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Optimal design of hybrid power generation system and its integration in the distribution network

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A B S T R A C T

The inability of conventional energy sources to fully meet the rapidly increasing energy demands in today's world has led to the growing importance of hybrid power generation systems that incorporate renewable energy sources. This work proposes an optimally designed multi-source standalone hybrid generation system comprising of photovoltaic panels, wind turbine generators, batteries and diesel generator. This design aims at minimizing emissions and cost, expressed in the form of the Net Present Value (NPV) of the system, while simultaneously maximizing its Energy Index of Reliability (EIR). The designed hybrid power generation system is further integrated into the distribution system as a Distributed Generation (DG); this is to optimally improve the performance of the distribution system by minimizing the total losses and the total voltage deviation of the distribution system. The combined cost and emissions incurred due to the energy purchased from the grid and the energy generated by DG are also reduced. For this purpose an improvised Multi-Objective Particle Swarm Optimization (MOPSO) algorithm is developed taking care of contradicting objectives. The proposed optimization algorithms are implemented using MATLAB for a standard IEEE 69-bus distribution system, using an hour-wise annual data of Spain. The location and size of DGs and the type and number of each generating source of the hybrid system are considered as decision variables. The effectiveness of the proposed optimal design using the improvised MOPSO algorithm is established in comparison with Improved Hybrid Optimization by Genetic Algorithm (i-HOGA) results.

Introduction

Hybrid power generation systems, especially those including renewable sources of energy, are preferred in the modern context, as conventional sources of energy struggle to cope up with rapidly increasing demand of electricity. These hybrid generation systems are designed to function either as a standalone system – a system which supplies a set of loads without being connected to the electricity grid; or as a grid-connected system – a system which is integrated to the electricity grid in the transmission or distribution level.

In the recent past, the use of hybrid power generation systems has garnered extensive research and publication. Dalton et al. [1] concluded that multi-source hybrid energy systems provide better quality and reliability than single source systems. Luna-Rubio et al. [2] stated that efficient and economical employment of renewable energy sources in a hybrid system would necessitate the need for their optimal sizing. Koutroulis et al. [3] proposed a genetic algorithm (GA) based cost minimization of a stand-alone hybrid solar-wind system in order to determine the optimal number and type of each energy source. Dufo-Lopez and Bernal Agustin [4] put forward a dispatch strategy to obtain the optimal configuration of the PV/Diesel system by simultaneously minimizing the total cost, pollutant emissions and the total not met load using multi-objective evolutionary algorithm and genetic algorithm.

Recent literature has focussed on the various ways of integrating hybrid renewable based DGs in the distribution system. Singh and Parida [5] have considered minimization of cost to optimally place solar, wind and fuel cell based DGs using Analytic Hierarchy Process. Atwa et al. [6] proposed a new method for optimally allocating different types of renewable DG units. The problem is formulated as MINLP, with an objective of minimizing the system's annualized energy losses. Kayal and Chanda [7] introduced a multi-objective constrained PSO based approach to place, wind and solar based DG units for optimal power loss reduction and voltage stability improvement of the distribution network. In most

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of the literature, different optimization algorithms [8] were proposed to separately solve the hybrid energy system and the integration of renewable DG's into the distribution system. Each of these algorithms either aims at reducing the power loss and improving the voltage stability of distribution network or minimizing the total cost and improving the reliability of stand-alone hybrid energy system.

This paper proposes a new methodology to integrate the hybrid DG's into the distribution system while simultaneously optimizing the type and size of energy sources allied with the size and location of DG's in the distribution system. This is done considering many contradicting objectives in both hybrid energy system and distribution system. The suggested algorithm finds an optimal combination of type, number of PV and wind, battery, diesel hybrid energy sources to increase the reliability and to minimize the cost and emission. Different combinations of these sources are considered to meet the sample energy demand for a day of 9.22 kW h which is repeated for 365 days. The best combination is being selected as the hybrid DG for integration. This algorithm, then attempts to integrate the hybrid renewable DG's into the IEEE-69 bus distribution system with an aim of minimizing the distribution losses, voltage deviation, cost and emission which is due to the energy generated by the DG and that purchased from the grid. The optimization algorithm considers three hybrid renewable DG's optimally placed at multiple locations, taking the location and size of DG's as variables. The size of DG's thus obtained are considered as the load for the hybrid energy system optimization problem. As the radiation data, wind data, state of charge (SOC) of the battery varies for 8760 h, the load (DG size) thus obtained by the above optimization problem should also be converted to 8760 h. The load (DG size) thus obtained is converted to hour-wise data by matching the assumed sample load pattern of 9.22 kW h data. Taking this as the load, the optimal size of hybrid energy system to minimize the cost and to maximize the reliability of PV/Wind/Battery hybrid energy system is obtained. With this obtained reliability and size of DG (hybrid energy system), the Forward Backward sweep Power flow algorithm for the distribution network is used to obtain the voltage of different buses. Thus, this paper attempts to find the size and location of DG with the type, number of PV panels, Wind turbines and batteries. The total cost, emission, voltage deviation and the total losses in the distribution and hybrid energy system are simultaneously minimized. To solve both these multi-objective optimization problems, an improvised multi-objective particle swarm optimization (MOPSO) algorithm is formulated which includes Pareto optimality to arrive at multiple optimal solutions, sigma method and crowding distance to maintain the diversity among the non-dominated set of solutions obtained, and fuzzy set theory to arrive at a best compromised solution. The steps for the proposed methodology is as shown in Fig. 1.

System modelling

The designed hybrid power generation system consists of photovoltaic cells, wind turbine generators, batteries and diesel generators. Each generating unit is first mathematically modelled. For simplicity, current modelling is used, in which the output and input of each generating unit is expressed in terms of current. The schematic representation of the hybrid power system [4] is shown in Fig. 2.

The demand considered is an AC load. Output from solar and wind energy sources together is called renewable energy generation. Batteries get charged by and also discharge DC currents, with the help of a charge regulator in accordance with the considered dispatch strategy. All the DC current outputs are converted into AC by an inverter before supplying the load. The diesel generator on the other hand generates AC current, which is either directly supplied to the load or is used to charge batteries through a battery charger and the charge regulator.

PV panel model

PV generator is one of the renewable source generators which provides DC current at a voltage level of 48 V. The rating of each PV module is mentioned in the latter sections. As mentioned earlier, current modelling [4,22,23,25] is used to represent the output of a PV generator. The efficiency of a PV panel is low compared to other conventional sources. The maximum output, and hence the maximum efficiency, is obtained at the maximum power point. At any instant of time the power output of each PV panel is given by

$$P_{PV_i} = N_P \cdot N_s \cdot V_{PV} \cdot I_{PV_i} \tag{1}$$

where N_p is the number of PV panels connected in parallel, N_s is the number of PV panels connected in series, V_{PV} is the final DC voltage of the PV panel, I_{PV_i} is the current supplied by the PV panel during the ith hour which is given by:

$$I_{PV_i} = G_i \cdot I_p \tag{2}$$

where G_i is the ith hour irradiation of Zaragoza, Spain and i ranges from 1 to 8760 h. I_p is the final constant peak current of the panel, assuming that the necessary physical changes including losses are already made.

Wind turbine model

Wind turbine generator is the other type of renewable energy source generator used in the considered hybrid system. To maintain a constant base of voltage type among the renewable sources, the DC wind turbine is considered in this design [24,26,28]. The output of each wind turbine is modelled as a DC current, I_{wind}, given by

$$I_{wind} = P_{wind}/V_{wind} \tag{3}$$

where, V_{wind} is the voltage rating of the wind turbine and P_{wind} is the power from wind turbine [26,29], calculated as

$$P_{wind} = \begin{cases} P_{rated} \cdot (v - v_{in})/(v_r - v_{in}) & v_{in} \leqslant v \leqslant v_r \\ P_{rated} & v_r \leqslant v \leqslant v_{out} \\ 0 & v < v_{in} \text{ or } v > v_{out} \end{cases} \tag{4}$$

where, P_{rated} is the rated power of a wind turbine, v_r is the rated wind velocity, v_{in} and v_{out} are the cut-in and cut-out wind velocities and v is the net hourly wind velocity. Wind velocity changes with hub height and available wind data. The net hourly wind velocity is given by

$$v = v_{ref} \cdot \left(\frac{H_{wt}}{H_{ref}}\right)^{\alpha} \tag{5}$$

where, H_{wt} is the hub height of the wind turbine and H_{ref} is the reference hub height considered to obtain the wind velocity data, v_{ref},ν is the wind speed at the hub height H_{wt}, α is the power law exponent which varies with parameters such as elevation, time of day, season, nature of terrain, wind speed and temperature.

