

OPTIMAL MANAGEMENT OF MICROGRID USING HEURISTIC SEARCH ALGORITHM

A Dissertation submitted in fulfillment of the requirements for the Degree

of

MASTER OF ENGINEERING
in
Power Systems

Submitted by

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Optimal Management of Microgrid Using Heuristic Search Algorithm** ", in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of **Ms. Manbir Kaur**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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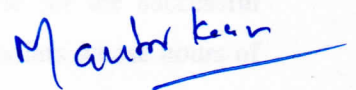


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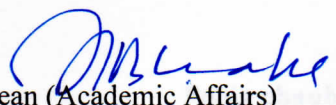
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NOMENCLATURE

$C_{DG,it}$	Diesel generator fuel cost (\$/h).
N	Number of generators
d_i, e_i, f_i	Cost coefficient of diesel generator
$C_{FC,t}$	Fuel cost of fuel cell (\$/h)
$P_{DG,it}$	Output power of the diesel generator (kW)
P_{ct}	Output power of fuel cell (kW)
η_{ct}	Fuel cell efficiency
$C_{MT,t}$	Fuel cost of microturbine (\$/h)
P_{mt}	Output power of microturbine (kW)
η_{mt}	Efficiency of microturbine
C_{nl}	Natural gas price
$P_{WT,t}$	Wind turbine output power (kW)
V_{ci}	Cut in wind speed (m/s)
V_{co}	Cut out wind speed (m/s)
$P_{WT,r}$	Wind turbine rated power in watts (kW)
V_r	Rated wind speed (m/s)
V_t	Actual wind speed (m/s)
a_i, b_i, c_i	Wind turbine coefficient
$P_{PV,t}$	Photovoltaic cell output power (kW)
G_{ISTC}	Irradiation at standard test condition (W/m^2)
$G_{ING,t}$	Incident irradiance (W/m^2)
P_{STC}	Maximum power of module at standard test condition (kW)
k_T	Temperature coefficient ($^{\circ}C$)
T_{cell}	Cell temperature ($^{\circ}C$)
T	Time in hours.
STC_i	Startup cost of i th generating unit (\$/h)
PE_{it}	Purchased electricity (\$/h)
E_{it}	Emission level (kg/h)

ABBREVIATIONS

MG	Microgrid
OM	Operational and management
DG	Diesel generator
MT	Microturbine
FC	Fuel cell
WT	Wind turbine
PV	Photo voltaic cell
MPPT	Maximum power point tracking
AH	Ampere hour
SOC	State of charge
MF	Membership function
EP	Electricity price.
BS	Battery state
LD	Load demand
SDG	Solar daily generation
Chg	Charging
Dsc	Discharging
BSA	Backtracking search algorithm

ABSTRACT

A microgrid is a small scale power system that operates either independently or in combination with the main grid. The intent of using the microgrid is to act as a backup power supply or to boost the main grid during the heavy load demand. Microgrid consists of renewable energy sources like wind turbine and photovoltaic cell to enhance the stability and reliability of the power system. The management of the microgrid takes into account the optimization of the operating cost of the generation unit within the operating limits and the emission rate of the gases. Battery output power which is used to find optimized results is forecasted using fuzzy logic technique. The optimized operation of the microgrid is performed by using Back tracking search algorithm. Back tracking search algorithm (BSA) is a heuristic search technique based on the single control parameter having crossover and mutation operator. In BSA, randomly generated population is stored in the memory for calculating the search direction matrix and the explore the search space bounded by the constraints. In order to show the effectiveness of the global search technique, it is applied on the five scenarios of the microgrid.

1.1 BACKGROUND

Electricity is an essential component in modern society and with increase in consumers and load, the demand of electricity is increasing day by day. At the same time traditional energy resources used for electricity generation, such as fossil fuels, are depleting. Further, environmental effects caused by the harmful emissions from fuel based conventional power stations have initiated the global debate. Further with conventional power plants, overall energy conversion efficiency is poor due to waste heat. The recent suggestions to operate generators with smaller capacity from fossil fuels and to use the heat generated for local heating purposes are implemented effectively.

Investing the alternate energy sources, which are more environmental friendly or innovative technologies to use existing energy more effectively are at a top priority of leading engineers in the world. A number of renewable energy resources like photovoltaic, wind, hydro and tidal exist as (relatively) environmental benign methods to generate electricity. The challenges surrounding renewable energy sources however are their cost competitiveness, dependency on favourable environmental settings and other technical barriers as well. Integration of renewable energy sources face many technical and environmental issues. These sources typically would be connected to a weak distribution network which in turn introduces power quality issues within the network.

The micro-grid concept is a solution which has been suggested to use alternative energy sources effectively while enabling increased amount of renewable to connect to the utility network. A typical micro-grid contains several generating units which are known as micro-sources (<100kw). Further a micro-grid could be connected to the main power network to export or to import power. Micro grids operate with two conceptual approaches:

Firstly net power flow to or from the main utility network is controlled, improving the apparent behaviour of local micro-sources.

Secondly the micro-grid may island from the main network, and continue to supply power to loads during network disturbances.

1.2 NEED OF MICRO-GRID

In August 2003, 10 million people in Canada and 45 million people in US suffered from blackout for three days. Research shows that in spite of the enhanced regulation deliberate to prevent such events, it can't be eliminated totally. Reducing the impact of large number of

blackouts, micro-grid has been developed by researchers as a way to improve power grid reliability and decrease the dependence on the long distance transmission grid.

1.3 DEFINITION OF MICROGRID

The definition and typical composition of a micro-grid are both not standardized and still evolving. According to R.H. Lasseter “**the micro-Grid is assumed as a group of, load connected to it and generating microsources which are operating as a single controllable system that provide both power and heats to its local area [1].**”

Alternatively “A micro-Grid can be defined as an low level voltage network (e.g., small cities, an industrial park etc.) connected to its loads which are several small modular generation systems connected to it, providing both power and heat to local loads [2].”

Thus micro-Grid is small scale version of the centralized electricity system or localized station with its own power resources, generation and loads. It can be intended as backup power or to bolster the main power grid during periods of heavy demand. It is designed to fulfill the customer’s requirements such as it enhances the local reliability, support local voltages, reduces the feeder losses, diminish CO₂ emission and also provide increases efficiency by using the waste heat and improves voltage sag. The projects for energy surety micro-grid of military bases are one example of this enhanced micro-grid reliability [3].

1.4 MODES OF OPERATION

Micro-grid operates in two different modes.

- **Grid connected mode of operation**

In grid connected mode, it is operated in parallel with the main grid. Thus, the micro-grid can export or import the energy from or to the main grid to control the power flows and also manage the energy for the storage devices. In this mode, system dynamics can be improved to large extent by the grid because of the small size of the diesel generator units [4]. During the transient in the micro-grid, the power balancing should be provided by a power storage device like batteries, super-capacitor or flywheels. After the blackout, the micro-grid should be coordinated properly with the main utility grid, that is frequency and voltage amplitude should matched properly. Thus, depending upon the customer’s requirement, the micro-grid together with the main grid supply the power to the connected loads.

- **Isolated mode of operation**

This is one of the key features of the micro-grid. The following are the two main scenarios of operating the micro-grid in islanded mode.

- **Preplanned islanded operation**

If the event like long time voltage dips or general faults are present in the main utility grid then the islanding operation must be started.

- **Non-planned isolating operation**

Whenever there is blackout due to a detachment of the main grid or any sudden permanent fault occurs on main grid, the micro-grid should be able to observe this fault by using any proper algorithm and disconnect itself from the main grid.

1.5 MOTIVATION

Presently lot of research has been done in the area of microgrid. Various microgrid architectures have been presented and are reported in the paper such as [1], [5, 6], [8-10]. When the different sources are connected to built a microgrid, the system performance become unpredictable and this unpredictable behavior of MG can be corrected by the proper management of MG.

Thus the development of the appropriate MG management is the heart of the MG research and researchers are further investigating the benefits and feasibility that the MG may provide. This work is concerned with management of the MG which helps in taking correct decision and reduces emission level and operating cost properly.

1.6 OBJECTIVE OF THE DISSERTATION

The objective of this dissertation is to develop the management methodology which make the MG energy generation a low operating cost affair, environmental friendly and very efficient. The problem is considered as a single objective and a multiobjective problem of cost and emission with two cases of with battery storage device and without battery storage device in microgrid. In this study, the efficient and cost effective management approach for microgrid is investigated subjected to the satisfaction of constraints up to a confidence level and the operating cost includes the fuel cost of DG, MT and FC, operating and management cost (OM), start up cost, sale and purchased cost etc. whereas total emission include the emission from the microsources like DG, MT and FC. The proposed management system considers the following objectives:

- Optimal use of local generators.
- Fulfilment of load demand.
- Minimizing the operational cost.
- Reducing the level of emission.

1.7 OPTIMIZATION TECHNIQUE

Optimization is a process of obtaining the best results under the given conditions. In engineering field, engineers may have to take certain decisions at a number of stages and the ultimate goal of all these decisions is either to reduce the efforts or to maximize the benefits. This minimizing the efforts and maximizing the benefits can be expressed as a function of some decision variable. Thus the aim of the optimization is to find the conditions which give the minimum and maximum value of the function. There are several classical optimization technique like Euler, Bernoulli, Lagrange, Cauchy etc are introduced in [12]. Stochastic optimization techniques like Genetic Algorithm, Tabu search, simulating annealing etc are discussed in [16].

Back tracking search algorithm (BSA) [14] is also a optimization technique used in this dissertation. it is a dual population technique as it uses both the current and the historical population while optimizing the objectives. The proposed technique finds the optimal solution while taking different objectives into account which include the best emission level, best operational cost and best compromise between them as well as Pareto optimal set is used to find the trade-off between the objectives.

1.8 OUTLINE OF DISSERTATION

The work in dissertation is organized as follows:

Chapter-1 includes an introduction and background about the microgrid.

In **Chapter-2** (literature review), focus is provided on work has been done in the field of the microgrid.

Chapter-3 describes the component of the microgrid and related mathematical equations. The MG under consideration includes PV's, WT's, DG's, MT's, FC's and battery storage. A problem formulation is shown both as single objective problem and multiobjective problem.

Chapter-4 is implementation of the solution methodology on the problems which includes the forecasting of battery storage system and Back Tracking Search Algorithm.

Chapter-5 includes the results and discussion.

CHAPTER-2

LITERATURE REVIEW

The literature review gives a detailed survey on the definitions of microgrid explained by different authors and certain management techniques implemented by them.

Lasster [1] has defined the microgrid as a group of loads and microsources which are operating as a single controllable system that provides power to its local load. This concept gives the new definition to the operation of diesel generator (DG). It allows high penetration of number of DG units without requiring any re-design of the distribution system.

Arulampalam *et al.* [7] has described the microgrid as an arrangement of generating units, loads and storage devices which are interfaced with power electronics devices. This arrangement of units is connected to the distribution network and appear as single power network unit..

Hatziargy *et al.* [11] has defined it as “Interconnection of small generating units to low voltage distribution systems which create a new type of power system”.

Pepermas *et al.* [13] has presented that several countries defined the diesel generator on the basis of different voltage level while others considered a principle that diesel generator is connected to those circuits which directly feed the consumers demand where as some countries defined diesel generator on the basis of some other characteristics like using renewable etc.

Ackermann *et al.* [15] has stated that, “distributed generating unit is an electrical power source that is directly connected to the distribution network. The difference between the transmission and distribution networks is based on the authorized definitions.

However, the most accepted definition is given by Dr. Robert H. Lasseter [17] is – The CERTS microgrid is assumed as an aggregation of microsources and loads which are operated as a single system to provide power and heat. To provide a necessary flexibility, most of the micro generating units must be power electronics based to insure the operation of the microgrid as a single controllable system.

Microgrid may be operated in any of the two ways i.e. either in utility grid connected manner or in isolated manner. When microgrid is operated with the main grid, it has a capability to isolate itself from the main grid during the events.

L. Mariam *et al.* [18] has identified the benefits of grid connected or isolated microgrid with storage devices.

Lasseter et al. [19] has claimed that the micro-grid provide a good reliability when its generating unit and load are intentionally isolated from the main grid than that provided by the microgrid when connected to the main grid.

Some microgrid architecture was proposed in the literature such as [1, 5, 6, 8, 9, 10]. The function of the energy management system in microgrid is to make decision regarding the optimal use of the generating unit for providing the electricity and heat. All these decisions are based on the weather, the price of electricity, heat requirement of the local equipment, fuel cost and many other considerations.

J. Nanda et al. [47] considered the economic-emission load dispatch problem with two conflicting objective of cost and emission minimization. In this paper, author proposed a linear and non linear goal programming algorithms to solve this multiobjective problem.

J. Nanda et al. [48] presented a classical technique to solve the economic emission and load dispatch problems with some line flow constraints based on co-ordination equations.

J. Andersson [49] presented a investigation on multiobjective optimization technique in engineering problems. He discussed the general optimization methods and different ways of performing multiobjective optimization like weighted sum approach, non-linear approach, fuzzy logic techniques etc.

T.C Green et al. [50] have presented a paper to reduce the fuel consumption rate of the considered system while keeping all the constraints (load demand and minimum reserve power) in limits. The problem in this paper is considered as a single objective function which doesn't include any emission level and management cost.

M. Elmusrati et al. [51] presented a multiobjective problem in communication. Here author considered the two conflicting objective of power consumption and quality of service.

A. F Mohammad et al. [52] proposed a single objective problem of cost minimization of microgrid with battery storage. Cost includes the operating cost and emission cost. The aim of the optimization technique was to minimize the cost function while satisfying the constraints.

W. Zhang et al. [53] has presented a new formulated technique based fuzzy set theory and particle swarm optimization to solve multiobjective problem on reactive power and voltage control issues.

