC and MT units at time k, ${P_{gen}}_{i,k}^{max}$ and ${P_{gen}}_{i,k}^{min}$ maximum and minimum power limits of FC and MT respectively, ${Cost_{gen}}_{i,k,ini}^{sg}$ and ${Cost_{gen}}_{i,k,final}^{sg}$ are initial and final cost segment of FC and MT generation. $Cost_{fuel}^{gen}$ is the fuel cost of FC and MT. a_i, b_i and c_i are the cost coefficients of FC and MT respectively.

7) Load Model

In this paper, the time-varying ZIP load model is represented. The constant impedance, constant current and constant power load model for residential, commercial and industrial loads has been carried out for the analysis.

The expressions for zip load model is represented as follows;

$$P_{i,k}^{ZIP} = Pd_i\left[Z_p\left(\frac{V_i^k}{V_{min}^k}\right)^2 + I_p\left(\frac{V_i^k}{V_{min}^k}\right) + P_p\right] \tag{19}$$

$$Q_{i,k}^{ZIP} = Qd_i\left[Z_q\left(\frac{V_i^k}{V_{min}^k}\right)^2 + I_q\left(\frac{V_i^k}{V_{min}^k}\right) + P_q\right] \tag{20}$$

$\forall \{Z_i + I_i + P_i = 1\}$, where, Z_i, I_i and P_i are the constant impedance, constant current and constant power load parameter for different type of costumer [28]. Pd_i and Qd_i are the load demand at each bus i. The active and reactive part of ZIP load is shown in Fig 3.

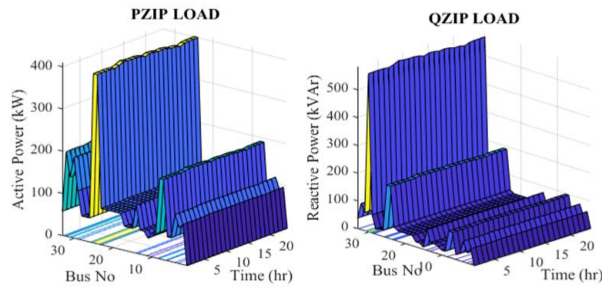

Fig. 3 ZIP Load profile [35]

8) Micro –Grid

The network consistence of IEEE-33 bus test system.

In Fig.4 the FC at 21st bus, MT-1 and MT-2 at bus 5th and 11th, WT at 15th bus and PV at 30th bus have been installed for optimal size of battery storage at 19th bus.

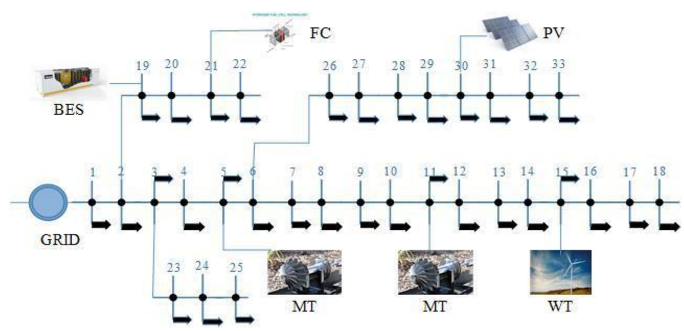

Fig. 4 MG network with Energy Resources

B. Problem formulation

The following objective function has formulated as:

1) Objective function formulation

The multi-objective function is to maximising the total benefit of grid-connected micro-grid and minimising the daily energy loss profile of the network. The multi-objective function f_1 and f_2 formulated as follows;

$$max\{f_1\} = Market_{Benefit} - Batt_{CPD} \tag{21}$$

$$min\{f_2\} = \sum_k^T \sum_i^{nb} G_{ij}^k\{(V_i^k)^2 + (V_i^k)^2 - 2V_i^k V_j^k$$
□□□cos□ik−δjk (22)

$$Market_{Benefit} = \sum_k^T \left\{Price_{Market} \cdot \sum_i^{nb} {P_{gen}}_i^{k} - UCCdisp \right. \tag{23}$$

$$UCC_{disp} = \sum_k^T \sum_i^{nb} \left\{rRn_{i,k} + Cost_{i,k}^{gen} + \left(U_{i,k}^{wind} voll^{wind}\right) \cdot \right.$$
$Pi,kwind+Ui,kPVvollPV\cdot Pi,kPV$