Battery model

Battery banks serve as a backup storage and are either charged or discharged according to the dispatch strategy [4,27]. The maximum value of the State of Charge (SOC) of a battery is equivalent to

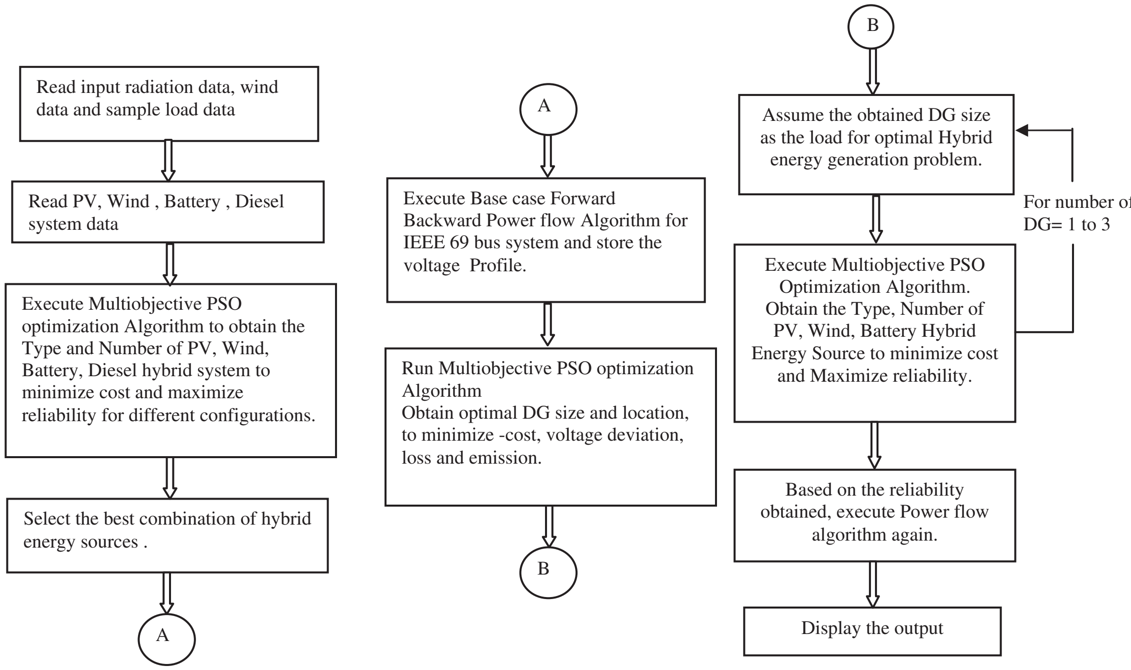

Fig. 1. Project flow diagram.

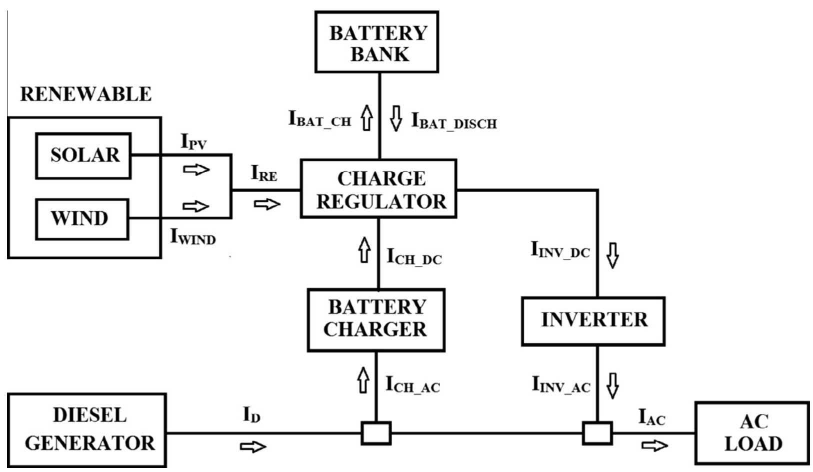

Fig. 2. Block representation of the hybrid power system.

its nominal capacity, while its minimum value depends on the maximum Depth of Discharge (DOD) as expressed below.

$$SOC_{\min} = N_{bat\_p} C_N (1 - DOD_{\max}) \quad (6)$$

$$SOC_{\max} = N_{bat\_p} C_N \quad (7)$$

where, C_N is the nominal capacity of one battery in Ah, N_{bat_p} is the number of batteries in parallel, $DOD_{\max}$ is the maximum depth of discharge of batteries. The state of charge for the next time step is given by

$$SOC(t + \Delta t) = SOC(t) \cdot (1 - \delta) + I_{bat}(t) \cdot \Delta t \cdot \eta_{bat} \quad (8)$$

where, δ is the self discharge coefficient of battery and η_{bat} is the efficiency of battery and $I_{bat}(t)$ is the battery's current in the previous step.

Maximum current a battery can provide at one time step is given by

$$I_{bat,\max}(t + \Delta t) = \max\left[0, \min\left[I_{\max}, \left(\frac{c}{\Delta t} \cdot SOC_{charge} + SOC_{discharge} \cdot \frac{1 - c}{\Delta t}\right)\right]\right] \quad (9)$$

$$\left.\begin{aligned} SOC_{charge} &= (SOC_{\max} - SOC(t)) \\ SOC_{discharge} &= (SOC(t) - SOC_{\min}) \end{aligned}\right\} \quad (10)$$

where, $I_{\max}$ is the maximum charge current, c is a binary variable defined as in (11), $SOC(t)$ is the state of charge of battery banks at a time t, $SOC_{\min}$ and $SOC_{\max}$, as expressed in (6) and (7), are the minimum and maximum allowable state of charge on the battery bank.

$$c = \begin{cases} 1 & \text{battery is charging} \\ 0 & \text{battery is discharging} \end{cases} \quad (11)$$

Diesel generator model

Diesel generator is another source of backup considered for this hybrid system. In accordance with the dispatch strategy, the AC output of diesel generator is either directly used to supply loads or used for charging batteries through a battery charger that converts the AC current to DC. A linear model [4] is considered for hourly fuel consumption,

$$fuel\_used = B \cdot P_{Ngen} + A \cdot P_{gen}\ \text{l/h} \tag{12}$$

where, P_{Ngen} is the rated capacity of diesel generator in kW, P_{gen} is the output power of diesel generator in a particular hour in kW, A and B are the fuel curve coefficients [4], whose values are taken as

$$\begin{aligned} A &= 0.246\ \text{l/kW h} \\ B &= 0.08415\ \text{l/kW h} \end{aligned} \tag{13}$$

Distribution system load model

Loads can be static or dynamic. The various static load models are:

- Constant impedance model – load power varies with the square of voltage magnitude.
- Constant current model – load power varies with the voltage magnitude only.
- Constant power model – load power does not vary with voltage magnitude.
- Exponential load model – load power varies with the voltage magnitude in an exponential relationship.

For simplicity, the constant power load model is chosen for this work. The real and reactive power of the loads in this model is assumed to be constant and they do not vary with the magnitude of bus voltage.

Distribution power flow (forward–backward sweep) algorithm

The forward and backward sweep algorithm is based on Kirchoff's voltage and current laws (KVL and KCL). It is an iterative method which comprises of two major steps, namely the backward sweep and the forward sweep [18]. The backward sweep of the algorithm involves the calculation of branch currents. The current in a branch k is calculated according to KCL, by summing up all the load currents and branch currents in the buses and branches that precede the branch k from the backward direction. The branch voltage drops are then computed from the branch currents. The forward sweep of this algorithm involves the computation of bus/node voltage. The voltage at bus k is computed according to KVL, by subtracting the branch voltage drops from the voltage at the bus connected in front of the bus k in the forward direction.