A. Barin et al. [54] has proposed a multiobjective approach which is based on the BallmenZadeh algorithm and fuzzy logic technique is used to allocate the DG unit on appropriate sites.

A. F Mohammad *et al.* [55] proposed a mesh adaptive direct search algorithm to optimize the cost objective function of the microgrid. The proposed cost function includes the emission cost, start up cost as well as operational cost.

A. F Mohammad *et al.* [56] the mesh adaptive direct search algorithm is proposed for multiobjective problem. The two conflicting objective are minimization of cost and emissions whose results are compared with the multiobjective sequential quadratic programming.

3.1 INTRODUCTION

The micro-grid is assumed as a group of many small generating units and local loads which whole work as a single network. The architecture of considered micro-grid is shown in Figure 3.1. Sensitive loads are connected to feeder 1 and 2 which should be supplied during the events. The third feeder is connected to the conventional loads only. The microsources consisting of a wind turbine (WT), a photovoltaic cell (PV), a micro turbine (MT), a fuel cell (FC), a diesel generator set (DG) and a energy storage device (battery). The microgrid can be operated with grid or in islanding mode, thus the static switch (SD) is used to disconnect the feeder 1 and 2 from the main grid when any events happen. Photovoltaic and wind turbine is natural source of energy where as fuel is required for the diesel generator set, microturbine and fuel cell. The diesel oil is used as a fuel input to diesel generator unit where as the hydrogen gas is used as a fuel to FC and MT. Each component of microgrid can be modeled separately based on the characteristics of respective components.

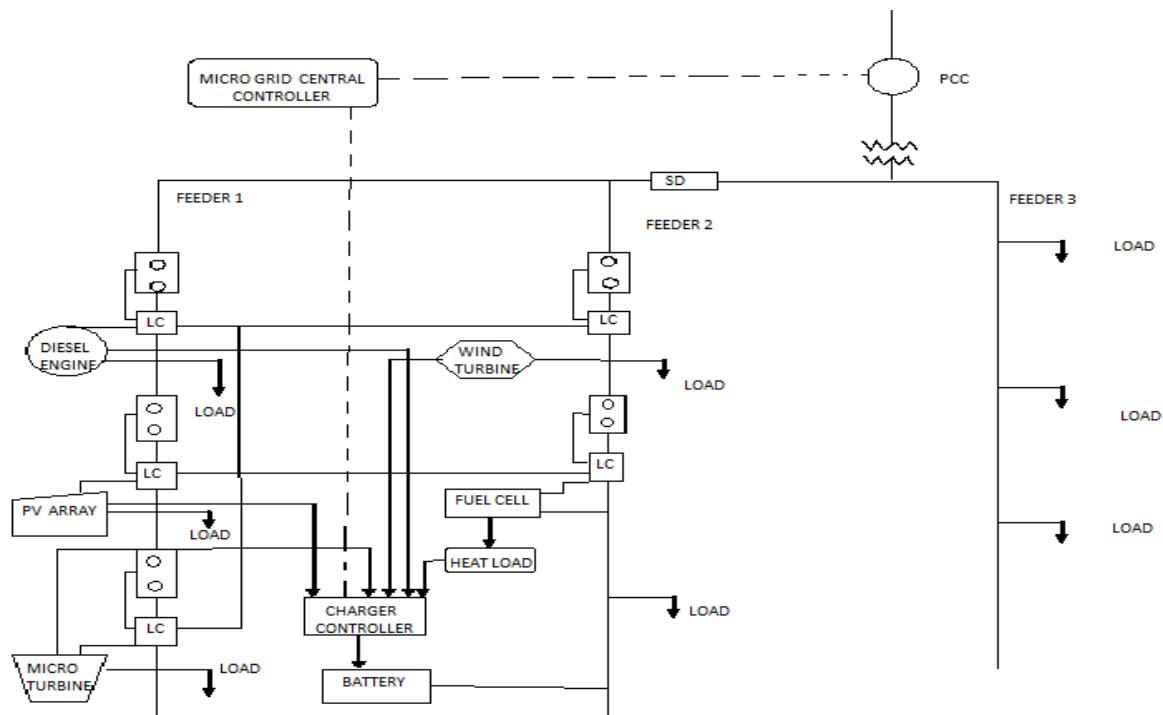


Fig. 3.1 Architecture of microgrid [57]

3.2 DIESEL GENERTOR

Diesel generators were the first among distributed generation technologies. Their high efficiency and reliability make them suitable for many applications, ranging from smaller units of 1kW to larger units of several tons of MW power plants. The engines with smaller ratings are mainly designed for transport applications where as engines with larger rating are designed for power generation, mechanical drives and marine propulsion. Diesel prime mover must have a high speed dynamic response and should have a good capability to reject the disturbance to handle the sudden change in load demands by the consumer. The fuel consumption rate of the DG set as function of speed and mechanical power can be modeled as a first order model which relates the consumption rate of fuel to the mechanical output of the engine [20]. The output of the generator should be varied with the change in the load in order to fulfill the customers demand. This can be done with the help of the governor which control the fuel flow and thereby, regulate the input of the generator and hence the output power.

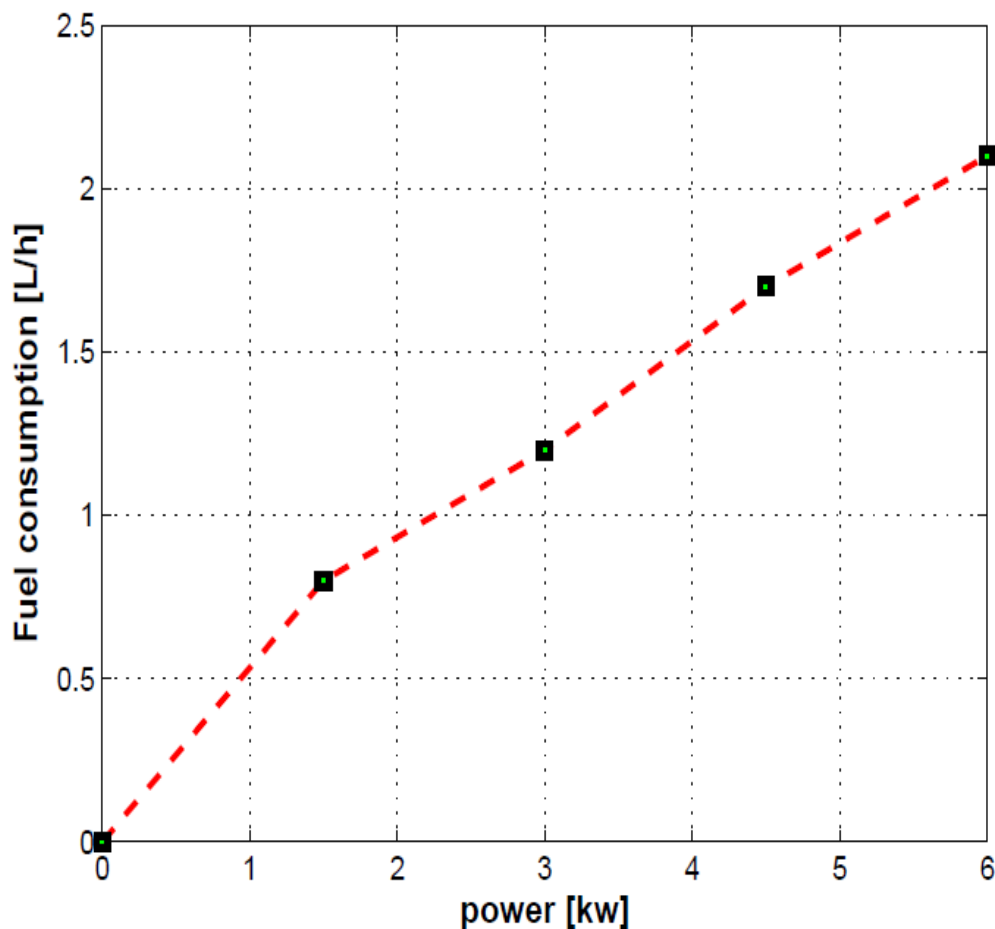


Fig. 3.2 Fuel consumption of diesel engine [21]

3.2.1 Cost Model of DG

Diesel engines are the very common component of the MG. The fuel cost of DG power unit can be articulated as a function of its output power and can be represented as a quadratic polynomials [22]. The total cost for diesel generator in \$/h can be written as

$$C_{DG,it} = \sum_{i=1}^N (d_i + e_i P_{DG,it} + f_i P_{DG,it}^2) \quad \dots\dots 3.1$$

Where

N = No. of diesel generators.

$t = 1, 2, \dots, T$, time (hours)

d_i, e_i, f_i = Cost coefficient of i th generating unit.

$P_{DG,it}$ = output real power of the DG i in (kW) where $i = 1, 2, 3, \dots, N$.

Fuel consumption data of a 6 kW DG set in L/h at 1/4, 1/2, 3/4 and full loads is given in [23]. All the data for above equation are given in appendix-I. In figure 3.2, fuel consumption is shown as a function of output power.

3.3 FUEL CELL (FC)

Fuel cell is a device which generates power by the electro-chemical reaction between positively charged hydrogen ion and oxygen. This electrochemical conversion is very efficient and leaves only heat and water as its by-products, which is the main reason for the increase interest in this technology [24]. The first fuel cells were discovered and developed by Sir William Grove in 1842 [25] with a use of four primitive cells. In 1960, NASA demonstrated a application of the FC, after this demonstration companies interest is increases in this technical era because of its high efficiency, power quality and environmental friendly. United technologies corporation power was the first company who manufactured and commercialized a large number of fuel cell system to use them in universities, hospitals and office buildings.

The basic structure of FC compromises the anode, the cathode and the electrolyte and the design feature of the basic fuel cell are

- Electrolyte substance.
- Fuel, generally hydrogen is used as a fuel.
- Anode catalyst is platinum powder, whose purpose is to break down the fuel into ions and electron.
- The function of cathode analyst is to turns the ion into waste chemical carbon dioxide etc.

The hydrogen fuel is first supplied to the anode where it gets oxidized and yields electron, which moves through the outer circuit. The oxidant gets reduced at the cathode and consume electron from the external circuit. Ions balance the flow of electron through external circuit by moving through electrolyte. Figure 3.3 shows the cathode reaction, operation principle and the ion associated to the fuel cell types.

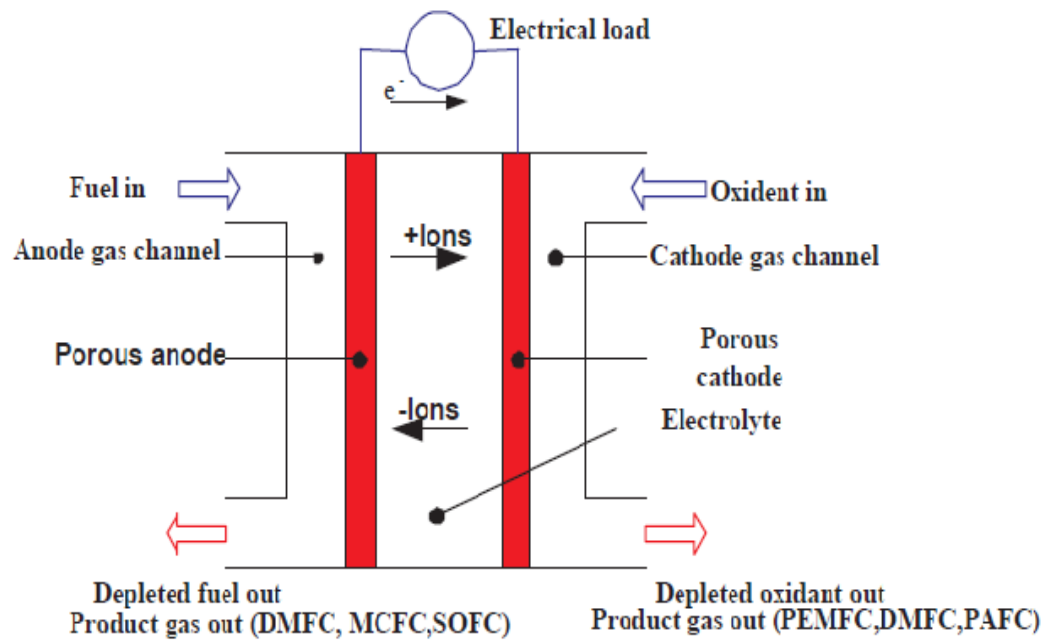


Fig. 3.3 Operation principle and cathode reaction of common fuel types [21].

The electric efficiency of hydrogen fuel cell is same or higher for low temperature fuel cell. The chemical reaction of PEMFC, PAFC, AFC, MCFC and SOFC are given below

Table 3.1 Chemical reaction present in different type of fuel cells.

Fuel cell type	Anode reaction	Mobile ion	Cathode reactions
PEMFC, PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	H^+	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
AFC	$H_2 \rightarrow 2H^+ + 2e^-$	OH^-	$1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$
MCFC	$H_2O + CO_3^{2-} \rightarrow H_2O + CO_2 + e^-$	CO_3^{2-}	$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$

SOFC	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	O^{2-}	$1/2O_2 + 2e^- \rightarrow O^{2-}$

Where the symbols have their usual meaning.

Electrolyte is the main difference in different fuel cells which effect the structure and operating principle of the fuel cell. Table 3.2 shows the major technologies, listed in [25, 26].