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(24)

$$Cost_{i,k}^{gen} = STC_{i,k}^{gen} + SDC_{i,k}^{gen} + U_{i,k}^{gen}\left\{a_i({P_{gen}}_i^{\ k})^2 + \right.$$
biPgenik +ci +sgnsgsisgΔPi,ksg (25)

$$Batt_{CPD} = \left\{\left(\frac{rt.(1+rt)^{yr}}{(1+rt)^{yr}-1}\right)\cdot Batt_{fc} + Batt_{MC}\right\}\frac{Batt_{Size}}{365} \quad (26)$$

where, UCC_{disp} unit commitment cost for generating unit, $Rn_{i,k}$ spinning reserve for ith unit at kth time, $Cost_{i,k}^{gen}$ is operating cost of generation unit .i.e. FC and MT. $P_{i,k}^{wind}$ is power output of i^th Wind Turbine unit at k^th time. $voll^{wind}$ and $voll^{PV}$ are the value of Wind Turbine and PV respectively. $P_{i,k}^{PV}$ is power output of i^th PV unit at k^th time. $U_{i,k}^{wind}$ and $U_{i,k}^{PV}$ are the on/off status of Wind Turbine and solar PV respectively. $Batt_{CPD}$ is the battery cost per day, rt is interest rate, yr is number of year to use battery, $Batt_{fc}$ and $Batt_{MC}$ are the fixed and maintenance cost of battery storage.

Constraints Equations are as follows;

(i) Power balance constraints;

$$P_i^k = \left(Pg_i^k + Pgrid_i^k - Pd_{ZIP,i}^k\right)$$

$$= V_i^k\sum_{j=1}^{n} V_j^k\left(G_{ij}^k\cos\cos\left(\delta_i^k - \delta_j^k\right) + B_{ij}^k\right.$$
sinsin δik −δjk (27)

$$Q_i^k = \left(Qg_i^k + Qgrid_i^k - Qd_{ZIP,i}^k\right)$$

$$= V_i^k\sum_{j=1}^{n} V_j^k\left(G_{ij}^k\sin\sin\left(\delta_i^k - \delta_j^k\right) - B_{ij}^k\right.$$
coscos δik −δjk (28) $\forall\, i\,\epsilon\, SB\ \&\ k\,\epsilon\, ST$

where $\forall i = 1,2\ldots.nb, \forall j = 1,2\ldots.nl$, 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.

(ii). Power generation constraints:

$$Pg_i^k = P_{gen,i}^k + N_{wind}(i)\cdot {P_{wind}}_i^{\ k} + N_{PV}(i)\cdot {P_{PV}}_i^{\ k} + N_{batt}(i)\cdot\left({P_{ch}}_i^{\ k} - {P_{dis}}_i^{\ k}\right) \quad (29)$$

$$Qg_i^k = {Q_{gen}}_i^{\ k} + N_{wind}(i)\cdot {Q_{wind}}_i^{\ k} \quad (30)$$

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

(iii). Ramp rate constraints;

The ramp rate constraints for generation of fuel cell and micro turbine has been represented as;

$${P_{gen}}_i^{\ k} \le {P_{gen}}_{i,k}^{\ max}\left[U_{i,k}^{gen} - X_{i,k+1}^{gen}\right] + SD_{i,k}^{gen}\cdot X_{i,k+1}^{gen}$$
$${P_{gen}}_i^{\ k} \le {P_{gen}}_i^{\ k-1} + RU_{i,k}^{gen}\cdot U_{i,k-1}^{gen} + SU_{i,k}^{gen}Y_{i,k+1}^{gen} \quad (31)$$
$${P_{gen}}_i^{\ k} \ge {P_{gen}}_{i,k}^{\ min}U_{i,k}^{gen} \quad (32)$$
$${P_{gen}}_i^{\ k} \ge {P_{gen}}_i^{\ k-1} - RD_{i,k}^{gen}\cdot U_{i,k}^{gen} - SD_{i,k}^{gen}\cdot X_{i,k}^{gen} \quad (33)$$