Dispatch strategy

The hybrid system consists of PV generators, wind turbine generators, battery banks and diesel generator. The use of all, or most, of the sources at a particular time in order to maximize the reliability can drastically increase the total cost of the system during that period. In order to attain a maximum reliability and yet maintain a reasonable cost for the system, different dispatch strategies like *Load following strategy*, *Cycle charging strategy* or *Combined strategy* can be used [4].

Load following strategy

The main aim of this strategy is to meet the load. The load is met primarily by the renewable sources of energy. In case the load during an hour exceeds the capacity of renewable energy source, either the batteries or diesel generator or sometimes both backup sources are used, in order to keep the cost low. It is mainly based on the critical discharge load (L_d) which is the net load above which the marginal cost of generating energy with the diesel generator is less than the cost of drawing energy from the batteries [4]. At the critical discharge load, the cost of generating energy with diesel generator is equal to the cost of drawing power from the batteries. This is expressed as

$$C_{OM\_gen} + C_{rep\_gen\_h} + C_{fuel} \cdot (B \cdot P_{Ngen} + A \cdot L_d) = \frac{C_{cycling\_bat} \cdot L_d}{\eta_{inv}} \tag{14}$$

where C_{OM_gen} is the operation and maintenance cost of diesel generator and C_{fuel} is the hourly fuel (diesel) cost, $C_{rep\_gen\_h}$ is the hourly replacement cost of diesel generator and $C_{cycling\_bat}$ is the cost of cycling energy through the batteries.

Cycle charging strategy

In this strategy, the diesel generator is made to run at full power or at a rate not exceeding the maximum energy that the batteries are capable of absorbing. [4] This strategy is used when batteries are not able to meet the net load. The diesel generator, in such cases, charges the battery with any surplus power left over after meeting the load. With this strategy, the diesel generator will continue to run until the batteries reach a maximum SOC set point, $SOC_{\max}$.

Combined strategy

This strategy combines both load following and cycle charging strategies, to achieve a much less expensive yet reliable design of the considered hybrid system. The decisions on this strategy are based on Critical charge load (L_c) in kW. The critical charge load is the net load where the cost of generating the exact power with the diesel generator for an hour, is the same as the cost of supplying the very same load for an hour using the batteries that have been previously charged by the diesel generator [4]. This is mathematically represented as

$$\begin{aligned} &C_{OM\_gen} + C_{rep\_gen\_h} + C_{fuel} \cdot (B \cdot P_{Ngen} + A \cdot L_c) \\ &= \frac{A \cdot C_{fuel} \cdot L_c}{\eta_{ch} \cdot \eta_{bat} \cdot \eta_{inv}} + \frac{C_{cycling\_bat} \cdot L_c}{\eta_{inv}} \end{aligned} \tag{15}$$

where L_c is the critical charge load. According to this strategy, if the net load is lower than the critical charge load, the Cycle charging strategy is applied; and if the net load is higher than the critical charge load, the Load following strategy is applied.

In every hour, the total load in DC is given by (17) .The load is first supplied by the renewable sources of energy, $I_{re} = I_{pv} + I_{wind}$. The remaining load to be supplied by the remaining sources of energy is termed as the net load in DC, which is mathematically expressed as

$$I_{load\_DC} = I_{AC} \cdot \frac{V_{AC}}{V_{DC} \cdot \eta_{inv}} \tag{16}$$

$$I_{net\_DC} = I_{load\_DC} - I_{re} \tag{17}$$

where, V_{DC} and V_{AC} are the DC and AC voltage levels of the system and η_{inv} is the inverter efficiency. The value of I_{net_DC} being positive if there is an excess load which is not met by the renewable sources of energy and negative if there is an excess of renewable energy generation after meeting the load. The diagrammatic representation of the flow of this dispatch strategy is shown in Fig. 3.

Optimization objectives

The hybrid generation system proposed is to be integrated into the distribution system. Aiming at providing an uninterrupted supply to the consumers at a voltage within allowable limits and reasonable cost, various objectives like cost and emissions from grid, system losses and voltage deviations are considered for optimization of the distribution system [15,17,19,20]. This optimization algorithm is performed by varying the location and size of DG. The internal design of the DG is further tuned by optimizing the cost, reliability and emissions of the hybrid generation system.

The detailed mathematical modelling of each objective involved in both the optimization problems is described in this section.

Distribution system losses

To achieve an optimal configuration of the distribution system, the power losses in the system ought to be minimal. Real power loss in a branch 'br' is calculated using

$$P_{loss\_br} = I_{br}^2 \cdot R_{br} \tag{18}$$

where, I_{br} is the current in branch *br* and R_{br} is the resistance of the branch *br*. The total active power loss of the considered distribution system, as described in (19), is minimized by considering it as an optimization objective.

$$\min \sum_{br=1}^{nbr} P_{loss\_br} \tag{19}$$

Distribution system voltage deviations

Apart from minimizing the power losses in the distribution system, the main factor influencing the quality of power supply to the consumers is a constant voltage level. The voltages at all nodes/buses in a distribution system should be within allowable limits, to avoid damage to the distribution network and to the equipments in the consumer side. The maximum allowable voltage deviation limit in a distribution system is considered as ±6%. The voltage deviation at bus 'bs' is calculated using

$$V_{bs\_dev} = V_{th} - V_{bs} \tag{20}$$

where, V_{th} is the desired voltage threshold value and V_{bs} is the voltage at bus *bs*.

Minimizing the squared value of voltage deviations at the buses will improve the voltage profile and eventually result in a profile with all the voltages satisfying the limits. Thus the sum of squared deviations of voltage at each bus, as described in (21), is considered as an objective to be minimized.

$$\min \sum_{bs=2}^{69} V_{bs\_dev}^2 \tag{21}$$

Grid cost

Aiming at obtaining a better optimal configuration of the distribution system, the cost of energy purchased from the grid is minimized. The cost of energy purchased from the main sub-station, as described in (22), depends on the load factor and energy price at a particular hour.

$$Cost_{Grid} = P_{sub} \times LF \times \rho_r \times 8760 \tag{22}$$

where, P_{sub} is power purchased from the grid, *LF* is load factor and ρ_r is energy price.

Minimizing the total cost of energy purchased from the grid, along with the simultaneous optimization of the other objective, results in a better configuration of the distribution system.

Grid emission

Emissions due to the energy purchased from the grid mainly arise due to the generating units energizing the grid. Like the cost of energy purchased from the grid, the emission due to the energy purchased from the grid is a function of the load factor and the emission rate of the grid. The total annual emission due to energy purchased from the grid is given by

$$Emission_{Grid} = P_{sub} \times LF \times ER_{Grid} \tag{23}$$

where, P_{sub} is power purchased from the grid, *LF* is load factor and ER_{Grid} is the emission rate of the grid. This objective is also proposed to be minimized simultaneously along with the optimization of all the other objectives.

Hybrid system reliability

The major concern for the power system operators is to meet the load at all times, that is to increase the reliability of the power system. Reliability is a measure of the quality of power supply. High reliability is aimed to be achieved in the proposed design of the considered hybrid system. There are many ways to assess the reliability of the system, like analyzing the value of Expected Energy Not Served (EENS), Loss of Power Supply Probability (LPSP), Energy Index of Reliability (EIR), etc. This paper uses EIR [9] to measure the reliability of the hybrid system.

Energy Index of Reliability (EIR) is calculated from EENS by

$$EIR = 1 - \frac{EENS}{E} \tag{24}$$

where, *E* is the yearly energy demand, and *EENS* for a time duration of *T* hours is given by

$$EENS = \sum_{t=1}^{T} (P_{net\_DC}(t) - P_{bat\_avail}(t) - P_{gen\_DC}(t)) \cdot U(t) \tag{25}$$

where, $P_{net\_DC}(t)$ is the hourly net load power (not met by renewable) in DC, $P_{bat\_avail}(t)$ is the hourly maximum power a battery can provide, $P_{gen\_DC}(t)$ is the hourly power supplied by diesel generator in DC and $U(t)$ is a unit step function defined by

$$U(t) = \begin{cases} 0 & generation > demand \\ 1 & generation \leqslant demand \end{cases} \tag{26}$$

EENS gets a value greater than zero only when the load is not fully met. The value of EENS is proportional to the amount of not met load power. If the amount of not met load is high, the value of EENS increases, and consequently the value of EIR decreases. The ideal value of an EIR is 1, when the load is fully met. This objective thus needs to be maximized in this optimization process.