Table 3.2 Major fuel cell technologies

Fuel Technology \ Parameter	PEMFC	PAFC	MCFC	SOFC
Electrolyte	Proton exchange membrane	Phosphoric Acid	Molten carbonate	Solid oxide
Operational temperature (°C)	80	200	650	800-1000
Electric efficiency based on natural gas (%)	30-35	35-40	45-55	45-55

All fuel cells gives the D.C value of current and voltage whose value depend upon the number of cell in series and cell voltage. The fuel cell should be equipped with the DC to AC conversion device to obtain the AC quantities.

3.3.1 Cost Model of FC

Fuel cells are generally operate at electrical efficiency around 40 to 60 percentage which is generally calculated as the ratio of the operating voltage of a single cell to the reversible voltage (1.482V) [27]. Typical efficiency curve of the PEM fuel cell is shown in figure 3.4 below [27, 28]. The cost function for the fuel cell can be presented as:

$$C_{FC,t} = C_{nl} \sum_t \frac{P_{ct}}{\eta_{ct}} \quad \dots 3.2$$

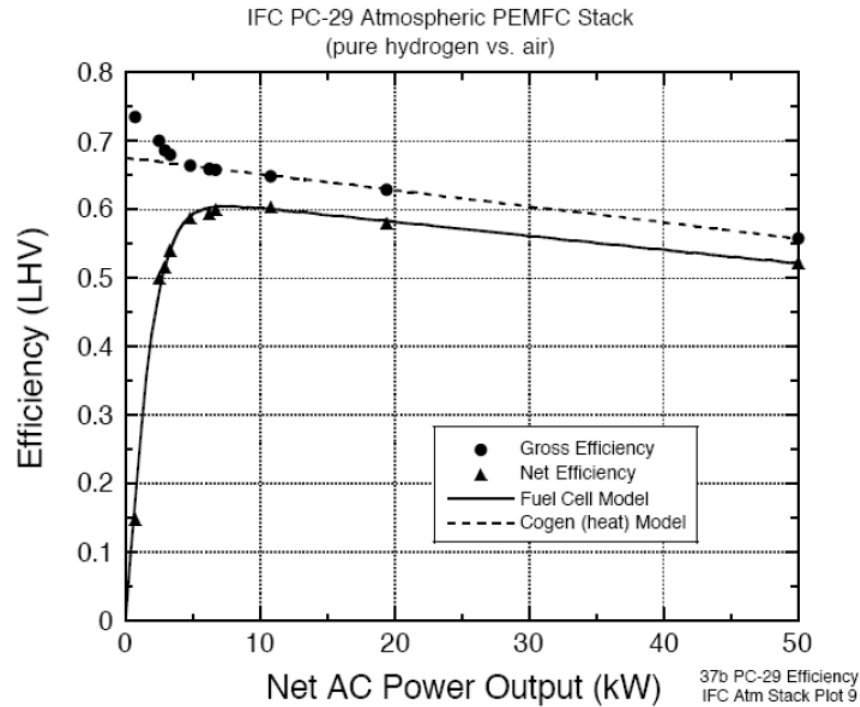


Fig 3.4 Efficiency curve.

Where

C_{nl} = Natural gas price.

P_{ct} = Net electrical output in interval t .

η_{ct} = Cell efficiency at interval t .

t = Time interval in hours

Fuel cell efficiency is assumed between 30% to 50%.

3.4 MICROTURBINE (MT)

These are the high speed gas turbines which are ranging from 25 kW to 500kW [29]. The operational principle of microturbine is same as the general gas turbines depending on brayton cycle [29]. Small gas turbine engines were developed initially by Alison in 1960s for ground transportation purposes [30]. Input mechanical energy of the microturbine is forwarded to its generator system which is then converted into a electrical energy. Nominal frequency of the generator varies in the range of 1.4-4 kHz.

3.4.1 Components of microturbine

The main components of microturbine is given in figure 3.5 which includes a turbine, exhaust gas outlet, heat exchanger, compressor, electrical system, supervision and control system etc.

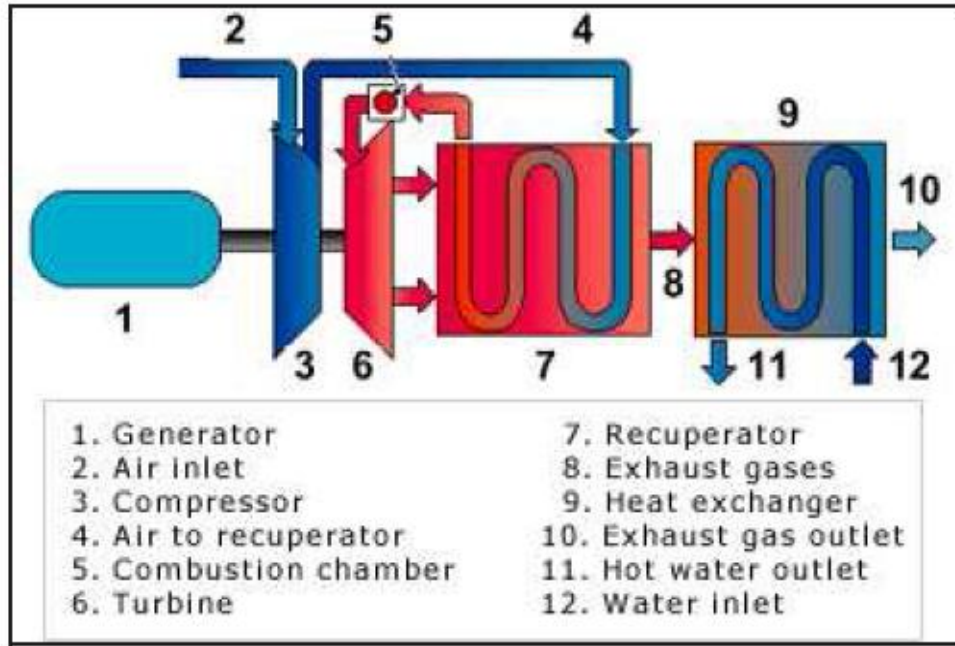


Fig. 3.5 Main component of microturbine unit

The air is first enters into to the compressor. This compressor is then increases the pressure of this air, depending upon its size. This high pressure air is then mixed with the fuel and burnt into the combustion chambers at constant level of pressure. The excessive hot flue gases enter into the turbine and provide the mechanical energy which rotates the turbine. During this procedure, the flue gases are expands to lower pressure and larger volume and also exhaust gases are release to the atmosphere [31].

3.4.2 Cost model of microturbine

Microturbine with its simpler design and few moving parts increase the reliability of the system. The efficiency of the microturbine increases with increase of the input power, unlike the fuel cell. Fuel cost of microturbine is given as follows:

$$C_{MT,t} = C_{nl} \sum_t \frac{P_{mt}}{\eta_{mt}} \quad \dots 3.3$$

where,

C_{nl} = Natural gas cost.

P_{mt} = Electrical output in interval t.

η_{mt} = cell efficiency at interval t.

t = Time interval in hours.

3.5 WIND TURBINE (WT)

A wind turbine is a most popular energy conversion device which converts that kinetic energy of the wind into electrical energy. These turbines are constructed in mainly two shapes i.e vertical and horizontal axis type. The smallest WT is generally used for battery charging purposes.

WT system consists of a rotor, a generator, a turbine blades and a coupling system. When a wind passes through the turbine blades, the wind exerts a force which rotates the rotor. The rotation of the rotor changes its speed until it is equal to the operating speed of the generator. This is generally done by the gear box or a generator. The wind generator output is then fed to the inverter to change it into A.C which can be used further.

3.5.1 Generating system of WT

The basic working principle of the WT carried out by its main components can be described in two steps: first is, the rotor uses kinetic energy from the wind passing through it and convert it into mechanical rotating force (torque). Second, this mechanical torque is converted into electrical energy by the generating systems. Figure 3.6 shows the basic principle of the WT.

Generally, any type of generator can be used with WT. Some of the generators are listed in [32] which can be used in wind turbines.

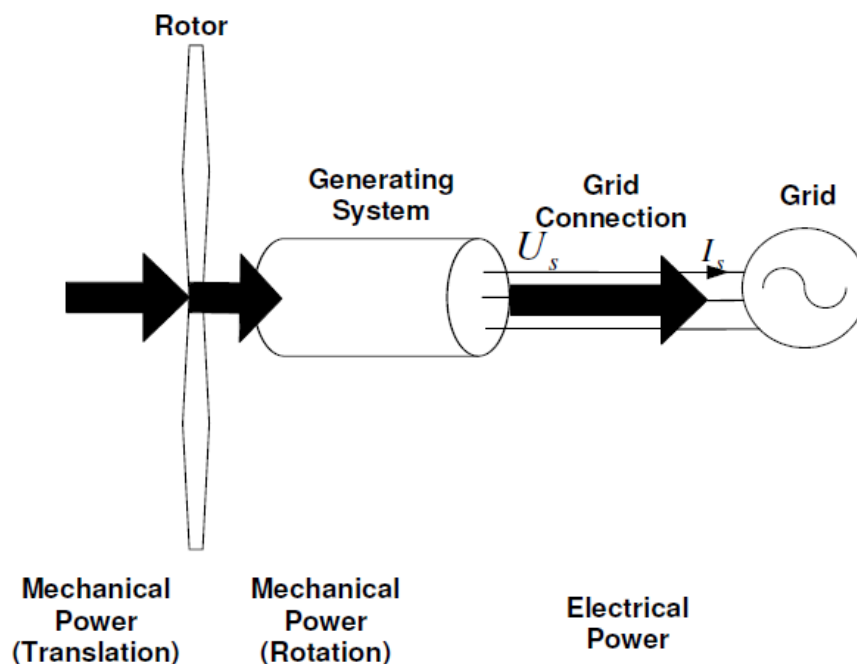


Fig. 3.6 Basic principle of the wind turbines.

3.5.2 Output power WT model

While designing the wind turbines model, two important factors must be kept in mind i.e availability of wind speed and power curves of the wind turbines because the wind speed directly affect the output power of the generator. Thus the output equation can be written as [33, 34]:

$$\begin{cases} P_{WT,t} = 0 & V_t < V_{ci} \\ P_{WT,t} = aV^2 + bV + c & V_{ci} < V_t < V_r \\ P_{WT,t} = P_{WT,r} & V_t > V_{co} \end{cases} \dots 3.4$$

Where

V_{ci} , V_{co} = Cut in and cut out speed in (m/s).

$P_{WT,r}$ = rated power in watts.

V_r , V_t = Rated and actual wind speed in (m/s) respectively.

In above equation shows that turbine can't generate power after its cut off speed V_{co} . According to the data sheet from manufacturer, the output power of wind turbine is approximately 130 W if the wind speed is above the 18 m/s [35, 36]. The figure 3.7 shows the output power of WT as a function wind speed for AIR403.

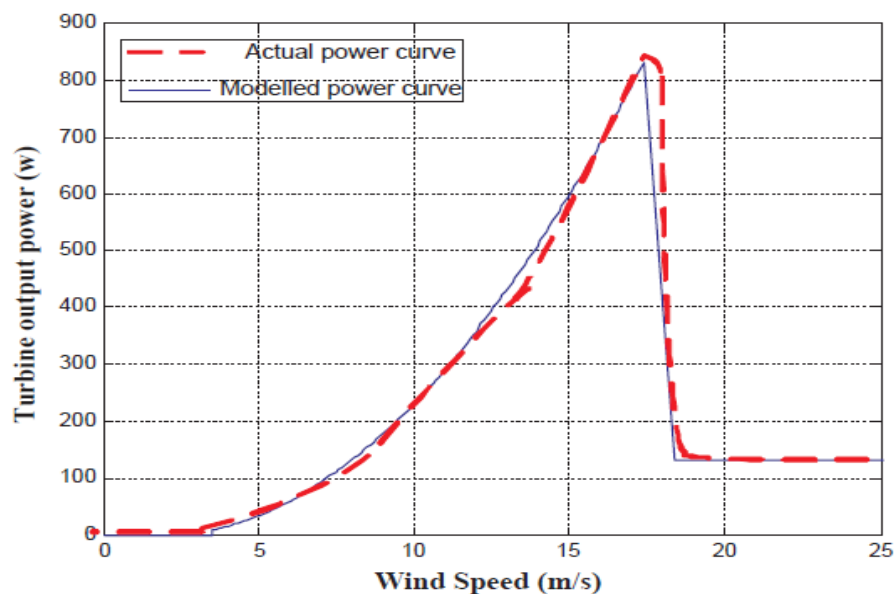


Fig 3.7 Power curve for AIR403 [21]

The parameters for this power curve are given in appendix-I.

3.6 PHOTOVOLTAIC CELL (PV)

After hydro and wind energy, photovoltaic is the third most important renewable energy source. Photovoltaic are an attractive source of power generation because of their small size and a noiseless operation. The main advantage of PV technologies is that any number of PV units can be added to meet the increase load demand [37] ,[38]. Major advantages of the PV power are [39].

- PV panels have no mechanically moving parts and hence, no noise.
- Power output can easily fulfill the peak load demands.
- Long life and low maintenance because no moving parts are present.
- Residential solar panels are easy to install on rooftops.
- Because of their light weight, they are highly mobile and portable.

PV cells are divided into four main categories: thin film cell, crystalline cell, dye-sensitized solar cell and multilayer cell. Several types of photovoltaic cells are listed in [40]. Figure 3.8 shows the diagram of inverter which is composed of following components.

- MPPT circuits.
- Storage devices.
- D.C converter to raise the voltage level.
- Inverter.
- Isolation transformer.
- Filters.