(iv). Start up/Down cost constraints;

$$Y_{i,k}^{gen} - X_{i,k}^{gen} = U_{i,k}^{gen} - U_{i,k-1}^{gen}$$
$$Y_{i,k}^{gen} + X_{i,k}^{gen} \le 1 \quad (34)$$
$$STC_{i,k}^{gen} = Cost_{i,k}^{ST}Y_{i,k}^{gen} \quad (35)$$
$$SDC_{i,k}^{gen} = Cost_{i,k}^{SD}X_{i,k}^{gen} \quad (36)$$

(v). Start up/Down Time constraints

Minimum up time (UT_i) constraints is modelled as;

$$\sum_{k}^{T-UT_i+1}\left(1 - U_{i,k}^{gen}\right) = 0$$
$$\sum_{k=sg}^{sg-UT_i+1}\left(U_{i,k}^{gen}\right) \ge UT_i\cdot Y_{i,k}^{gen}$$
$$\sum_{k=sg}^{T}\left(1 - Y_{i,k}^{gen}\right) \ge 0 \quad (37)$$
$$\forall\, sg = T - UT_i + 2\ldots..T$$

Minimum down time (DT_i) constraints is modelled as;

$$\sum_{k}^{T-UT_i+1}\left(U_{i,k}^{gen}\right) = 0$$
$$\sum_{k=sg}^{sg-UT_i+1}\left(1 - U_{i,k}^{gen}\right) \ge DT_i\cdot X_{i,k}^{gen}$$
$$\sum_{k=sg}^{T}\left(1 - U_{i,k}^{gen} - X_{i,k}^{gen}\right) \ge 0 \quad (38)$$
$$\forall\, sg = T - DT_i + 2\ldots..T$$

where, $U_{i,k}^{gen}, X_{i,k}^{gen}, Y_{i,k}^{gen}, \in (1,0)$, is the binary variables. $SD_{i,k}^{gen}$ and $SU_{i,k}^{gen}$ are shut down and start-up cost constants of FC and MT. $Cost_{i,k}^{SD}$ and $Cost_{i,k}^{ST}$ are the cost coefficients of shut down and start up for FC and MT respectively. $STC_{i,k}^{gen}$ and $SDC_{i,k}^{gen}$ are start-up and shut down cost for generating unit.

(vii). Power Loss equation

$$\left|P_{ij}^k\right| = \left|\sum_{k}^{T}\sum_{i}^{nb} G_{ij}^k\left\{(V_i^k)^2 + (V_j^k)^2 - 2V_i^kV_j^k\cos\cos\left(\delta_i^k - \delta_j^k\right)\right\}\right|$$
$$\le Pl_{max}^k \quad (39)$$

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:

(viii). Constraints for Transmission line

$${P_{fsmin}}_j^{\ k} \le {P_{fs}}_j \le {P_{fsmax}}_j^{\ k},\ i \in S_{fs}$$
$${Q_{fsmin}}_i^{\ k} \le {Q_{fs}}_j \le {Q_{fsmax}}_j^{\ k},\ i \in S_{fr}$$
$${P_{frmin}}_j^{\ k} \le {P_{fr}}_j \le {P_{frmax}}_j^{\ k},\quad i \in S_{fr}$$
$${Q_{frmin}}_i^{\ k} \le {Q_{fr}}_j \le {Q_{frmax}}_j^{\ k},\ i \in S_{fr} \quad (40)$$

(ix). Capacity Limits of the generation system

$$P_{Gi}^{min} \le Pg_i \le P_{gi}^{max},\ i \in S_G \quad (41)$$
$$Q_{gi}^{min} \le Qg_i \le Q_{gi}^{max},\ i \in S_G \quad (42)$$

(x). Voltage and angle limits

$$V_{i,k}^{min} \le V_i^k \le V_{i,k}^{max},\ i \in S_B \quad (43)$$
$$\square_{min}{}_i^{\ k} \le \delta_i^k \le {\delta_{max}}_i^{\ k},\ \forall i = 1,2\ldots.nb \quad (44)$$