Hybrid system cost

Apart from ensuring continuous supply, a power system should also provide electric energy at an affordable price. But, in the process of increasing the reliability, the cost of energy drastically rises due to the increased use of resources. One of the main objectives in the design of any power generation system is an optimal reliability at a reasonable cost. Some of the cost functions that are being used in the literature are Annualized Cost of the System (ACS), Net Present Value (NPV), etc. This paper incorporates the minimization of the Net Present Value (NPV) of the system [4] in the design process.

The Net Present Value of cost includes the initial capital cost called as acquisition cost, and two other costs, namely, replacement cost and operation and maintenance cost are computed for the whole life period of the system. Mathematically, the NPV value is given by

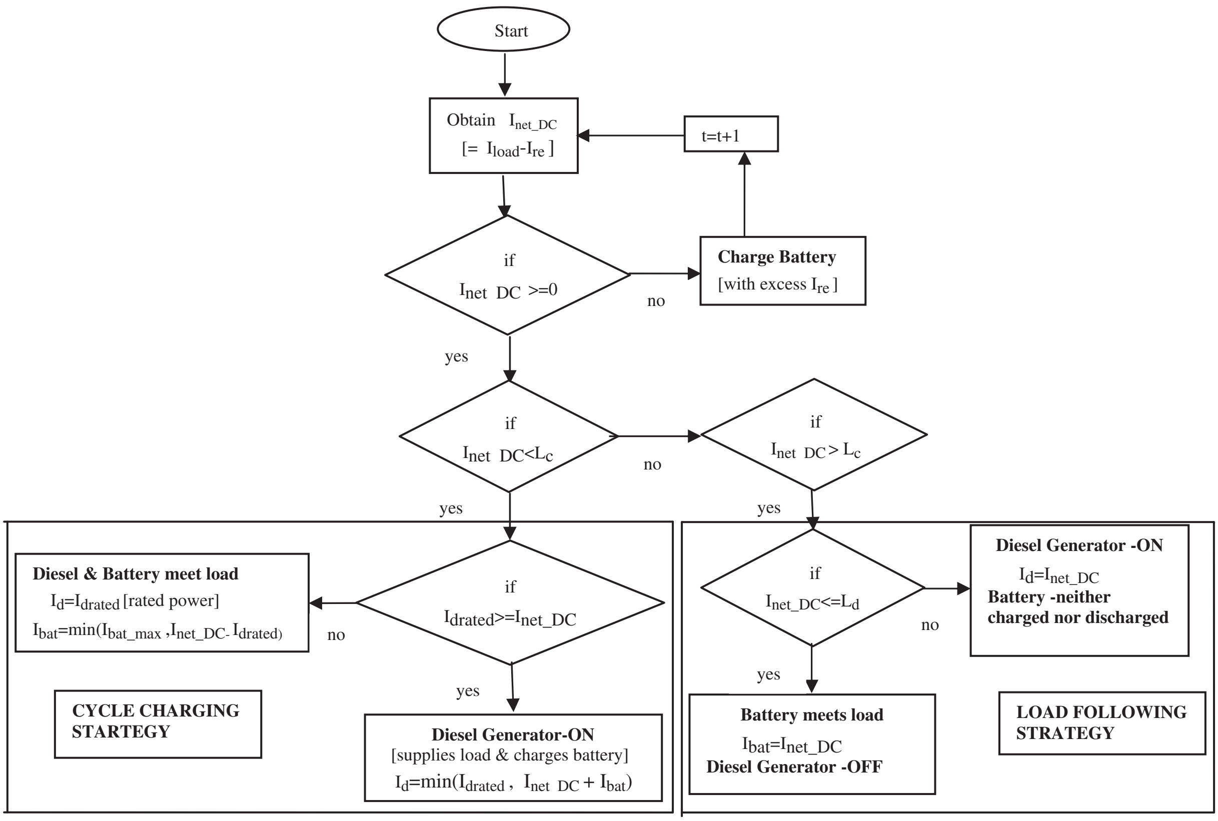

Fig. 3. Flow chart of dispatch strategy.

$$NPV = C_{ACQ} + C_{OM} + C_{REP} \quad (27)$$

where, C_{ACQ} is the acquisition cost which is the same as the initial capital cost, C_{OM} is the operation and maintenance cost and C_{REP} is the replacement cost. The NPV of each component of the hybrid system, which include the PV panels, batteries, inverter, charge regulator and diesel generator, is computed separately.

The total cost incurred for the system during the considered duration is given by (28). It includes the net present values of each component of the system and the cost of fuel.

$$Cost = NPV_{pv} + NPV_{wind} + NPV_{bat} + NPV_{inv} + NPV_{reg} + C_{diesel\_gen} + C_{diesel} \quad (28)$$

where, NPV_{pv}, NPV_{wind}, NPV_{bat}, NPV_{inv} and NPV_{reg} are the net present values of photovoltaic panels, wind turbine generators, batteries, inverter and charge regulator respectively; C_{diesel_gen} is the total cost of diesel generator and C_{diesel} is the total fuel (diesel) cost which is given by

$$C_{diesel} = C_{fuel} \cdot fuel\_used \quad (29)$$

where, C_{fuel} is the cost of fuel per litre and *fuel_used* is the amount of fuel consumed per hour as in (12).

Hybrid system emission

Pollutant emissions in the considered system are the emissions of CO_2 from a diesel generator, which is given by

$$emission = fuel\_used * emission\_factor \quad (30)$$

The emission factor is a constant which depends on the type of fuel. For diesel, the emission factor is 3.5 kg CO_2 per litre of fuel.

System optimization model

Multi-Objective Particle Swarm Optimization algorithm (MOPSO) [9,12,14,16,30] has been implemented for the hybrid power generation system to obtain the maximum reliability, minimum cost and emission. The Particle Swarm Optimization (PSO) is a population based stochastic optimization procedure inspired by certain social behaviors in bird groups and fish schools. A swarm of particles is considered to be moving in a search space to find the best food (optimum solution). Each particle is known along with its position (variable) and velocity (of motion towards food). Assuming there is one best solution in the whole search space for a single objective PSO, all the particles move, by varying their positions and velocities iteratively, to ultimately reach it. It is not possible to get a unique optimum solution for a MOPSO problem, due to the concept of non-dominance. So the swarm searches for multiple-optimum solutions, which are non-dominated with each other, called the Pareto Optimal solutions. These Pareto optimal solutions are used to determine the guide for each particle. But selecting the best local guide from the set of Pareto optimal solution is a difficult task. There exist several MOPSO methods based on the selection of the best local guide. This paper implements i-MOPSO algorithm using a sigma method for selecting the best local guide. This algorithm also incorporates the crowding distance with the mutation operator to maintain the diversity of non dominated solution in the external archive and a fuzzy membership function to obtain the best compromised solution.

Improvised MOPSO algorithm

The improvised MOPSO algorithm developed aimed at directing the swarm towards the Pareto optimal front. The step-wise procedure of this algorithm is detailed below.

Step 1: Input the system data
Step 2: Initialize the PSO parameters like the population size, maximum number of iterations, etc.
Step 3: Randomly generate a swarm of particles and initialize the velocity of each particle.
Step 4: Initialize two archives, *pbest* for personal best value of each particle and *A* for the non-dominated set archive.
Step 5: For count = 1 to maximum iterations, do the following:
5a. Evaluate the fitness value for each particle.
5b. Update the *pbest* memory
5c. Update the archive *A* of non-dominated solutions based on Pareto optimality.
5d. Limit the size of the non-dominated set archive, *A*.
5e. Compute best local guides lg *best* using Sigma method.
5f. Update velocity and position of each particle.
End
Step 6: Display the Pareto optimal front
Step 7: Compute the best compromised solution using fuzzy membership functions.