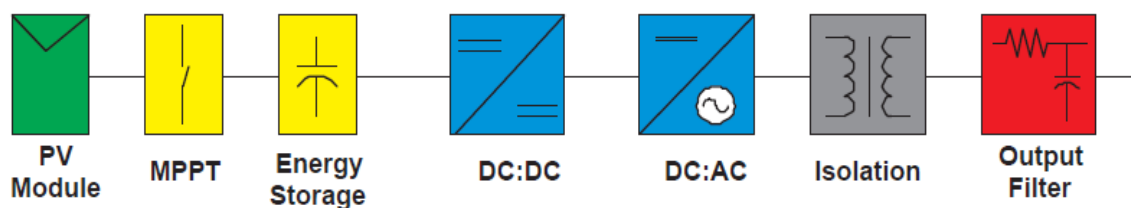


Fig. 3.8 Diagram of inverters for grid connected PV system.

3.6.1 Photovoltaic model

Photovoltaic systems are the generating system which converts the sunlight directly into the electrical energy. Thus the solar intensity directly effects the output power of the module [41, 42]. The PV module is treated at standard test condition (1000W/m², 25° C cell temperature). The output power can be expressed as:

$$P_{PV,t} = P_{STC} \frac{G_{ING,t}}{G_{ISTC}} (1 + k_T (T_{cell} - T_{ref})) \quad \dots 3.5$$

Where

P_{STC} = Maximum power of the module at standard test conditions in Watt (STC).

$P_{PV,t}$ = Module output power at irradiance in Watt (G_{ING}).

$G_{ING,t}$ = Incident Irradiance (W/m^2) in interval t.

G_{ISTC} = Irradiation at STC 1000 (W/m^2).

k_T = Coefficient of temperature.

T_{cell} = Cell temperature ($^{\circ}C$),

T_{ref} = Reference temperature ($^{\circ}C$).

SOLAREX MSX-83 is used in this work whose characteristics are given in appendix-I.

3.7 BATTERY STORAGE DEVICE

Battery storage device is electrochemical device which stores energy from other sources, so that stored energy can be use later. The battery is required to discharge the power when the renewable energy resources or the micro generating units are insufficient to supply the load. At the same time the energy is stored in the battery whenever the supply from the renewable energy sources or microsources increases above the load demand. Battery capacity is generally represented in ampere hours (AH).

It is not possible for the storage devices to have a negative energy. To avoid this negative energy the maximum charging (SOC_{max}) and minimum discharging (SOC_{min}) is limited upto certain limits. Maximum charging limit and minimum charging limit of the battery is considered 90% and 20% of its AH capacity respectively.

3.8 PROBLEM FORMULATION

In developing the electrical power system which utilizes the microgrid sources, the major area of concern is to select the accurate power which fullfil the load demand while minimizing the operational cost and emission. Thus the microgrid comprising verity of component, the scheduling figured for each component to fulfil the load demand is modeled as an optimization problem.

- (i) To minimize the operational cost (\$/day).
- (ii) To minimize the emission (kg/day).
- (iii) To satisfy the operational constraints.

3.8.1 Operating Cost

The cost function of the microgrid serving the load demand is formulated as follows [43].

$$C(P) = \sum_{i=1}^N (C_{it} \times (P_{it})) + OM_{it}(P_{it}) + STC_i + PE_{it} - SE_{it} \quad \dots 3.6$$

Where

$t = 1, 2, \dots, T$, time in hours

C_{it} = Fuel cost of the ith power generating unit in \$/l for DG and in \$/kWh for FC and MT.

OM_{it} = Operational and Management cost of ith power generation unit in \$/h.

STC_i = Start up cost of ith power generation unit in \$/h.

P_{it} = Real output power from the ith generating unit in kWh (decision variable).

PE_{it} = Purchased electricity in \$/h.

SE_{it} = Sold electricity in \$/h.

Subjected to:

(i) Equality constraints:

Active power balance equation when no battery storage device is considered in the microgrid, is expressed as:

$$\sum_{i=1}^N P_{it} - P_{Lt} + (P_{PV,t} + P_{WT,t}) = 0 \quad \dots 3.7$$

Whereas active power balance equation can be expressed as follows when battery storage device is considered in MG

$$\sum_{i=1}^N P_{it} - P_{Lt} + (P_{PV,t} + P_{WT,t} + P_{batt}) = 0 \quad \dots 3.8$$

Where

P_{Lt} = Load demand kW in interval t.

$P_{PV,t}$ = Photovoltaic cell, output power (kW) in interval t.

$P_{WT,t}$ = Power output of WT in kW in interval t.

(ii) Inequality constraints:

The output power of each generating unit is bounded by minimum and maximum limits for stable operation.

$$P_{it}^{min} \leq P_{it} \leq P_{it}^{max} \quad , i = 1, 2 \dots \dots, N \quad \dots 3.9$$

Where

P_{it}^{min} = Minimum limit of power in kW.

P_{it}^{max} = Maximum limit of power in kW.

The operating and management cost is considered to be proportional to generated power where the proportionality constant is (K_{OM}) [43].

$$OM_{it} = K_{OM} \sum_{i=1}^N P_{it} \quad \dots 3.10$$

The main grid maintains the difference between the generated power from the microsources and the customers demand. Whenever the generated power from the micro generating units is not sufficient to meet the load demand, then the power has to be purchased from the main utility grid and cost of this purchased power should be added in the operating cost. Similarly whenever power generated from the microsources is more than the load demand, then there is a income from selling power. Thus, two different conditions are considered during the purchased and sold electricity. These two conditions are give follows:

$$PE_{it} = C_p \times \max (P_{Lt} - \sum P_{it}, 0) \quad \dots 3.11$$

$$SE_{it} = C_s \times \max (\sum P_{it} - P_{Lt}, 0) \quad \dots 3.12$$

Where

C_p = Tariff for the purchased power.

C_s = Tariff for the sold power.

3.9 EMISSION LEVEL

The total emission in Kg/h is modelled which include the environmental pollutants such as sulphur oxide SO₂, Nitrogen oxide NO₂ and Carbon oxide CO₂. Emission function can be written as a quadratic function of generator's output power [44]:

$$E_{it}(P_{it}) = \sum_{i=1}^N \alpha_i + \beta_i P_{it} + \gamma_i P_{it}^2 \quad \dots 3.13$$

Where α_i , β_i and γ_i are the emission coefficient of the power generating unit i. E_{it} is the emission level in (kg/h) and P_{it} is the real output power of generator unit i in (kW). Appendix-I shows the emission coefficient of a diesel generator set, a fuel cell and a microturbine [45]. Emission per day is estimated using data available in [45].

Five different scenarios of the microgrid operation are as follows:

Scenario 1: Single objective of cost minimization is considered without battery storage device in the microgrid, with equality and inequality constraints.

Scenario 2: Again the single objective of cost minimization is considered with battery storage device in the MG with more constraints is added.

Scenario 3: Single objective of emission minimization is considered while satisfying all the constraints.

Scenario 4: Multiobjective of cost and emission minimization is considered with no battery storage device in the MG while including all the constraints.

Scenario 5: Multiobjective problem is considered with battery storage device in microgrid, with all constraints.

CHAPTER- 4

SOLUTION METHODOLOGY

Solution methodology of this work is broadly divided into two main steps that are (i) Battery forecasting and then (ii) Finding optimal solution for the multiobjective problem using Back Tracking Search Algorithm.

4.1 BATTERY STORAGE FORCASTING USING FUZZY LOGIC

Battery storage device is a electrochemical device which store the energy so that it can be use later. Energy stored in the battery is DC. So, it has to be converted into Ac before supplying to any equipment. Storage devices are one of the biggest players in making economic benefits of microgrid. The efficiency of the microgrid is also depending upon the battery scheduling process. Proper battery scheduling can have a big impact on reducing the capital cost of microgrid. Thus the battery scheduling is the decision making phenomenon in energy management system. In fact, one method to solve the battery scheduling problems is to propose a system which is able to decide on the basis of forecasted and actual entities, whether the charging or discharging of the battery should be done at which suitable rates. In this regards, fuzzy technique is a decent mathematical method which is used to model the vagueness and imprecision of a human intellectual process. Such battery scheduling process depends upon the human's power to take decision under any uncertainty. Fuzzy logic technique is able to take decisions, depending on the forecasted information, about charging and discharging of the battery. This complete process assures the safe operation of the battery storage device, the minimization of the operational cost and the gaseous emission. Fuzzy logic expert system involves three basic process i.e. fuzzification, inference engine and defuzzification. Before explaining these three processes we must have knowledge of membership function.

4.1.1 Fuzzification

Fuzzification is the method of converting a crisp value into fuzzy. Fuzzification depends upon the uncertainty present in quantities which we consider to be crisp value. If the uncertainty occurred is due to ambiguity, imprecision or vagueness, than the quantity has the probability to be fuzzy and can be represented by its membership function. The scalar quantities is first fuzzified, i.e. it is converted into its membership function and then used as a input for a fuzzy system.

4.1.1.1 Membership function (MF)

All the information stored in a fuzzy set is represented by the MFs. The important difference between crisp and fuzzy sets is MFs; a crisp set has a single MF, where as fuzzy set can be represented by a number of MF. In fuzzy sets, the uniqueness is lost, but flexibility is added because the MFs can be adjusted accordingly to increase the utilization of a particular system. Typical trapezoidal membership function is shown in figure 4.1

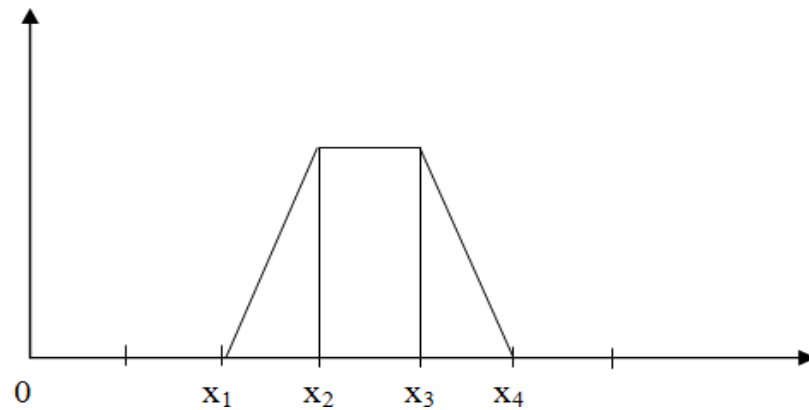


Fig. 4.1 Typical membership function

4.1.1.2 Feature of the membership function

- The core of the MFs is the region of the universe represented by complete membership, $\mu_A(x) = 1$.
- The support of the membership function is the region of the universe which is described by MF with non zero value, $\mu_A(x) > 0$.
- The boundaries of a membership function is the region of the universe containing elements having membership between zero and one i.e. $0 < \mu_A(x) < 1$.

4.1.1.3 Input membership functions

The input parameters used to build up the input MFs are given in table below.

Table 4.1 Input parameters for input membership function.

	TIME			BS				EP		
	Mr	Md	N	VL	L	M	H	L	M	H
X1	0	10	16	0	70	130	200	-	0.2	0.4
X2	6	12	20	0	110	180	290	-	0.35	0.65
X3	6	16	20	40	110	180	355	0.2	0.35	-
X4	12	18	24	80	150	230	355	0.25	0.5	-

	LD			RG			SDG		
	L	M	H	L	M	H	L	M	H
X1	0	5	9.5	0	106.7	266.7	-	2	5
X2	0	8	12.5	0	200	346.7	-	4	6.5
X3	4	8	14	80	200	400	1.3	4	-
X4	6	10.5	14	160	293.3	400	3	6	-

The fuzzy system employed for battery scheduling is developed by using the forecasted parameters which are as follows, time (T), Electricity Price (EP), battery state (BS), Load Demand (LD), renewable energy available (RG), daily generation from solar (SDG) and tomorrow's solar availability (TSA).

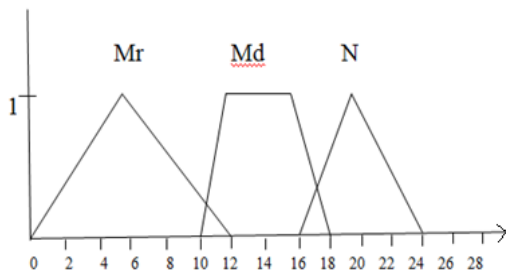


Fig. 4.2 (a) Time

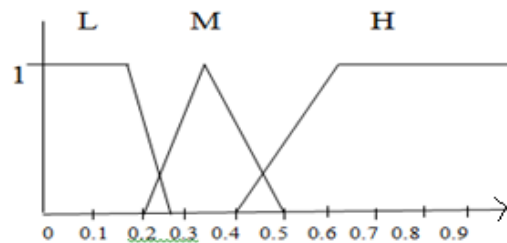


Fig. 4.2 (b) Electricity price

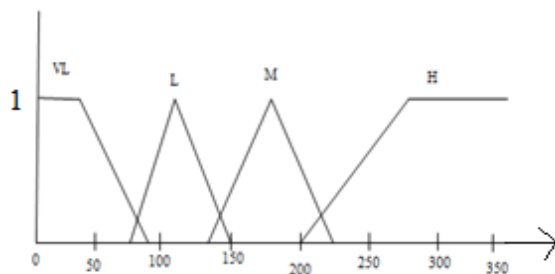


Fig. 4.2 (c) Battery state of charge

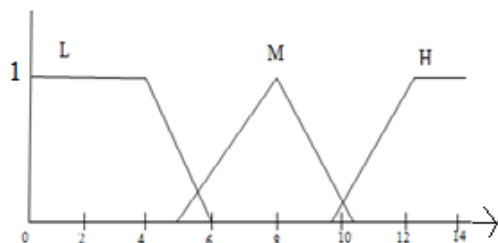


Fig. 4.2 (d) Load demand

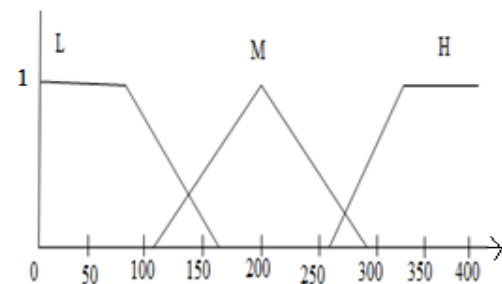


Fig. 4.2 (e) Renewable energy generation.