(xi). Power factor limits

$$pf_i^{lo} \le pf_i \le pf_i^{up},\ i \in S_B \quad (45)$$

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(xii) Energy storage constraints;

$$SOC_i^{min}(k) \leq SOC_i(k) \leq SOC_i^{max}(k) \quad (46)$$

$$SOC_i^{max}(1) = SOC_i^{max}(24) = 0.90 * N_{bat}(i)Batt_{Size} \quad (47)$$

$$0 \leq P_{ch_i}^{\ k} \leq 0.6 \cdot N_{bat}(i)Batt_{Size} \quad (48)$$

$$0 \leq P_{dis_i}^{\ k} \leq 0.6 \cdot N_{bat}(i)Batt_{Size} \quad (49)$$

$$P_{dis_i}^{\ k} \cdot P_{ch_i}^{\ k} = 0 \quad (50)$$

where, i is the total number of buses in the network .i.e. $\forall i = 1,2 \ldots .nb$. nb is the total number of buses., k= time 1…24 hrs.

III. ALGORITHM USED

In this paper, the outer and inner layer algorithm with MATLAB and GAMS interfacing is used. In the outer layer, the MATLAB is used for the required load data and load flow algorithm for obtaining the power loss. Whereas the inner layer, GAMS programming is executed for obtaining the battery size, total benefit, market benefit and other variables.

Step 1 Algorithm for outer layer as follows;

(a) Read the system data and ZIP load parameters.
(b) Solve the Monte-Carlo simulation for Wind Turbine and solar power calculation.

Step 2

(a) Run the load flow program for 24-hrs and obtain the base Case total energy loss.
(b) Select the candidate node having the highest energy loss for FC and MT location.

Step 3

(a) Set the initial value of minimum battery size for iteration.
(b) Obatin the total benefit, Market benefit, daily energy loss profile for each battery size.
(c) Obtaine the optimal battery size.
(d) Transfer the all control parameter from MATLAB to GAMS

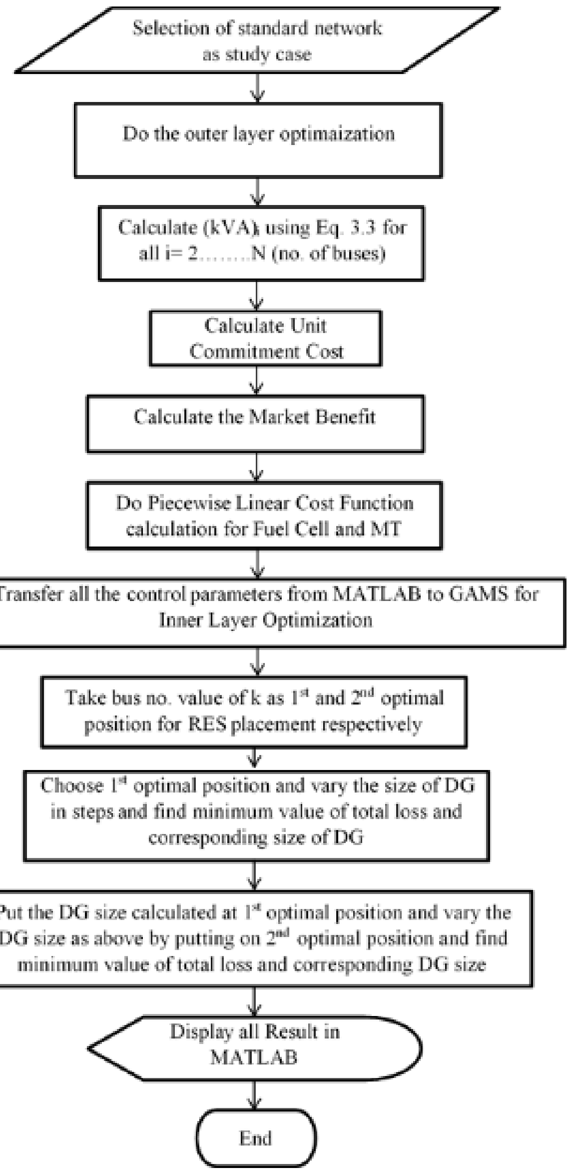

Fig. 5 Two-layer Algorithm used to solve Battery Size in MG

Step 4 Algorithm for inner layer as follows;

(a) Solve the objective function (21) and (22). Solve the constraints equation from (25) to (30) calculate Market Benefit using MINLP solver.
(b) Obtain the size of the battery (3) SOC, charging and discharging of the cell, and solve equation (46) and (50).
(c) Obtain the power output of FC and MT by solving constraints from (31) to (38).
(d) Obtain the cost segment using piecewise linear cost function by solving (10) to (18).