Pareto optimality

The multi-objective optimization requires maximization of reliability and minimization of cost and emissions simultaneously. Optimization of the set of contradictory objectives does not lead to a unique solution. Thus, the optimization is aimed at moving the entire swarm towards the Pareto optimal front, which constitutes a set of non-dominated solutions. The basic procedure of updating a non-dominated solution archive [10] is given below.

- Check for domination between the fitness values (i) and archive members (j).
- If i dominates j
  - o Delete j from the archive.
- If j dominates i
  - o Set $i = i + 1$ and check for the next solution.
- If both i and j are non-dominated
  - o Insert i along with j in the archive.

Crowding distance

As the number of iterations increases, the number of non-dominated solutions in the archive *A* might increase drastically, thus increasing the computation burden and time. In order to limit the size of the archive at the end of each of the iterations, crowding distance [10,11] is incorporated. The following procedure is followed to limit the size of the archive:

- Initialize distance for each particle, $d_i = 0$.
- Sort each objective function.
- Assign distance $d_i = \infty$ for boundary solutions and compute the distance for all other solutions using

$$d_i = d_i + \frac{f_m^{i+1} - f_m^{i-1}}{f_m^{\max} - f_m^{\min}} \tag{31}$$

- Sort the distances in descending order, and choose the 1st k solutions for the next iteration.

Thus, aiming at maintaining the diversity of solutions at a reduced computational time and burden, this paper limits the maximum size of the non-dominated set archive to 25.

Best local guide

In general, one unique global best position is assigned for the whole swarm. This might again lead to the loss of diversity of solutions from the Pareto front. In order to avoid this, best local guides, which serve as separate *gbest* for each particle, are used to guide the swarm. The best local guide, *lgbest* is computed using Sigma method [13] as follows:

- Compute sigma values
  - o σ_i for each particle
  - o σ_j for each archive member.
- Compute the distance $d = \sigma_i - \sigma_j$.
- The archive member which gives the least distance for particle i is its *lgbest*.

Velocity and position update

Each particle stores, the best position it obtained so far, as its personal best value in the *pbest* archive. This personal best value is computed based on the best function value. If the updated function dominates the function value of already present *pbest* in the archive, then the *pbest* is replaced by the updated variable or position value x.

The velocities and positions for each particle is updated based on its respective *pbest* and *lgbest* values. The velocity and position updates [9] are carried out as

$$v_i(t) = v_i(t-1) + c_1 \cdot r_1 \cdot (pbest_i - x_i(t-1)) + c_2 \cdot r_2 \cdot (lgbest_i - x_i(t-1)) \tag{32}$$

$$x_i(t) = x_i(t-1) + v_i(t) \tag{33}$$

where r_1 and r_2 are two random values; c_1 and c_2, taken as $c_1 = c_2 = 1.05$, are the constants pertaining to the personal and social influences of a particle's movement, respectively.

Best compromised solution

The Pareto front consists of a set of non-dominated optimal solutions, but the design procedure requires one optimal design to be implemented in real time. So it is essential to arrive at a single optimal solution from a set of non-dominated solutions after making suitable trade-offs. Manually choosing a best solution out of the whole Pareto front might involve inaccuracies. So, fuzzy set theory is incorporated into the MOPSO algorithm for decision making, in order to finally arrive at a best compromised solution. The following procedure is followed.

- Formulate the fuzzy membership function for each objective of each Pareto optimal solution as

$$\mu_i = \begin{cases} 1 & \text{if } f_i \leqslant f_i^{\min} \\ \frac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & \text{if } f_i^{\min} < f_i < f_i^{\max} \\ 0 & \text{if } f_i \geqslant f_i^{\max} \end{cases} \tag{34}$$

where μ_i is the membership value of the objective; $f_i^{\min}$ is the value of objective i which is completely satisfactory; $f_i^{\max}$ is the value of objective i which is completely unsatisfactory. The overall fuzzy membership value of a pareto optimal solution is the sum of all the μ_i for all the objectives of that solution.

- Compute normalized membership function for each solution as

$$\mu^k = \frac{\sum_{i=1}^{N_{obj}} \mu_i^k}{\sum_{k=1}^{M} \sum_{i=1}^{N_{obj}} \mu_i^k} \tag{35}$$

- The Pareto optimal solution with maximum μ^k is the best compromised solution.

System data

Spain system data are considered for the implementation of the design using the improvised MOPSO algorithm. The algorithm is executed using MATLAB for an hour-wise annual data, i.e. 8760 h. The variables considered in the optimization are as mentioned below:

- Type of PV panel.
- Number of PV panels in parallel.
- Type of wind turbine.
- Number of wind turbines.
- Type of battery.
- Number of batteries in parallel.
- Type of diesel generator.

The system load voltage level is 230 V and the DC voltage level of the system is 48 V. The different types are so chosen for the database that they have the same voltage ratings.

The designed hybrid power generation system is implemented into the distribution system. An IEEE standard 69-bus distribution system with an operating voltage of 12.66 kV is considered. The total real power load on the system is 3.803 MW and the total reactive power load is 2.693 MVAR. The voltage profile, loss, cost and emission of the system are proposed to be optimized using the improvised MOPSO algorithm by integrating the hybrid system as DG. The variables considered for optimization are as mentioned below:

- Location of each DG.
- Size of each DG.

The required optimal size of DG provided by the MOPSO algorithm would be used as the load for the hybrid system.

Hybrid system data

All possible and available types of each source of the hybrid system chosen from i-HOGA software and are given as input system data [4,23]. The algorithm chooses an optimal type and number of units of each source, in order to arrive at an optimal design.

PV panels of voltage rating 12 V DC are chosen. Four PV panels are connected in series to maintain a voltage base of 48 V DC. There are different types of PV panels with the same voltage rating from different manufacturers. Ten such types chosen from i-HOGA software are shown in Table 1. A number of PV panels to be placed in parallel are considered as another variable.

48 V DC wind turbines are chosen for the hybrid system, in order to maintain same voltage type (DC) and a level (48 V) as that of the other renewable source. Four types of 48 V DC wind turbines chosen from i-HOGA software are tabulated in Table 2. The rated velocity and lifespan for all the chosen wind types is 14 m/s and 20 years respectively.

Batteries of voltage rating 12 V are chosen for this design. Four batteries are connected in series to maintain a base voltage of 48 V DC in the system. Ten types of batteries of different makes chosen from i-HOGA are tabulated in Table 3. The type of a battery is chosen as a variable. The number of batteries to be placed in parallel is considered as another variable. The efficiency and float life for all the chosen battery types are 80–85% and 12–18 years.

Table 1
PV panel data.

PV panel type	Current (A)	Acquisition cost (€)	O&M cost (€/year)	Lifespan (Years)
1	0.82	47	0.47	25
2	1.32	109	1.09	25
3	1.64	80	0.8	25
4	3.13	154.9	1.55	25
5	3.73	200	2	25
6	4.06	216	2.16	25
7	5.51	248	2.48	25
8	8.23	277	2.77	25
9	8.33	478	4.78	25
10	8.73	354	3.54	25

Diesel generators of different kVA ratings and different manufacturers are considered. Six such types of diesel generators chosen from i-HOGA software database are tabulated in Table 4. The type of diesel generator is considered as a variable. Only one diesel generator is used. The emission factor for all the chosen types of diesel generator is 3.5 kg CO_2/litre. The cost of diesel in Spain is 1.441€/litre.

Distribution system data

The single line diagram and bus data of the IEEE standard 69-bus distribution system [21] are used in this study. For an easier analysis of the distribution system, each of the load and line data are converted into per unit. The MVA base for this system is taken as 100 MVA and the operating voltage (12.66 kV) of the system is considered as its base voltage.

Input data

The proposed algorithm is based on the case study of Zaragoza region in Spain, which is located at the latitude of 41°39′ N and longitude of 1°0′ W. The solar irradiation and wind velocity data of Zaragoza, Spain are considered as the inputs for implementing the design.

Load data

The total energy required to be met by the hybrid system for a day is given by the size of the DG provided by the optimization result of the distribution system. The hourly load profile for a day is formulated equivalent to that of a 9.22 kW h load pattern as shown in Fig. 4. This same load profile is repeated for 365 days to obtain an 8760 h load profile.