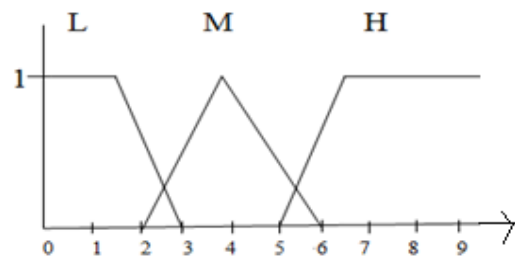


Fig 4.2 (f) Solar daily generation

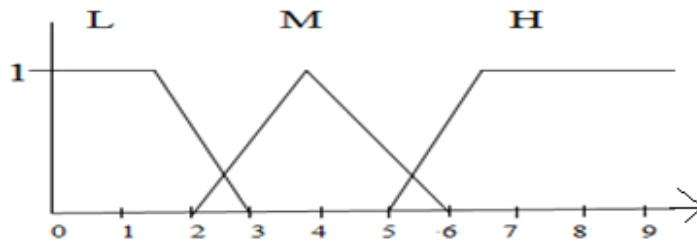


Fig 4.2 (g) Solar generation for next day.

Fig. 4.2 (a) shows the MFs for time where Mr indicates morning, Md indicates midday and N stands for night. Fig. 4.2(c) represents the battery state of charge which can be very low (VL), low (L), medium (M) and high (H). Fig. 4.2(b) shows the EP membership functions assigned into three membership sets as low (L), medium (M) and high (H). Fig. 4.2(d) shows the load demand (LD) membership function which can be assigned as L (low), M (medium), H (high). Fig. 4.2(e) shows renewable energy generation (RG) as L (low), M medium, H (high).

4.1.2 Inference engine

An inference engine is a tool from artificial intelligence which is also a component of expert systems. The defined input membership function are sent to the inference engine which decides the rules to be evaluated; a typical fuzzy rule, 5 rules out of 30 rules are expressed as follows:

1. If (SDG is “H”) and (T is “Md”) and (TDA is “L”) and (BS is “H”) and (LD is “H”) and (EP is “M”) and (RG is “L”) Then (Discharging is “M”).
2. If (SDG is “H”) and (T is “Md”) and (TDA is “M”) and (BS is “H”) and (LD is “H”) and (EP is “M”) and (RG is “L”) Then (Discharging is “H”).
3. If (SDG is “M”) and (T is “N”) and (SDA is “L”) and (BS is “L”) and (LD is “L”) and (EP is “H”) and (RG is “L”) Then (Charging is “M”).
4. If (SDG is “M”) and (T is “N”) and (SDA is “L”) and (BS is “M”) and (LD is “M”) and (EP is “M”) and (RG is “L”) Then (Charging is “VL”).
5. If (SDG is “M”) and (T is “Mr”) and (TDA is “M”) and (BS is “L”) and (LD is “L”) and (EP is “H”) and (RG is “M”) Then (Charging is “H”).

These applied fuzzy rules shows an efficient battery scheduling based on the human proficiency and the aim is to decide the most suitable action whether the charging or discharging of the battery should be done and at which convenient rate while considering the availability of the RG sources, LD and the EP. The rules are based on the practical conditions

where the charging of the battery is related to the low load period and high potential of the renewable sources for generation. When renewable energy generation is low, the battery scheduling will increase the charging rate of the battery during low load period (morning) so that the BS is full to meet the peak load demand. Thereby DG is able to fulfill the load demand and avoid expensive buying of energy from the main grid. The selection of the rules depends on the non-zero membership of the input values. The rules would only be considered if all the inputs have a non-zero MF. While evaluating the output, some of the rules are discarded depending upon the area of the membership function considered for example while evaluating the rule 2, the rule 5 and rule 6 is discarded.

4.1.3 Defuzzification

Defuzzification is the method of converting a fuzzy quantity to a precise value just opposite to the fuzzification process in which a fixed quantity is converted into a fuzzy quantity. The output of the fuzzy system is achieved by logically combining two or more MFs which defined the output linguistic variable. Thus, defuzzification gives the output signal of charging and discharging based on rules and the degree of membership which have been calculated through inference engine. For this process, there are several methods to convert degree of membership of output linguistic variables into numerical values for example height method, weighted average method, centroid method and mean maximum membership method. Here centroid method is used to calculate the defuzzified value which is explained as follows.

4.1.3.1 Centroid method

Centroid method is given by Sugeno in 1985; it is the most accurate defuzzification method. Following is the example of centroid method to find the crisp value of output linguistic variable. Let the output linguistic variable as shown in figure 4.3 where x^* is the defuzzified value which is given by an algebraic equation as:

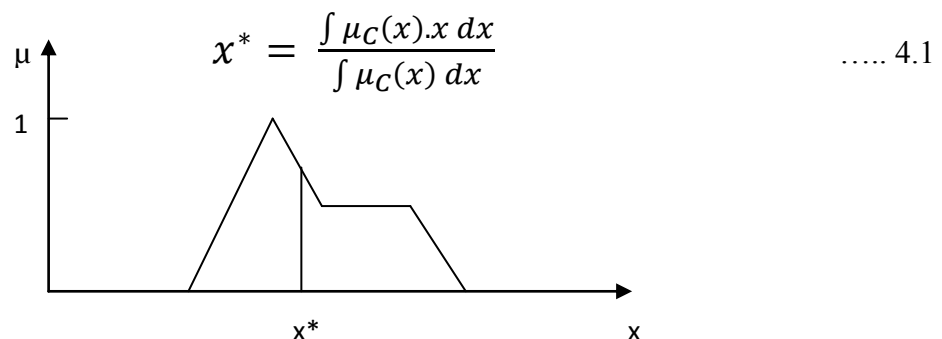


Fig. 4.3 output linguistic variable

To relate it to the real world, this resulted output is multiplied by the normalizing value to find the real charging (Chg) and discharging (Dsc) rate and the output with the higher value is considered as the real output. Finally, the output of the battery for each input of the fuzzy system can be expressed as:

$$P_{\text{batt}} = (\text{Chg} + \text{Dsc}) * \text{BS} \quad \dots 4.2$$

4.1.4 CONCLUSION

Fuzzy logic is the easiest way for battery scheduling. Results in table 4.2 shows the charging rate during the light load condition in morning and discharging rate during peak load condition in afternoon. Proper battery scheduling helps in determining the generation of conventional units.

Table 4.2 Output results of battery scheduling

Time	Charging rate	Discharging rate	BS (Watt)	Output	
				Chg (Watt)	Dsc(Watt)
1	0.356	0	176	62.656	0
2	0.882	0	178	156.996	0
3	0.883	0	105	92.795	0
4	0	0.6	250	0	-150
5	0	0.252	291	0	-73.332
6	0.6	0	203	121.8	0
7	0	0.6	239	0	-143.4
8	0	0.252	203	0	-51.156
9	0	0.6	179	0	-107.4
10	0.435	0	116	50.46	0
11	0.6	0	116	69.6	0
12	0.6	0	124	74.4	0
13	0.142	0	179	25.418	0
14	0	0.256	179	0	-45.824
15	0	0.6	176	0	-105.6
16	0	0.463	211	0	-97.693
17	0.514	0	140	71.96	0
18	0	0.372	168	0	-62.496
19	0.144	0	156	22.464	0
20	0.6	0	101	60.6	0

21	0.356	0	172	61.232	0
22	0	0.251	195	0	-48.945
23	0.713	0	128	91.264	0
24	0.882	0	172	151.704	0

Charging is positive because it is considered as a load for other microsources while discharging is negative because it is use to serve the load.

4.2 MULTIOBJECTIVE OPTIMIZATION

There may be a need to formulate problems with multiple objectives as the single objective with numerous constraints is not adequate to represent the problem. So, there is a array of objective function $F_i(x)$.

$$F_i(x) = [F_1(x), F_2(x) \dots F_m(x)] \quad \dots 4.3$$

Where m is the number of objective function and x is the decision variable.

That must be trade off in some way. As the numbers of objective increases, it became more complex to solve these conflicting objectives. Thus, the multiobjective optimization is an area of making a correct decision which minimizes the array of objectives $F_i(x)$ which is subjected to a number of constraints.

$$\min F_i(x) \quad \dots 4.4$$

Subjected to

$$G_i(x) = 0 \quad i = 1, 2 \dots \dots k_e \quad \dots 4.5$$

$$G_i(x) \leq 0 \quad i = k_e + 1, \dots \dots k \quad \dots 4.6$$

$$\text{lower limit} \leq x \leq \text{upper limit}$$

4.2.1 Multiobjective optimization method

The method which combines the several objective into one objective plays a very important role in ensuring the consistency of optimal solution. There is several multiobjective optimization method like weighted sum method, pareto optimal solution, hierarchical method etc.

Weighted sum method is used in this work which is explained below

4.2.1.1 Weighted sum method

Weight method is the simplest classical method. This method allows the multiobjective problem to be considered as a single objective problem. This single objective function is the summation of the multiple objectives $F_i(x)$ multiplied the weighting factor w_i . After the weighted sum method, the problem can be reformulated as:

$$\min \sum_{i=1}^N w_i f_i(x) \quad \dots 4.7$$

Where w_i lies between 0 and 1 and are selected in this way that their sum is equal to 1.

4.3 BACK TRACKING SEARCH ALGORITHM (BSA)

Back Tracking Search Algorithm (BSA) was introduced in [46] and is designed for solving numerical optimization problems. BSA is a novel population based stochastic technique that is widely used for nonlinear optimization problems. There is a single control parameter in this algorithm. BSA with its simpler configuration is fast and has capability of solving different optimization problems. BSA technique includes two new crossover and mutation operators to generate a trial population. BSA is known to be a memory based technique because it remembers a population from an arbitrarily chosen previous generation. BSA has a global exploration ability which helps in better convergence and obtain optimal solution as compared to other random search algorithms like PSO, ABC, etc.[46].

Its functional steps can be divided into five parts: initialization, selection-I, mutation, crossover and selection-II.

4.3.1 Initialization

First step is to initialize the population P_{ij} with the following equation

$$P_{ij} \sim U(low_j, up_j) \quad \dots 4.8$$

Where

$i = 1, 2, \dots, N$, (population size)

$j = 1, 2, \dots, D$, (problem dimension).

P_{ij} is the target individual in the population P and U is the uniform distribution.

4.3.2 Selection-I

In this step BSA determines the historical population $oldP_{ij}$ which is used to calculate the search space. Initial value of this population is determined using equation 4.9

$$oldP_{ij} \sim U(low_j, up_j) \quad \dots 4.9$$

At the starting of every iteration, there is an option to redefine $oldP_{ij}$ using the following rule:

$$\text{if } a < b \text{ then } oldP_{ij} := P_{ij} | a, b \sim U(0,1), \quad \dots 4.10$$

BSA has memory, as it remembers the historical population till it is not changed. After the $oldP_{ij}$ is determined, equation 4.11 is used to arbitrarily change the arrangement of entities in $oldP_{ij}$.

$$oldP_{ij} := permuting(oldP_{ij}) \quad \dots 4.11$$

Permuting function is used to shuffle the oldP.

4.3.3 Mutation

This stage generates the initial form of the Mutant using the following equation.

$$Mutant (T) = P_{ij} + F \cdot (oldP_{ij} - P_{ij}) \quad \dots 4.12$$

Here, F is mutation factor that control the magnitude of the search direction matrix ($oldP_{ij} - P_{ij}$). BSA generate the trial population which take the advantage of its experience from the previous generation. Here the value of $F=2 \cdot rndn$, where rndn is a random variable between 0 and 1.

4.3.4 Crossover

This process generates the final form of the trial population. The trial populations with better fitness value are used to develop the best population individuals. This process has two steps. First step calculate the binary integer valued matrix (map) of dimension N.D

$$\text{If } map_{ij} = 1 \quad \dots 4.13$$

$$\text{Then } T_{ij} := P_{ij} \quad \dots 4.14$$

BSA crossover is quite different from the other crossover techniques. Mixrate is one of the important parameter in crossover process as it controls the number of individuals that will mutate in a trial population.

At the end of this process there may be some individual in trial population that may be overflow from the search space limits. These individuals should be put into the limits.

4.3.5 Selection-II

In this stage, the population $T_{i,s}$ which have better fitness value than corresponding $P_{i,s}$ are used to update $P_{i,s}$ based on greedy selection.

$$fitnessT = objFunc (T) \quad \dots 4.15$$

$$\text{if } fitness(T_{ij}) < fitness(P_{ij}) \quad \dots 4.16$$

$$P_{ij} := T_{ij} \quad \dots 4.17$$

If the best value in $P_{ij} = P_{ij}(P_{best})$ has a better fitness value than the global minimum value obtain so far, then the global minimize is updated to be P_{best} .

4.3.6 Comparison of BSA with other Meta Heuristic Techniques

- Mutation and crossover operator in BSA is different from DE. Its crossover process is extra complex than the crossover mechanism of DE.
- BSA is quite similar to other comparison technique like PSO, ABC, JDE etc.
- It has much simpler structure than other comparison technique.

- Its process of boundary control is different in comparison to other techniques.
- BSA memorizes the population of randomly selected population which is used for calculating the search space matrix where as ABC, PSO and JDE do not use previous generation population.

4.4 INPUT REQUIRED

Optimization model consist the following points. The following data should be defined.