Step 6 Transfer the objective variables form GAMS to MATLAB and get the results.

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Step 7 Print the results.

The flow chart of the proposed hybrid algorithm is shown in Fig.5.

IV. SYSTEM DATA

The system data are given in this paper represented as follows;

A. Fuel Cell and Micro-Turbine Data

The FC and MT power generation data [5] is given in Table I.

Table- I: Generator data for FC and MT [5]

Type	a	b	c	Pmin	Pmax
FC	0.0	0.35	80	100	1000
MT	0.0	0.50	50	100	1000
MT	0.0	0.13	30	100	2000
	RU	RD	UT	DT	
FC	30	30	0	0	
MT	64	64	0	0	
MT	40	40	2	2	
	CostSD	CostST	R10	P10	
FC	57.1	57.1	500	1000	
MT	50.6	50.6	500	1000	
MT	42.6	42.6	1000	0	
	SU	U0	d	r	
FC	80	3	30	0.10	
MT	140	2	30	0.10	
MT	110	1	150	0.10	

B. Solar and Wind Turbine cost data

Table- II: The input data for the energy sources [29], [30] & [31].

	Acquisition cost ($)	Operation and Maintenance Cost ($/year/kW)	Replacement Cost ($/Lifetime)	Lifespan (year)	Rating
PV module	2400	18	2.85 @ 25 year of life time	25	800 (kW)
Wind Turbine (1MW)	3724.5	31	3009.5	20	1000 (kW)
Battery Storage	600	20	4.64 @ 1.45 year		100 (kWh)

The input data used in this paper has shown in Table- II. The cost estimation data for the PV-based DG and wind-based DG have been taken from the National Renewable Energy Laboratory (NREL) [29], [30] & [31]. The data for battery, regulators and investors are taken from the literature [32].

V. RESULTS AND DISCUSSION

In this section, the results for the sizing of battery storage is discussed. The multi-objective function has been solved, as explained in section 2. There are two case scenario has been considered as follows;

Case 1: Size of energy storage with wind and solar-based renewable energy sources.

Case 2: Size of energy storage without wind and solar-based renewable energy sources.

A. Case 1

In this case study, the size of battery energy storage has obtained with WT, PV, FC and MT.

1). Result for the outer layer

In this section, the result for the outer layer has been discussed. The maximum and minimum size of battery storage obtained is 3000 kWh and 100 kWh. The incremental capacity of battery ($\Delta Batt_{size}$) taken is 100 kWh. Therefore the total 30 number of iteration is taken. In Fig.5, the minimum daily energy loss obtained is 3042.892 kWh. Therefore the size of battery storage is 900 kWh at minimum energy loss.

Table-III: Result for battery energy storage size at each size of battery

Size of Battery (kWh)	Battery Cost per day ($)	Total Benefit ($)	Market Benefit ($)	Daily Energy Loss (kWh)
100	66.97696	-7606.6	-7539.63	4270.897
200	133.9539	2046.153	2180.107	4054.654
300	200.9309	2445.144	2646.075	3890.979
400	267.9078	-22.0854	245.8224	3612.016
500	334.8848	5317.934	5652.818	4346.567
600	401.8617	-10084.2	-9682.35	889.8202
700	468.8387	4028.243	4497.081	3925.117
800	535.8156	1606.186	2142.002	3969.417
900	**602.7926**	**7379.872**	**7982.664**	**3042.892**
1000	669.7696	7647.786	8317.556	3965.747
1100	736.7465	6358.572	7095.319	4576.981
1200	803.7235	8251.035	9054.759	3793.969
1300	870.7004	5782.677	6653.377	3203.448
1400	937.6774	-5348.67	-4410.99	3994.263
1500	1004.654	-3761.92	-2757.27	3821.006
1600	1071.631	8875.188	9946.819	3565.436
1700	1138.608	8850.938	9989.546	4109
1800	1205.585	4921.203	6126.788	3641.643
1900	1272.562	-3942.97	-2670.41	3884.087
2000	1339.539	-7530.15	-6190.61	3631.245
2100	1406.516	2060.561	3467.077	4484.755
2200	1473.493	5008.265	6481.758	3288.303
2300	1540.47	678.5209	2218.991	3903.079
2400	1607.447	-4494.92	-2887.47	4215.521
2500	1674.424	5243.989	6918.413	3875.806
2600	1741.401	6603.386	8344.787	3649.042
2700	1808.378	7046.523	8854.901	3940.553
2800	1875.355	2221.064	4096.419	3949.684