Solar radiation data

The monthly average solar irradiation data are taken from the NASA meteorological data as shown in Table 5. This monthly average data is then converted to an hourly data for 8760 h using the software HOMER. The obtained 8760 h irradiation data is plotted and shown in Fig. 5.

Wind velocity data

The monthly average wind velocity data furnished in Table 6 are taken from the NASA meteorological data. This monthly average data are then converted to an hourly data for 8760 h using the software HOMER. This 8760 h wind velocity data are plotted and shown in Fig 6.

Table 2
Wind turbine data.

Wind turbine type	Rated power (P_{rated}) in kW	Hub height (H) in m	Cut-in velocity (v_{in}) in m/s	Cut-out velocity (v_{out}) in m/s	Acquisition cost in €	Replacement cost in €	O&M cost in €/yr
1	1	11	3	20	3724.5	3009.5	110.5
2	1.5	13	3	20	6337.5	4777.5	127.4
3	3	15	3	20	9821.5	7800	196.3
4	6	15	2	20	15672.8	13000	291.2

Table 3
Battery Data.

Battery type	Nominal capacity (Ah)	Acquisition cost (€)	O&M cost (€/hr)	Max current (I_{max})	Del	No. of cycles [N_{cycle}]
1	68	166	1.7	13.6	0.03	1110
2	78	254.9	2.55	15.6	0.02	1400
3	97	150	1.49	19.4	0.05	450
4	106	194.9	1.95	21.2	0.05	450
5	120	160	1.6	24	0.05	450
6	134	154	1.54	26.8	0.05	450
7	170	464	4.64	34	0.03	1110
8	189	174.9	1.75	37.8	0.05	450
9	190	562	5.61	38	0.02	1400
10	296	961	9.6	59.2	0.03	1110

Table 5
Monthly average solar & wind data (Zaragoza, Spain).

Month	Avg. irradiation (kW h/m^2)	Monthly avg. wind velocity (m/s)
Jan	2.47	6.00
Feb	3.82	6.24
March	5.55	7.20
April	5.68	10.80
May	6.13	12.00
June	6.59	10.20
July	6.8	9.12
August	6.85	8.40
Sept	6.7	7.44
Oct	5.68	7.32
Nov	3.32	7.20
Dec	2.26	7.20

Table 4
Diesel generator data.

Diesel type	Rated power (kVA)	Acquisition cost (€)	O&M cost (€/h)	Lifespan (h)
1	1.9	700	0.12	10000
2	3	918.8	0.148	10000
3	4	1050	0.155	10000
4	5.5	1137.5	0.195	10000
5	7	1400	0.209	10000
6	11	3237.6	0.236	10000

Results and discussion

The hybrid power generation system under consideration has been designed and implemented for the data furnished in the previous section. The MOPSO algorithm has been applied to four different combinations of the power generation units which include: PV and Battery; Wind and Battery; PV, Wind and Battery; and PV, Wind, Battery and Diesel. The computational results of the above mentioned cases using the improvised MOPSO algorithm are validated in comparison with the i-HOGA software's simulation results.

The distribution system optimization in terms of minimization of total system losses, total voltage deviation, and the total cost and emission due to energy purchased from the grid is implemented using the improvised MOPSO algorithm for an IEEE standard 69-bus distribution system. This optimization is achieved by considering the location and sizing of three hybrid DGs as decision variables. After obtaining the best compromised optimal locations and sizes of the 3 DGs in the system, each hybrid DG is internally designed using MOPSO to obtain an optimal cost and reliability of the hybrid DG.

Hybrid system design optimization

The multiple criteria, optimal design of the hybrid generation system is implemented with the variables and their corresponding limits are as shown in Table 6.

Taking the swarm size as 50 and the maximum number of iterations as 100, the i-MOPSO algorithm was executed for the load profile shown in Fig. 4. The best compromised solutions obtained in this case are compared with that of i-HOGA software which uses MOGA as an optimization tool. The simulated results and the comparison are furnished in Table 7.Ten percentages of not met load are allowed for all the cases in i-HOGA. For PV-Battery system and PV-Wind-Battery system, i-MOPSO converges with lesser cost and reliability as compared to i-HOGA. For Wind-Battery system i-HOGA converges with lower cost and better reliability. As far as PV-Wind-Battery-Diesel system is concerned, emission is the main objective that should be minimized. In this case, i-MOPSO converges with the better result as compared to i-HOGA. On the whole, the i-MOPSO algorithm has better diversity and converges

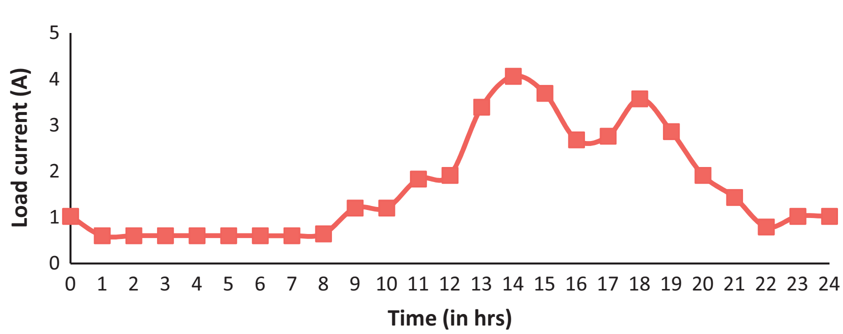

Fig. 4. Daily load profile assumed for 9.22 kW h.

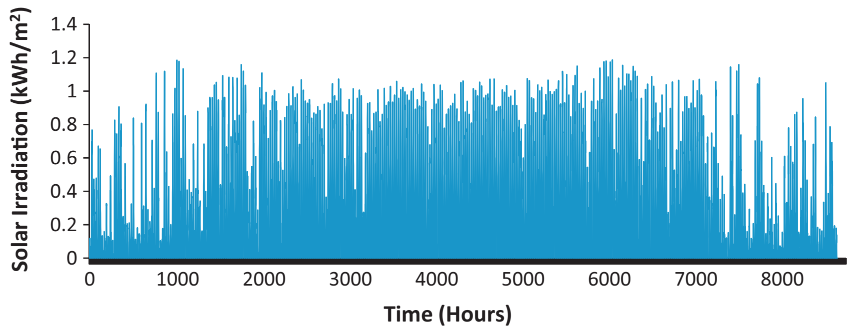

Fig. 5. Hourly insolation (Zaragoza, Spain).

Table 6
Limits on variables.

		Variables			
		PV panels	Wind turbine generators	Batteries	Diesel generator
Limits	Types	[1 10]	[1 4]	[1 10]	[1 6]
	Number	[1 100]	[1 2]	[1 25]	1

with the similar results as that of i-HOGA, based on the type and number of PV/Wind/Battery/Diesel that are selected [13,30].

It is observed that Wind-Battery Case has very poor reliability and also the maximum cost. So wind cannot be used as the only source in a DG. But when combined with PV, the reliability increased considerably. The reliability of this case (PV-Wind-Battery) is also greater than that of PV-battery system, with slightly greater cost. The inclusion of diesel gave a fully reliable system, but with considerable increase in cost. While being considered as a DG, the cost of the hybrid system is expected to be reasonable with an acceptable amount of reliability. Also, the total emission (from grid and DG) is expected to be lesser. Thus, PV-Wind-Battery system is chosen for integration into the distribution system as DG.

Base case distribution system

Distribution power flow algorithms mentioned in Section 'System modelling' F are executed for the distribution system data. The voltage profile obtained for the IEEE 69-bus system by both BIBC-BCBV and Forward–Backward Sweep algorithms is plotted in Fig 7.

It is observed that the voltage profiles obtained from both the power flow algorithms coincide. This obtained voltage profile is similar to the one shown in [14]. The values of all the objectives considered for optimization are computed and shown in Table 8.