- Load demand
- Locally available information: - solar irradiance (w/m^2), wind velocity (m/s), temperature ($^{\circ}C$), cost of fuel and natural gas price (\$/kWh).
- Purchased and sold tariff (\$/kWh).
- Start up costs in (\$).
- Performances curve of the sources..
- Operational and maintenance cost (\$/h).
- Total emission (Kg/h).

4.5 IMPLEMENTATION OF ALGORITHM

In order to achieve the reduction in emission and generation cost, it is important to define all the factors which are effecting the results. The following is the solution methodology of the problem considered.

Step1: Initialize the input parameters like wind speed (V), input irradiation (G_{ING}), generator coefficient (d, e, f), efficiency (η) etc.

Step2: Calculate the output power from wind turbine ($P_{WT,t}$) and photovoltaic cell ($P_{PV,t}$) using equation 3.4 and 3.5 respectively.

Step3: Calculate the difference between the load and the sum of the output powers of wind turbine ($P_{WT,t}$) and photovoltaic cell ($P_{PV,t}$). if load demand is not served go to next step otherwise go to step 13.

Step4: Battery power (P_{batt}) is forecasted for 24 hours by determining the charging (chg) and discharging (dsc) rate using fuzzy logic technique. Battery power is considered positive for charging interval and negative for discharging interval because charging of battery is considered as a load which is charged by other microsourses. Now, the net load is calculated.

Step5: Generate a real power (P_i) of microturbine, fuel cell and diesel generator randomly within their lower (P_{min}^i) and upper limits (P_{max}^i).

Step6: Check the mismatch between generation and net load.

If generation > net load, excess power is sold (SE_{it}) to the main grid using equation .

If generation < net load, required power is purchased (PF_{it}) from the main grid using equation.

Step7: Calculate the objective function which include overall cost (fuel cost $C_{DG,t}$, $C_{DG,t}$, $C_{FC,t}$, startup cost (STC), operating and maintenance cost (OM), purchased and sold cost) and emission of a diesel generator, microturbine, and Fuel cell using the weighted sum method.

Step8: Set the iteration (itr) count equal to 1.

Step9: Update the randomly generated real power (T_i) using mutation and crossover operator of back tracking search algorithm as explained above.

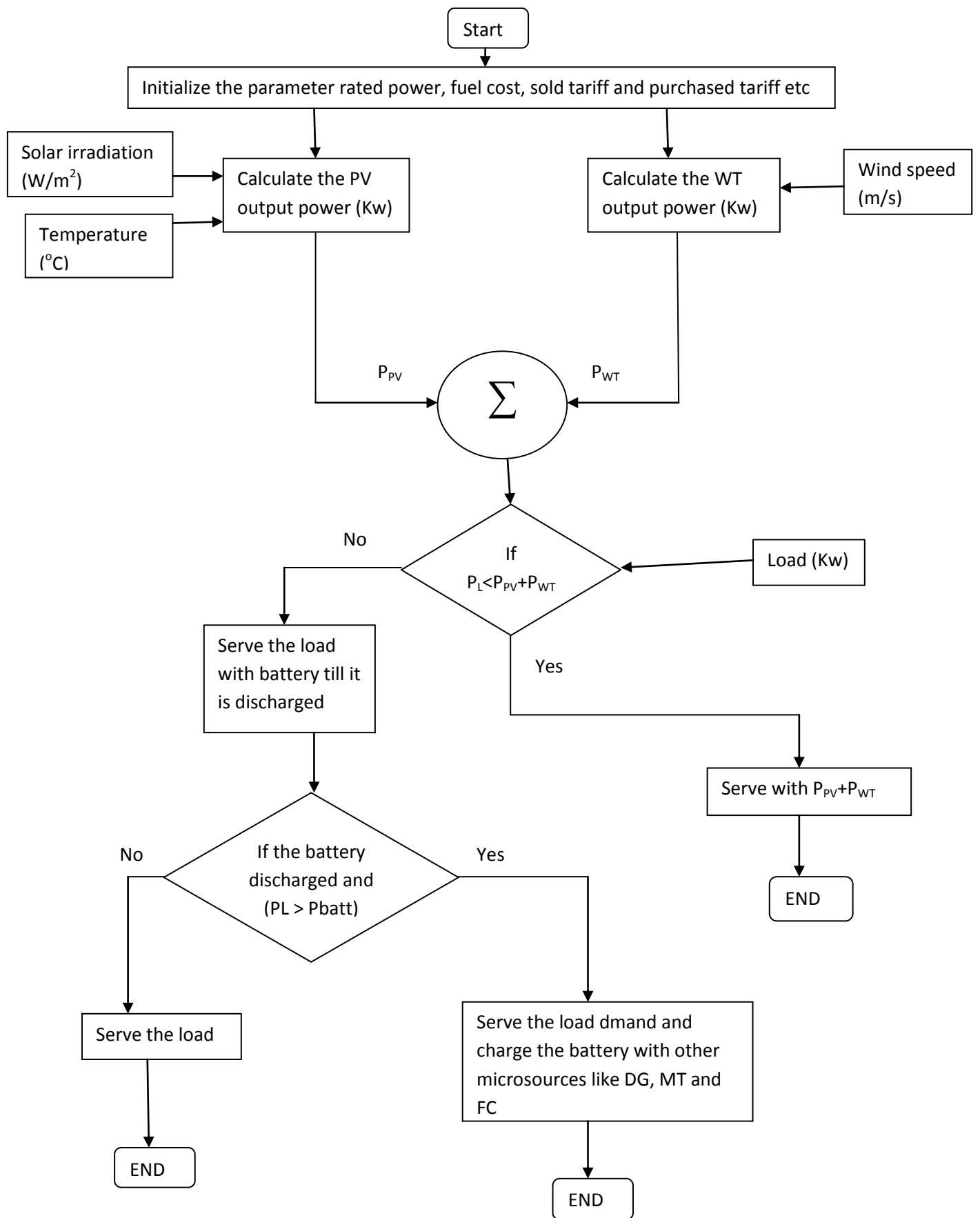
Step10: Calculate the objective function using this updated value.

Step11: Greedy selection is applied to the objective functions calculated from the old real power (P_i) and the updated power (T_i). Thus, the power (T_i) having best function is used to update the P_i . If the best fitness value is better than the minimum value obtained so far, the minimum value is updated to this best fitness value.

Step12: Check for the iteration

If itr < maximum iteration, set itr =itr+1 and go to step 9.

Step13: Global minimum is found which is equal to the minimum value obtained so far, end.



Flowchart

CHAPTER-5

RESULT AND DISCUSSION

In this dissertation, micro-grid consisting of PV cell, wind turbine, micro-turbine, diesel generator and fuel cell are considered. The purpose of the dissertation is to minimize the operational cost and emission level of the micro-grid within the boundaries of the operational limits. In order to find the optimal solution of the microgrid, back tracking search algorithm is implemented with five different scenarios presented in chapter- 4. The algorithm is attempted to provide a fine balance between two objective functions which keep them close to their optimum values.

5.1 INPUT CURVES

The input data in terms of cost coefficients, emission coefficients, battery charging/discharging rate, number of units of each micro-source, maximum and minimum power generation limits of units, start up costs, operating efficiency of turbines, cut-in and cut-out wind speed data for wind units, operating and maintenance cost coefficients, sale and purchase tariffs of utility grid is given in the appendix. The physical parameter data in terms of wind speed and temperature for wind unit and PV cell for one particular day is considered. For the wind turbine the hourly wind speed data is shown in fig. 5.1 and solar irradiance and reference temperature data for PV cell is shown in fig. 5.2 and 5.3. The losses in the microgrid system are neglected. The hourly load demand is represented in the curve shown in fig. 5.3

5.1.1 Wind speed curve

The output power of wind turbine depends on the velocity of the wind, thus it is required to have information about the wind speed at every interval of time for one complete day. This variation of wind speed (m/s) is shown in figure 5.1.

It is assumed that wind speed over an hourly interval is constant. The wind speed is used to calculate the output power of wind turbine using equation 3.4. The calculated power output from wind unit is mentioned in table 5.1

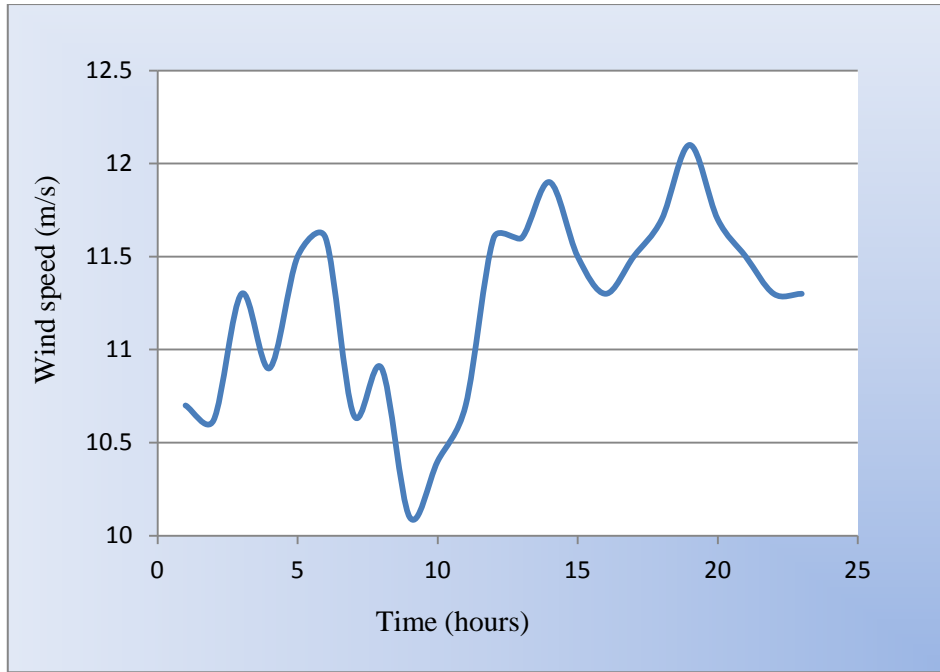


Fig. 5.1: Input wind speed

Table 5.1: Output power of One wind turbine Unit

Hour	Wind speed (m/s)	Output Power (W)	Hour	Wind speed (m/s)	Output power (W)
1	10.7	270.10	13	11.6	327.50
2	10.62	265.20	14	11.9	347.90
3	11.3	307.70	15	11.5	320.80
4	10.9	282.40	16	11.3	307.70
5	11.5	320.80	17	11.5	320.80
6	11.6	327.50	18	11.7	334.20
7	10.65	267.00	19	12.1	361.80
8	10.90	282.40	20	11.7	334.20
9	10.1	234.80	21	11.5	320.80
10	10.4	252.10	22	11.3	307.70
11	10.7	270.10	23	11.3	307.70
12	11.6	327.50	24	11.3	307.70

5.1.2 Reference temperature

The output power of photovoltaic cell represented by equation 3.5 shows that it is directly dependent upon the reference temperature and incident irradiance. The data used for

reference temperature and incident irradiance is shown through the following curve for 24 subinterval of one day.

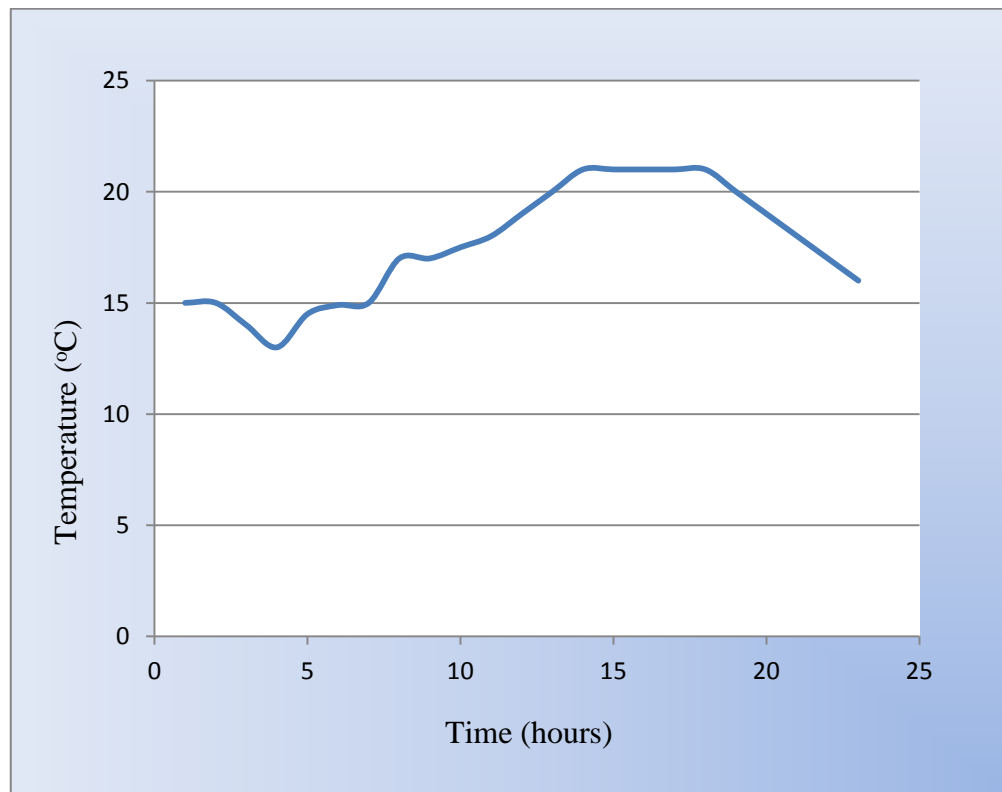


Fig 5.2: Hourly Reference Temperature Curve.