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2900	1942.332	4476.257	6418.589	4435.717
3000	2009.309	-5127.37	-3118.06	3745.243

The battery cost per day obtained is $ 602.7926, cost of unit commitment obtained is $ 7496.482, the total benefit obtained is $ 7379.872, the market benefit obtained is $ 7982.664 and fuel cost of FC & MT obtained is $ 7261.927. The maximum market benefit obtained is 9989.54($) for battery size of 1700 kWh, but the energy loss obtained is 4109 kWh. Therefore the best size selection of battery storage is 900 kWh.

In the Table-III the cost of market benefit (MB) and minimum energy loss for the size of battery energy storage along with solar and Wind Turbine power is shown.

In this paperwork, the analysis of battery storage of 900 kWh has been carried out along with the solar and Wind Turbine-based renewable energy sources.

2). Result for inner layer optimization

In this section, the results for inner layer optimisation is discussed. The battery size obtained in outer layer case is 900 kWh; therefore the inner layer analysis has been done for 900 kWh capacity.

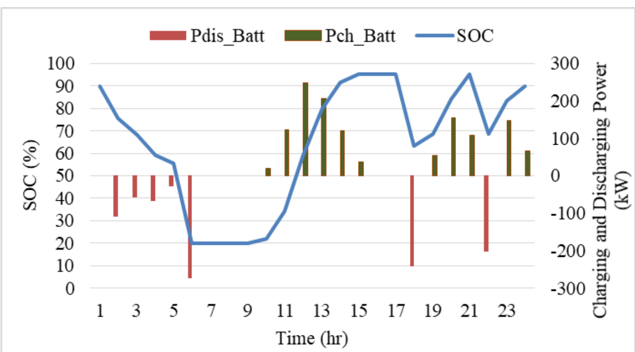

Fig. 6 State of Charge of battery storage with renewable energy sources

In the above Table-III the size of battery energy storage obtained is 900 kWh for minimum energy loss of the distribution network. In Fig.6 red bars are shown to discharging power and green bars for charging power of battery storage, whereas the blue line shows the state of charge for battery in percentage. The negative power indicates the power supplied by battery storage.

The fixed cost of battery storage is 600 ($/kWh) and maintenance cost of BES is 20 ($/kWh). The interest rate is 6.5% and the life of BES is 3 year taken in this paperwork.

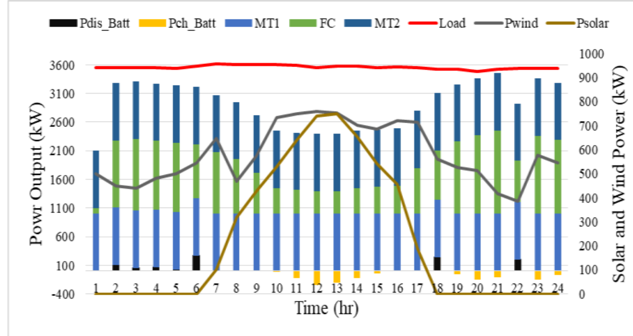

Fig. 7 Power output of fuel cell, Micro-Turbine, battery storage with Wind Turbine and solar based renewable energy sources

The minimum discharge and charging power of the battery set is 0 kW, whereas the maximum discharging and charging power set is 20% of battery storage size. The initial SOC set is 90% at time k of 1 hour. The final SOC for 24th hours is set at 95 % of SOC. Therefore the life of battery storage is better. The Li-ion battery has been selected for this paperwork.