Distribution system optimization

The distribution system optimization is implemented by considering the location and size of each of the three DGs as variables. The limitations on the maximum installed capacity of DGs [8] is given by

$$\sum_{i=1}^{Ndg} P_{DGi} \leqslant \gamma \left(\sum_{j=1}^{nbs} P_{Lj} \right) \tag{36}$$

where γ is the penetration level, P_{DGi} is the size of ith DG, N_{dg} is the total number of DGs proposed to be installed in the distribution system, P_{Lj} is the active power load on bus j and nbs is the total number of buses in the distribution system.

The variables considered for this optimization, along with their corresponding limits are furnished in Table 9. The lower and upper limits on the size of each DG are fixed by assuming the minimum and maximum values of γ as 0.1 and 0.4 respectively.

Taking the swarm size as 50 and the maximum number of iterations as 100, the proposed MOPSO algorithm was executed in the data given in the previous section, for various combinations of objective functions which leads to the following cases:

Case 1: Loss and Voltage Deviation.
Case 2: Loss, Voltage Deviation and Grid Cost.
Case 3: Loss, Voltage Deviation and Grid Emission.

The objectives are formulated as detailed in Section 'Optimization objectives'. The proposed algorithm is simulated for all the three cases. A set of non-dominated values is obtained in each case. The function values of the solution set obtained for three cases are plotted and the Pareto optimal fronts, thus obtained are shown in Figs. 8–10.

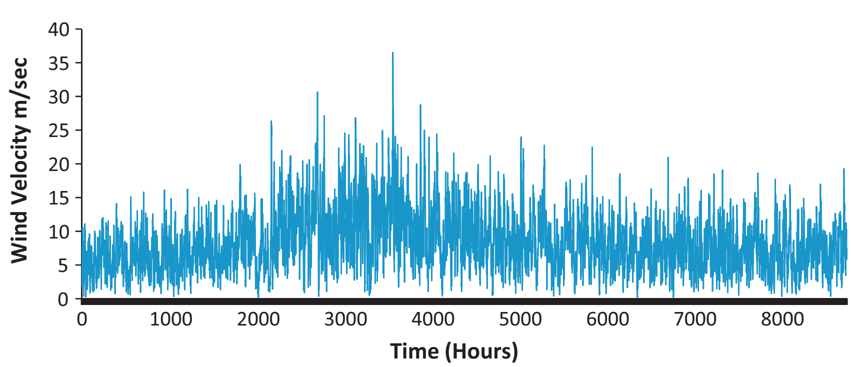

Fig. 6. Hourly wind velocity (Zaragoza, Spain).

Table 7
Best Compromised Solutions for Sample Load.

	PV + Bat		Wind + Bat		PV + Wind + Bat		PV + Wind + Bat + Diesel	
	i-MOPSO	i-HOGA	i-MOPSO	i-HOGA	i-MOPSO	i-HOGA	i-MOPSO	i-HOGA
Function values								
Cost (in €)	22731	29166	40956	40722	32771	34014	138513	137480
Reliability (EIR)	0.9176	0.932	0.8979	0.9	0.9828	1	1	1
Emissions (kg CO_2)	–	–	–	–	–	–	5235	5251
Variable values								
PV Type	8	10	–	–	8	10	7	1
Number of PV	7	6	–	–	20	15	12	14
Wind Type	–	–	4	3	2	2	3	2
Number of Wind	–	–	1	1	1	1	1	1
Battery type	8	8	2	8	6	2	7	8
Number of Batteries	4	5	5	5	9	12	5	2
Diesel Type	–	–	–	–	–	–	5	1

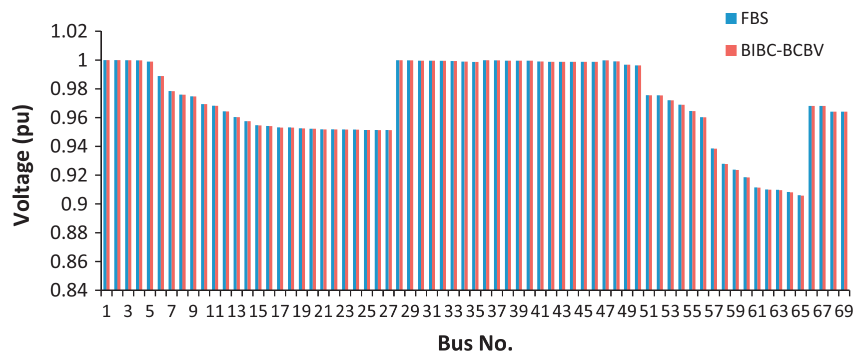

Fig. 7. Voltage profile [Base Case].

Table 8
Objective values [Base Case].

Loss (in kW)	Voltage Deviation	Grid Cost (in €)	Grid Emission ($kg\ CO_2/yr$)
239.4	0.06397	1285900	2332

Table 9
Limits on variables for distribution system optimization.

Variables	Limits
DG location (each)	[2 69]
DG size (each)	[125 kW 510 kW]

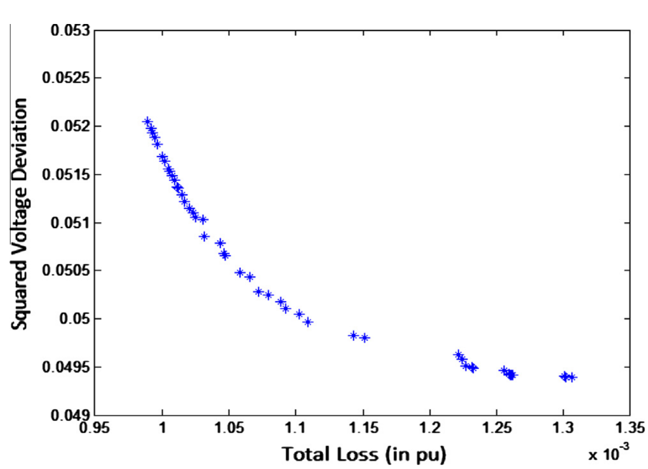

Fig. 8. Pareto front [Loss + Voltage Deviation].

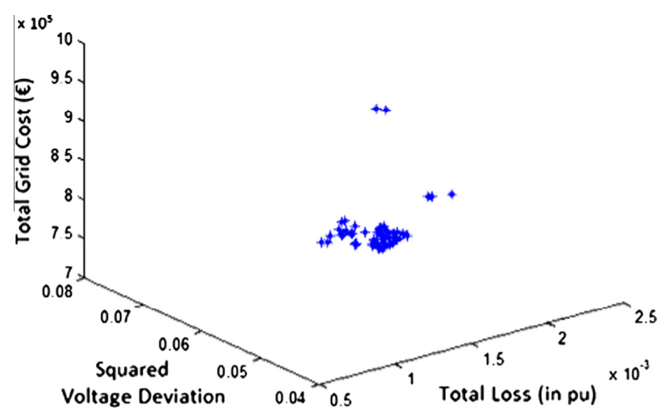

Fig. 9. Pareto front [Loss + Voltage Deviation + Grid Cost].

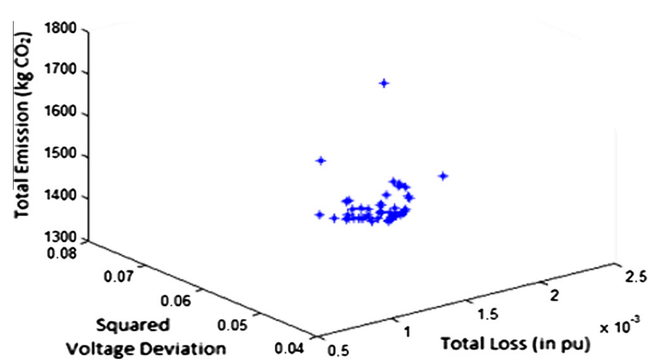

Fig. 10. Pareto front [Loss + Voltage Deviation + Grid Emission].

Table 10
Optimized results of hybrid DG in distribution network.