5.1.3 Incident irradiance

The output power of photovoltaic cell which depends upon this reference temperature and incident irradiance is shown in table 5.2

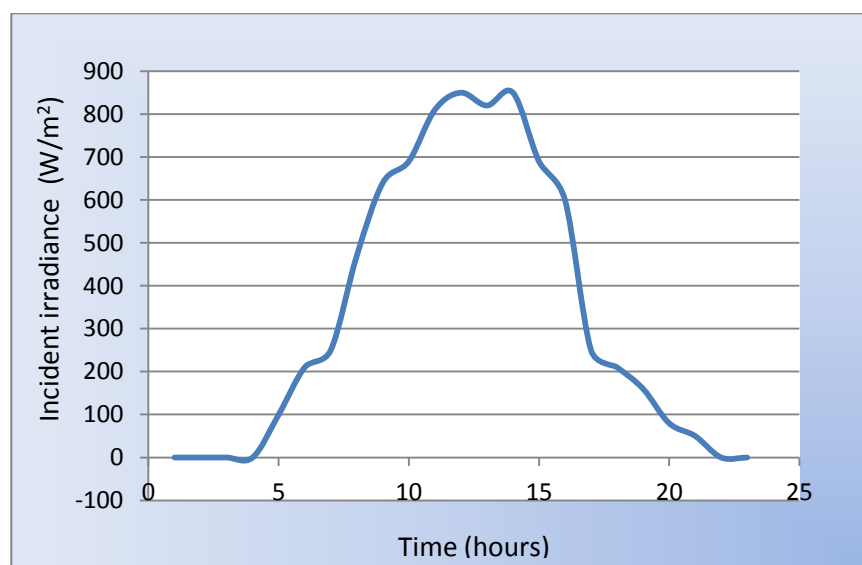


Fig 5.3: Input incident irradiance.

Table 5.2: Output power of photovoltaic cell

Hour	Reference Temperature (°C)	Incident irradiance (m/sec ²)	Output power (W)
1	15	0	0
2	15	0	0
3	14	0	0
4	13	0	0
5	14.5	100	8.60
6	14.9	210	18.10
7	15	250	21.5
8	17	470	40.2
9	17	640	54.7
10	17.5	690	58.9
11	18	810	69.0
12	19	850	72.2
13	20	820	69.4
14	21	850	71.6
15	21	690	58.1
16	21	600	50.6
17	21	250	21.1
18	21	210	17.7
19	20	160	13.5
20	19	80	6.8
21	18	50	4.3
22	17	0	0
23	16	0	0
24	15.5	0	0

5.1.4 Load demand

Figure 5.4 shows the load demand curve where load demand is varying between 4 kW to 14 kW for one day having 24 subintervals.

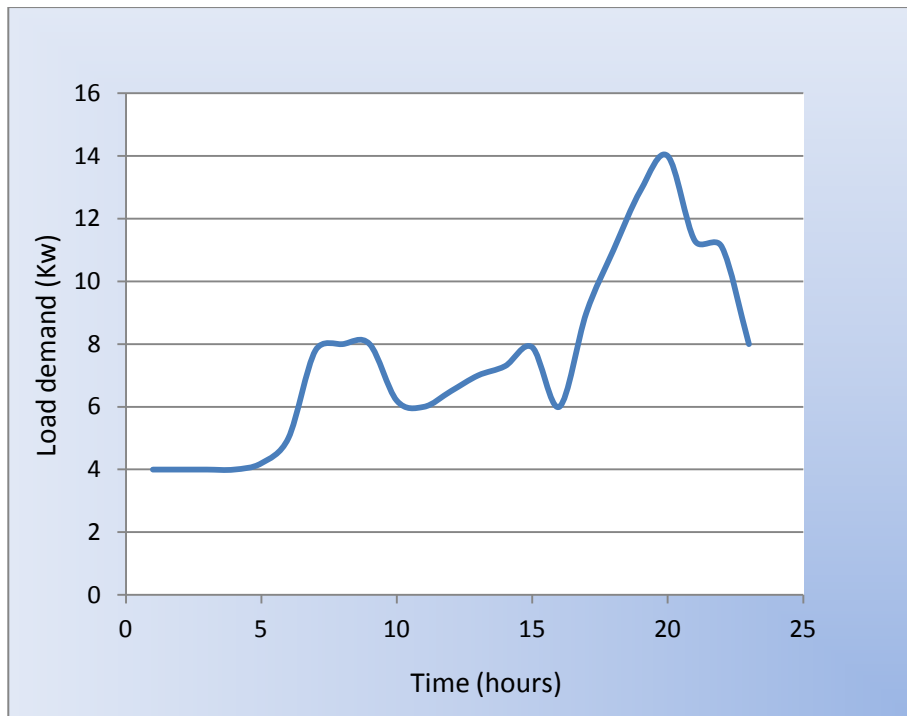


Fig. 5.4: Load demand curve

Net load demand is calculated after serving the load with photovoltaic cell and wind turbine which is shown in table 5.3.

Table 5.3: Net load demand after serving the load with wind turbine and photovoltaic cell

Hour	Net load demand (kW)	Hour	Net load demand (kW)
1	3.7299	13	6.6031
2	3.7348	14	6.8805
3	3.6923	15	7.5210
4	3.7176	16	5.6417
5	3.8705	17	8.6581
6	4.6544	18	10.6481
7	7.5114	19	12.5247
8	7.6775	20	13.6590
9	7.7104	21	10.9749
10	5.8890	22	10.7923
11	5.6609	23	7.6923
12	6.1003	24	5.6923

5.2 RESULTS

The problem of microgrid is formulated as multiobjective problem. Battery storage unit is incorporated. The availability of battery storage unit is predicted using fuzzy logic. The solution methodology implemented for battery storage unit is explained section 4.1. The microgrid is assumed to be integrated with utility system. Results obtained for the five different scenarios are presented here. The power available from photovoltaic cell and wind turbine is used first. The problem is first considered as a single objective of operating cost minimization and emission minimization individually. The results for single objective problems are given in test problem with consideration of scenario1, 2 and 3.

5.2.1 Scenario1: Minimization of single cost objective function without microgrid.

In first scenario, only the cost objective is considered in which load demand is to be met within the maximum and minimum limits of power without considering the battery storage device. In this scenario, the whole procedure is done using BSA.

Table 5.4: Optimized operating cost for scenario1.

	Load demand (kW/day)	Operating cost (₹/day)	Mismatch (kW)
Without Penalty function	179.2	1875.04	-
With penalty	179.2	3070.21865	0.0039

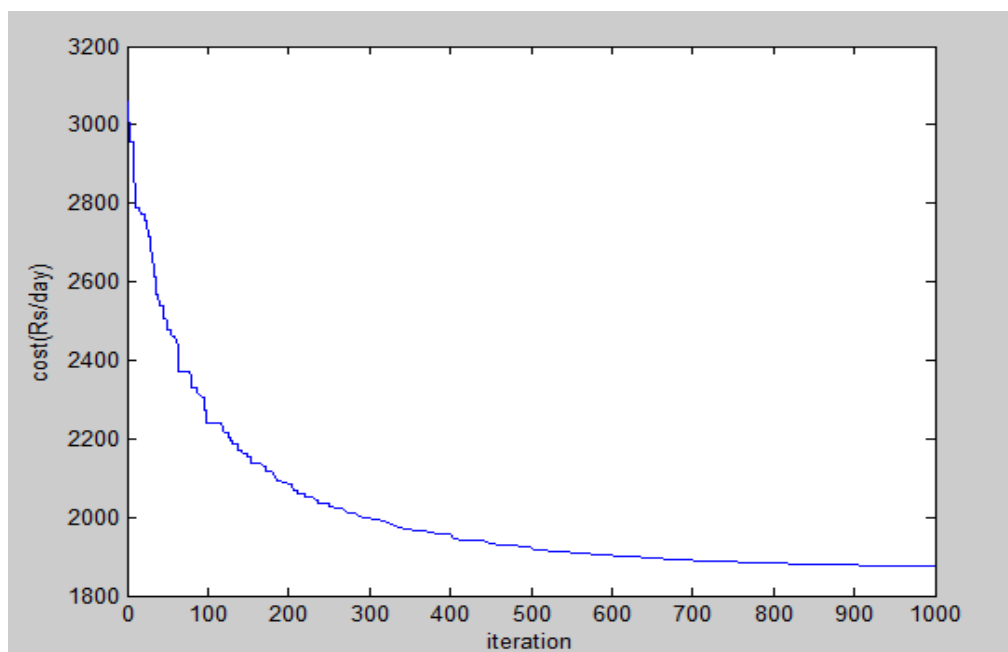


Fig. 5.5: Single objective of cost minimization without battery.

Figure 5.5 shows the convergence of total operating cost which includes fuel cost, operational and management cost, startup cost, purchased or sold cost.

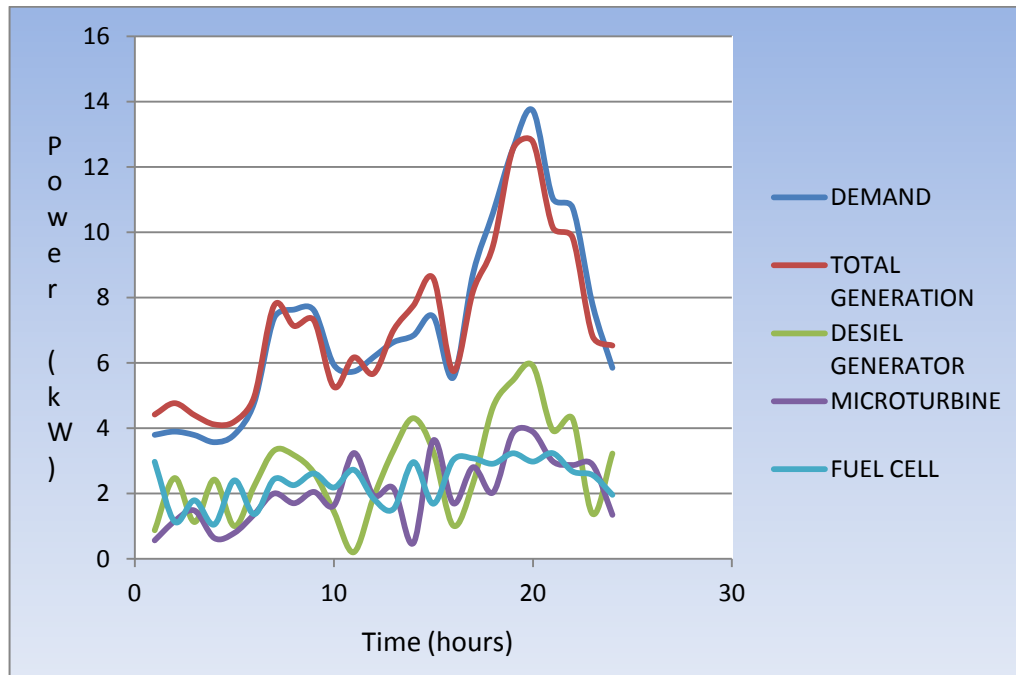


Fig. 5.6: Optimal generation with penalty function for scenario1.

5.2.2 Scenario2: Minimization of single cost objective function with microgrid

In second scenario, only the cost objective is considered in which load demand is to be met within the maximum and minimum limits of power while considering the battery storage device in microgrid. This scenario is also implemented using BSA. The net load demand after considering the forecasted output of battery is shown fig below.

Table 5.5: Optimized operating cost for Scenario 2.

	Load demand (kW/day)	Operating cost (₹/day)	Mismatch (kW)
Without Penalty function	179.2	1874.024	-
With Penalty function	179.2	3147.09175	0.0274

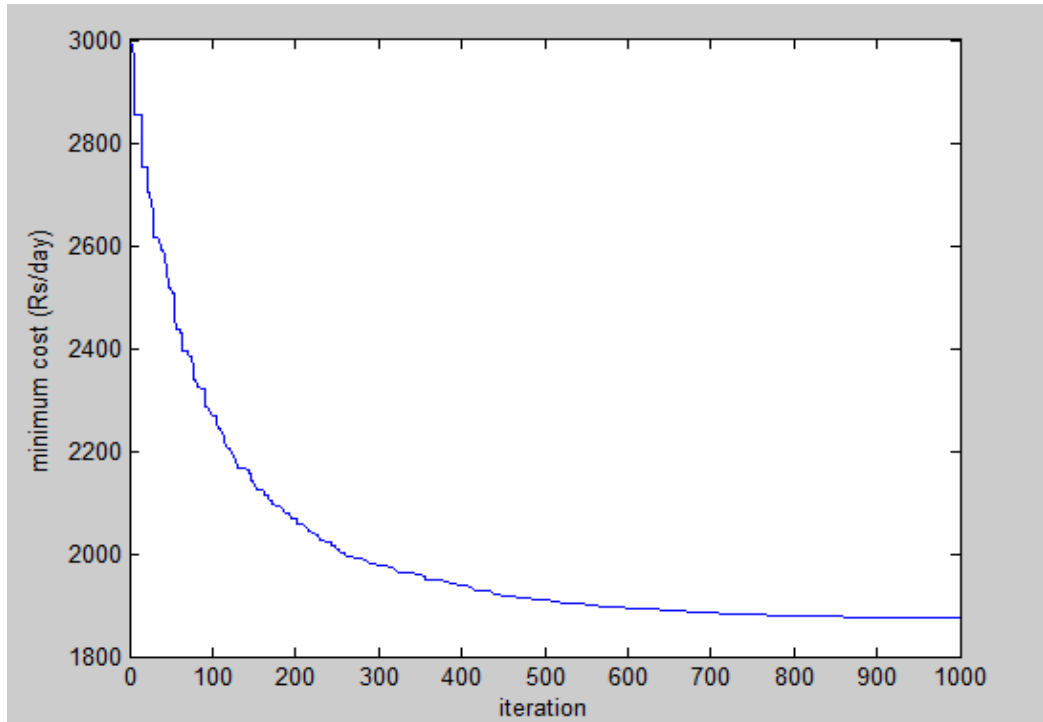


Fig. 5.7: Single objective of cost minimization with battery storage device.