In Fig.7 the power output of fuel cell, micro-turbine, and battery storage with Wind Turbine and solar has been shown. The solar, Wind Turbine-based renewable has been installed at 30th and 15th bus. The micro-turbine (MT1 and MT2), fuel cell are installed at 13th, 21st, and 18th bus, respectively. The obtained size of 900 kWh battery storage has been installed at 19th bus. The maximum power output obtained is 1457.50 kW of MT, 1000 kW of FC1 and FC2, 760 kW of Wind Turbine power and 748.7 kW of solar energy for 24 hours ZIP load. The required data has been taken from section IV.

B. Case 2

In this section, the size of battery storage has been obtained without renewable energy sources. The size of battery storage is obtained with MT and FC.

1). Result for the outer layer

In Table-IV the market benefit-cost and minimum energy loss point has been carried out for the optimal size of battery storage.

Table-IV: Result of outer layer for battery energy storage size at each iteration

Size of Battery (kWh)	Battery Cost per day ($)	Total Benefit ($)	Market Benefit ($)	Daily Energy Loss (kWh)
100	66.97696	17304.86	17371.84	4838.601
200	133.9539	17163.05	17297	4593.833
300	200.9309	13904.9	14105.83	4002.295
400	267.9078	18054.04	18321.94	5747.159
500	334.8848	2379.403	2714.288	4836.945
600	**401.8617**	**14521.22**	**14923.08**	**3854.554**
700	468.8387	14877.28	15346.11	5116.568

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800	535.8156	16070.36	16606.18	5450.305
900	602.7926	18912.82	19515.61	5209.669
1000	669.7696	-1749.97	-1080.2	3860.991
1100	736.7465	11029.84	11766.59	3904.356
1200	803.7235	14286.35	15090.07	5230.66
1300	870.7004	16444.22	17314.92	5191.115
1400	937.6774	11934.66	12872.34	4221.412
1500	1004.654	119.0748	1123.729	5209.266
1600	1071.631	9605.887	10677.52	4465.198
1700	1138.608	12685.79	13824.4	5158.918
1800	1205.585	12773.85	13979.44	5338.624
1900	1272.562	16776.83	18049.39	4151.34
2000	1339.539	15823.58	17163.12	5586.383
2100	1406.516	13689.3	15095.81	4572.34
2200	1473.493	12529.67	14003.17	5706.083
2300	1540.47	14629.05	16169.52	4590.122
2400	1607.447	16362.38	17969.82	5529.146
2500	1674.424	16043.89	17718.31	5181.696
2600	1741.401	14227.51	15968.91	4815.476
2700	1808.378	12014.09	13822.46	5155.262
2800	1875.355	15109.68	16985.03	4372.484
2900	1942.332	15628.77	17571.1	5812.47
3000	2009.309	11936.45	13945.75	4989.631

The minimum energy loss obtained is 3854.6 kWh for a battery of capacity 600 kWh and market benefit of 14923$ without renewable energy sources. The battery cost per day obtained is $ 401.8617, cost of unit commitment obtained is $ 6095.765, total benefit obtained is $14521.22, market benefit obtained is $14923.08 and fuel cost of FC & MT obtained is $5764.83. The maximum market benefit obtained is $18912.82 for battery storage of 900 kWh and energy loss of 5209.669 kWh. Therefore the energy losses have been increased with the size of battery and market benefit also. Consequently, the best size of the battery selected is 600 kWh. In this paperwork, the analysis has been carried out for 600 kWh battery along with FC and MT. In Table-IV the market benefit-cost and minimum energy loss-point has been carried out for the optimal size of battery storage. The minimum energy loss obtained is 3854.6 kWh for a battery of capacity 600 kWh and market benefit of 14923$ without renewable energy sources. The maximum market benefit obtained is $18912.82 for battery storage of 900 kWh and energy loss of 5209.669 kWh. Therefore the energy losses have been increased with the size of battery and market benefit also. Consequently, the best size of the battery selected is 600 kWh. In this paperwork, the analysis has been carried out for 600 kWh battery along with FC and MT.

2). Result for inner layer

In this section the inner layer optimization has been done for analysis of battery obtained size of 600kWh form outer layer optimization. Therefore the various variables are obtained for 600 kWh battery storage.