				Case 1		Case 2		Case 3	
Distribution system optimization	Function	Loss (kW)		100.59		113.86		112.67	
		Voltage deviation		0.0515		0.0509		0.0512	
		Grid cost (€)		–		822285		–	
		Grid Emission (kgCO$_2$)		–		–		1506	
	Variable	Location	DG 1	63		51		62	
			DG 2	61		62		53	
			DG 3	59		65		61	
		Size (kW)	DG 1	480.7		494.4		480	
			DG 2	503.5		498.4		465	
			DG 3	436.2		481		506.9	
Hybrid DG design optimization	Function	Cost (€)	DG 1	45145		46416		45065	
			DG 2	46372		46792		43656	
			DG 3	41052		45159		47590	
		Reliability (EIR)	DG 1	0.9519		0.9403		0.9753	
			DG 2	0.9343		0.9318		0.9968	
			DG3	0.9624		0.9461		0.9113	
				Type	Num.	Type	Num.	Type	Num.
	Variable	PV	DG 1	8	22	8	23	8	22
			DG 2	8	23	8	23	8	18
			DG 3	8	14	8	22	8	23
		Wind	DG 1	4	1	4	1	3	2
			DG 2	3	2	3	2	4	1
			DG3	4	1	4	1	4	1
		Battery	DG 1	6	7	8	7	6	6
			DG 2	8	8	6	8	6	4
			DG3	6	6	6	7	8	5
Distribution system re-optimization	Function	Loss (kW)		112.36		117.62		118.58	
		Voltage deviation		0.0506		0.0508		0.0510	
		Grid cost (€)		–		857846		–	
		Grid emission (kgCO$_2$)		–		–		1582	
	Variable	Location	DG 1	63		51		62	
			DG 2	61		62		53	
			DG 3	59		65		61	
		Size (kW)	DG 1	457.6		464.9		468.2	
			DG 2	470.4		464.5		463.5	
			DG 3	419.8		455.1		461.9	

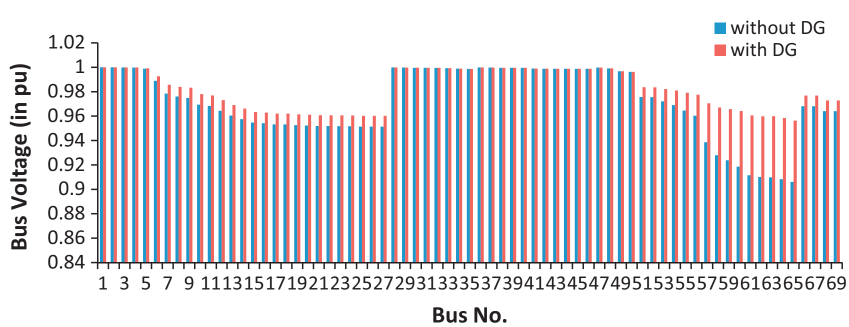

Fig. 11. Voltage profile [Loss + Voltage Deviation].

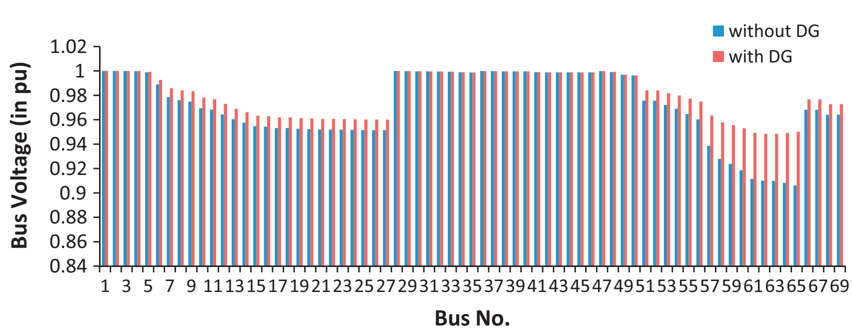

Fig. 12. Voltage profile [Loss + Voltage Deviation + Grid Cost].

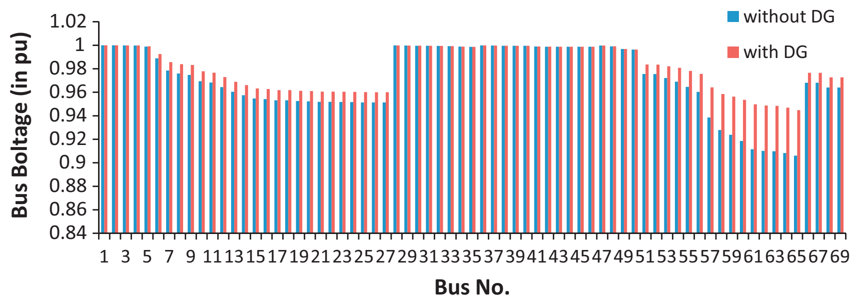

Fig. 13. Voltage profile [Loss + Voltage Deviation + Emission].

As the Pareto front consists of a set of non-dominated optimal solutions, one best compromised solution is obtained using the fuzzy membership function. Aiming at maintaining the diversity of solutions at a reduced computational time and burden, the maximum size of non-dominated set archive is limited to 25 in hybrid and distribution system optimization. The simulation has been performed many times (each with 100 iterations) and out of that one compromised solution is obtained. The function values of this best solution and their corresponding variable values are given in Table 10.

The i-MOPSO algorithm along with Forward Backward Power Flow has been used to optimize the size and location of three DG's in the IEEE 69 bus system, with the aim of reducing the losses [31], voltage deviation, grid cost and grid emission. The size and location of DG's for different cases with the best compromised solution for their objective functions are given in Table 10 (Distribution system optimization). The size of each DG's thus obtained are considered as the daily average load for the PV-Wind-Battery based hybrid system. The i-MOPSO algorithm has been run again to optimize the cost and reliability of this PV-Wind-Battery system to arrive at the number and type of PV Panel, Wind turbine and Battery. This result has been included in Table 10 (Hybrid DG Design Optimization). But it has been observed that the result thus obtained will not be able to meet the DG size with 100% reliability. So depending on the percentage of the reliability in each of the cases, the DG size has been changed. Finally, the Re-optimization is performed with this varied DG size in accordance with the reliability .The optimized result such as loss, voltage deviation, grid cost and grid emission thus obtained for that sizing and location has been shown in Table 10 (Distribution system Re-optimization).

The results for all the three cases are compared with the base case and improvement in the IEEE 69-bus system has been observed. In Case 1, the optimal locations of hybrid DG's at the buses 63, 61, 59 significantly contribute to the decrease in power loss and voltage deviation of 53.06% and 20.90% respectively. In Case 2, the optimal location of hybrid DG's placement are identified as the buses 51, 62,65 with the decrease in power loss, voltage deviation and cost as 50.86%, 20.58% and 33.29% respectively. Similarly, in Case 3, the hybrid DG's optimal locations at buses 62, 53 and 61 contribute to the decrease in power loss, voltage deviation and grid emission of 50.46%, 20.275% and 32.16% respectively. The voltage profile of the system, has been improved considerably in all the three cases. The improved effects on the voltage profile thus obtained for each case is plotted and shown in Figs. 11–13.

Conclusions

A hybrid power generation system, including solar power, wind power, battery and diesel generator are designed on the basis of cost, reliability and emission criteria. A Pareto optimal front is obtained from the set of non-dominated solutions using MOPSO algorithm for an 8760 h Spain data; a single best-compromised optimal solution is obtained using the fuzzy membership function. It is evident from the results that wind cannot be used as the only source to supply a load. But when combined with PV, the reliability is observed to be much greater. This in turn is observed to be greater than PV battery system, with a slight increase in cost. The inclusion of diesel gave a fully reliable system, but with a significant increase in cost. While being considered as a DG, the cost of the hybrid system is expected to be reasonable with an acceptable amount of reliability. Also, the total emission (due to both grid and DG) is expected to be lesser. Thus, PV, Wind and Battery system is found to be the best choice with respect to reliability, cost and emission criteria. The optimal combination of these energy sources is considered as DG and three such DG's are integrated into IEEE-69 bus distribution system, thereby obtaining optimal location and size of the DGs with respect to power loss, voltage deviation, cost and emission. In this paper a new methodology to design the best combination of energy sources and also its integration into the distribution system arriving at the size, location of DG, choice, type and number of PV panels, wind, battery, cost, emission and the losses simultaneously have been evolved. As this hybrid integrated system requires, the i-MOPSO algorithm to be run three times to get the final result, the time and the complexity involved are considerably high which has to be compromised. In the future this work can be extended to obtain a better optimal DG integration by considering the number of DG's as an additional variable.

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