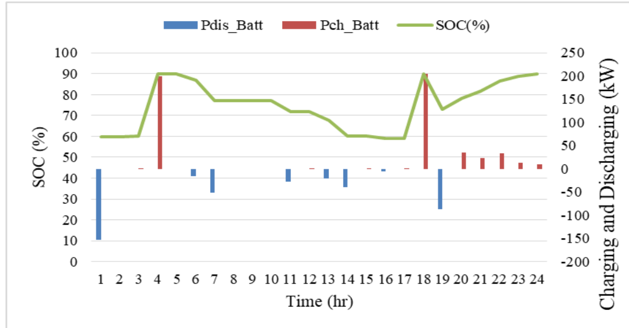

Fig.8 State of Charge of battery storage without renewable energy sources

In the Fig.8 the SOC, charging and discharging power of battery without renewable energy sources is shown. The size of 600kWh battery storage is carried out for minimum energy loss

The time required for charging and discharging is 2 hours for the battery. The minimum SOC is set at 20% and maximum at 95% of battery capacity. The charging and discharging power limit is set at 50% of the full capacity of battery storage.

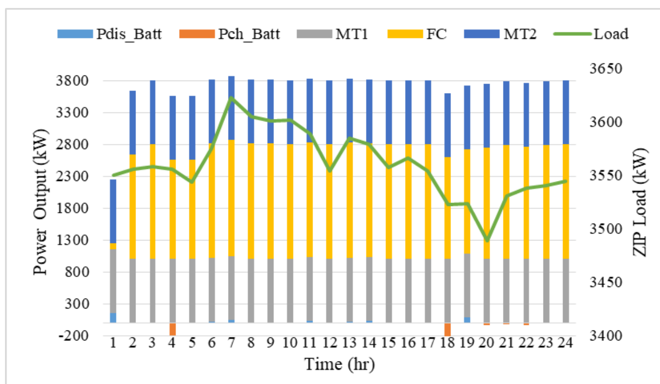

Fig.9 Power output for 24 hrs load variation

In Fig.9 the power output of fuel cell, micro-turbine and battery storage with Wind Turbine and solar has been shown. The two numbers of micro-turbine (MT1 and MT2), fuel cell (FC) are installed at 13th, 21st, and 18th bus, respectively. The obtained size of 600 kWh battery storage has been installed at 19th bus. The maximum power output obtained is 1457.50 kW of MT, 1000 kW of FC1 and FC2, 760 kW of Wind Turbine power and 748.7 kW of solar energy for 24 hours ZIP load.

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VI. CONCLUSION

The optimal size of battery energy storage (BES) can be obtained by the method presented in this paper. This method has been tested in IEEE-33 bus test system with considering the network constrained. The time-varying ZIP load model, as explained in section IV, has been considered for observation of the battery impact on the system.

The battery energy storage size obtained for case 1 are 900 kWh at the lowest energy loss point, and 2700 kWh at the maximum benefit point. The size of BES at the maximum benefit point, the energy loss is maximum as compared with the lowest energy loss point.

Similarly, for Case-2; the size of BES obtained are 600 at lowest energy loss point and 900 kWh at maximum benefit point. Although, the losses has been increased to 26.011% with consideration of the maximum benefit point for sizing of BES. Therefore the following points are concluded as follows;

1) The battery size obtained is 900 kWh for case 1. In this case the energy loss determine is 3042.89 kWh.
2) The battery size obtained is 600 kWh for case 2. The energy loss determine is 3854.553952kWh.
3) The energy loss is increased in case 2 up to 26.6% with concerning case 1. Therefore the use of renewable energy source in MG is beneficial for daily energy saving.
4) The total benefit in case 2 increased up to 48 % with respect to case 1, because of the maintenance cost of renewable energy source in case 1.
5) The fuel cost of FC and MT in case 2 obtained is $ 5674 and in case 1 obtain is $ 7261. The increment of fuel cost in case1 is 21.85 %.
6) It is concluded that in case 1 at maximum benefit point (at BES size 1700 kWh) the daily energy loss is increased to 14.65 % with optimal BES of 900 kWh point.
7) The maximum benefit point in case 2 (at BES size of 900 kWh) the daily energy loss is increased to 26.011 % with optimal BES of 600 kWh.

It is concluded that the optimal size of BES obtained is 900 kWh in case1 and 600 kWh in case 2 with considering the minimum daily energy loss.

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