Figure 5.7 shows the convergence of cost while the battery storage device is connected in microgrid. Table 5.1 shows the optimized convergence cost for both scenario1 and scenario2. The operating cost in 2nd scenario is less than the 1st scenario as some of the load demand is served by the battery and also the battery charging takes place in the interval of low electricity price.

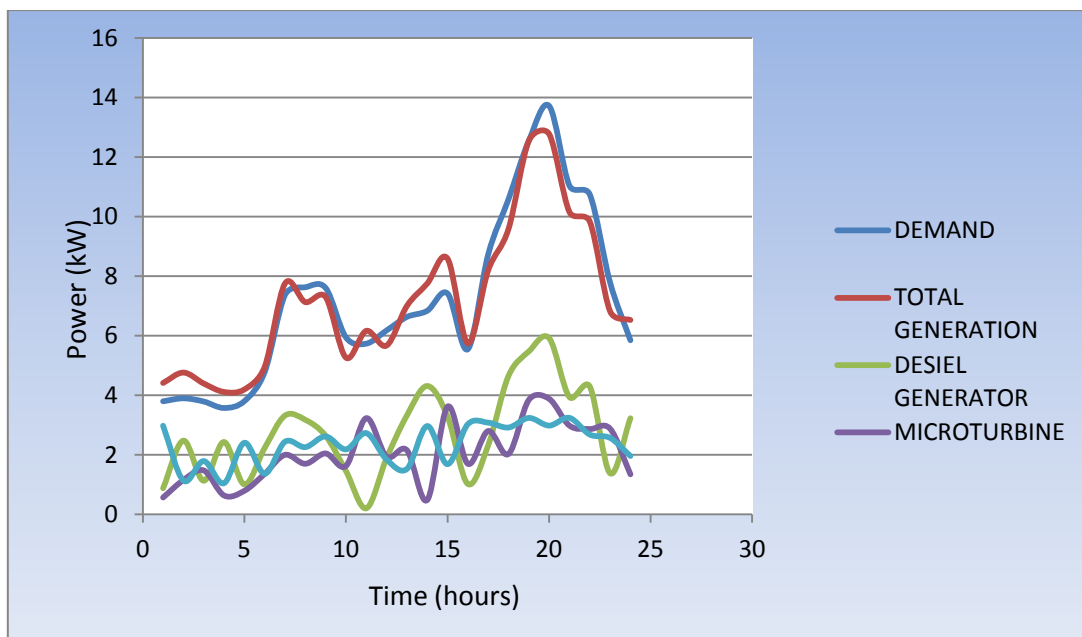


Fig. 5.8: Optimal generation with penalty function for scenario2.

5.2.3 Scenario3 : Single objective of emission minimization.

This scenario represented the emission objective, considered individually to minimize the emission level of the microgrid.

The main aim of implementing this scenario is find the minimum emission level so that the obtained results could be compared with the multiobjective results.

Table 5.6: Optimized emission level for Scenario 3

	Load demand (kW)	Emission (kg/day)	Mismatch (kW)
Without Penalty function.	179.2	15.7863	-
With Penalty function	179.2	16.0935	0.0064

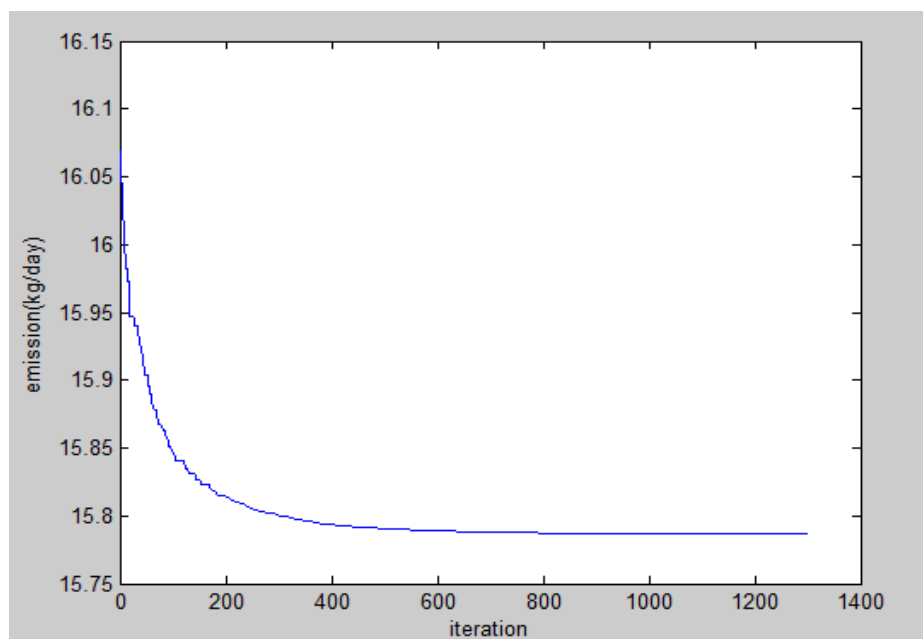


Fig. 5.9 Single objective of emission minimization.

Now, the problem is converted into multiobjective problem where both the operational cost and emission level are optimized simultaneously.

Weight method is used to combine these two objectives into single objective problem. In this method, some weight is assigned to the multiple objectives randomly generated between 0 and 1 and whose sum is equal to one. Thus, the overall objective is become

$$C = \omega CF + (1 - \omega)E$$

Where

ω = weight.

CF = Cost function (\$/day).

E =Emission level (kg/day).

The value $\omega=1$ indicate the minimum operational cost and we get the best solution for operating cost objective. When $\omega=0$, it indicate the minimum emission level and we get the best result for the emission objective. The result for the multiobjective problem is shown scenario 4 and 5.

5.2.4 Scenario4: Multiobjective minimization of operational cost and emission level without battery.

In this scenario, two conflicting objective functions that are operational cost and emission level are combined in a manner to get the optimized results without considering the battery storage device.

Table 5.7: Multiobjective optimized cost and emission for scenario4.

	Load demand (kW)	Cost (₹/day)	Emission (Kg/day)	Mismatch (kW)
Without penalty function	179.2	2975.707524	16.0497	-
With penalty function	179.2	3166.9101	16.0999	0.0786

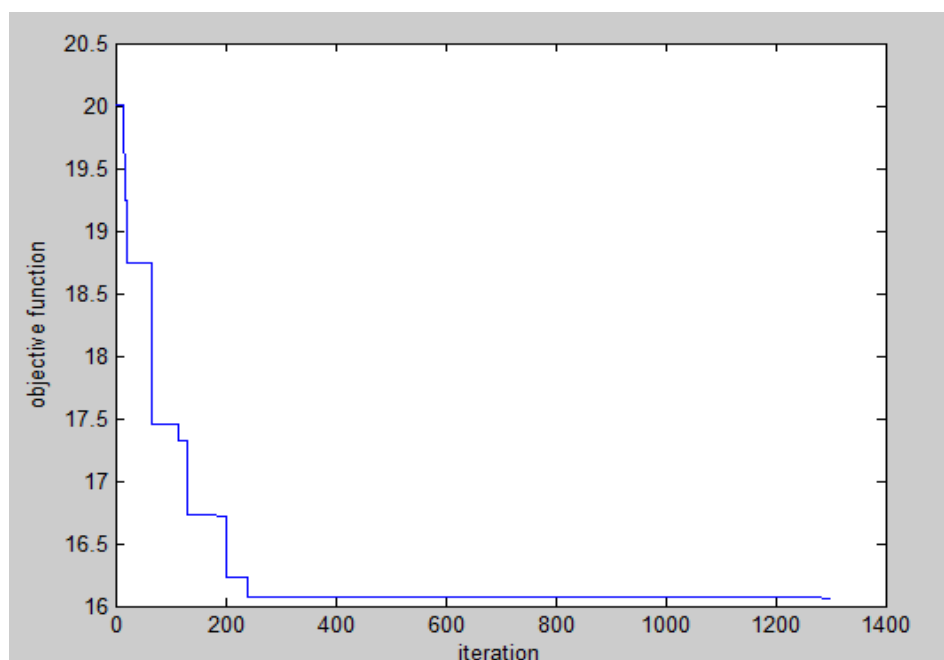


Fig. 5.10 Multiobjective optimization without battery

Figure 5.10 shows the convergence of objective function which include cost and emission objective. Figure 5.11 shows the optimal generation from microsources for 24 subinterval of complete one day.

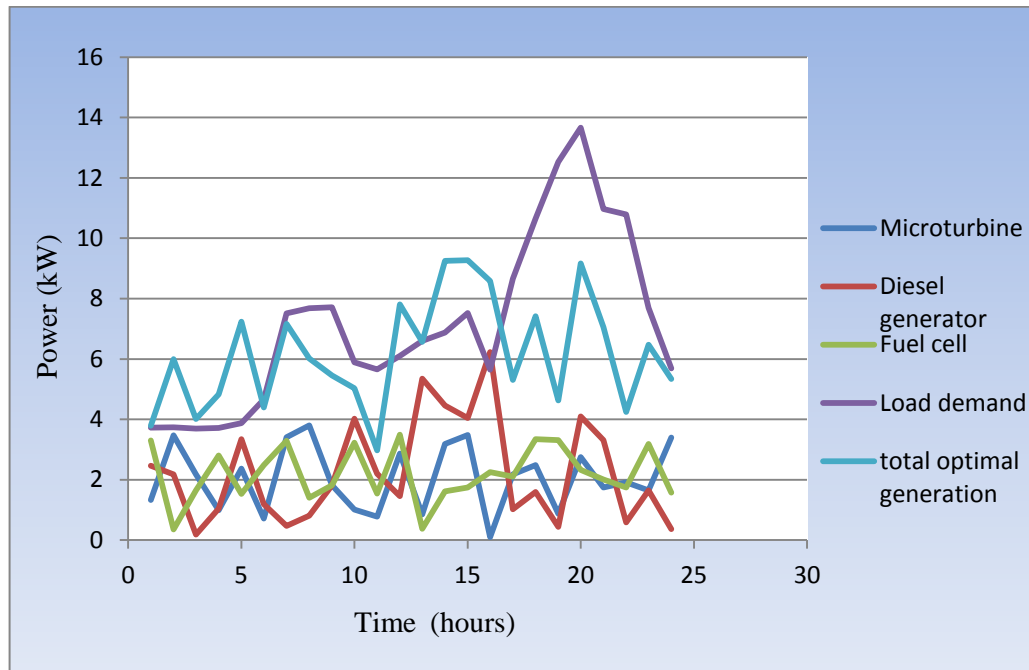


Fig. 5.11 Optimal generation without penalty function for scenario4.

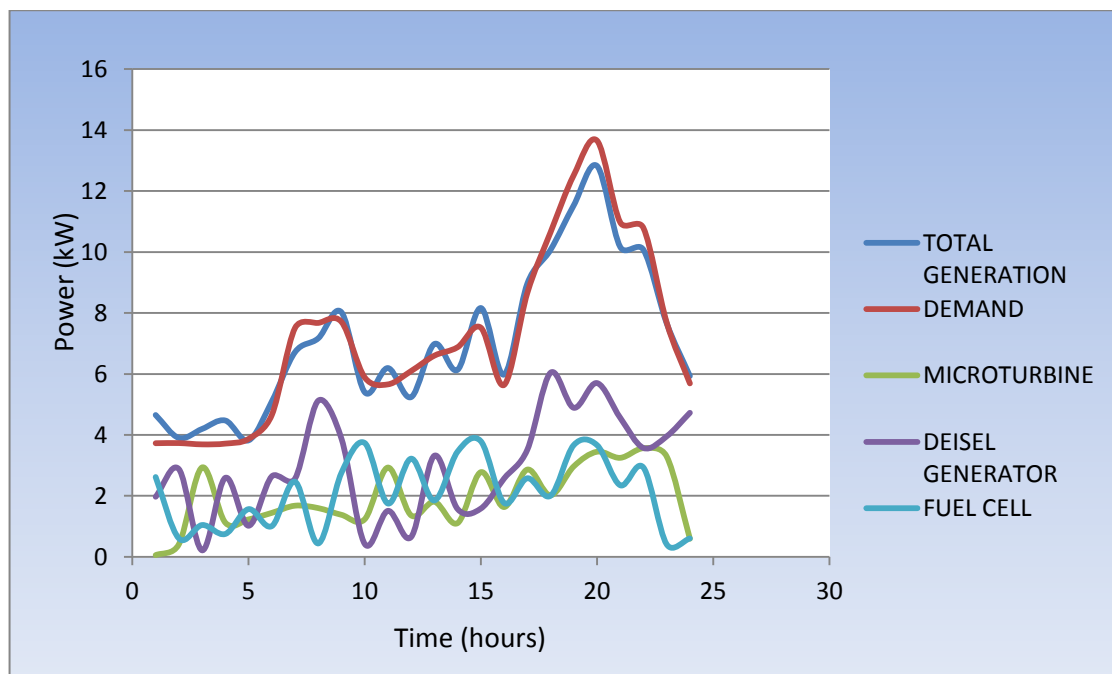


Fig. 5.12: Optimal generation with penalty function for scenario4.

The weighted sum method is used to convert the two objectives (cost and emission minimization) into multiobjective problem. The obtained tradeoff between cost and emission for 4th scenario is shown in figure 5.13.

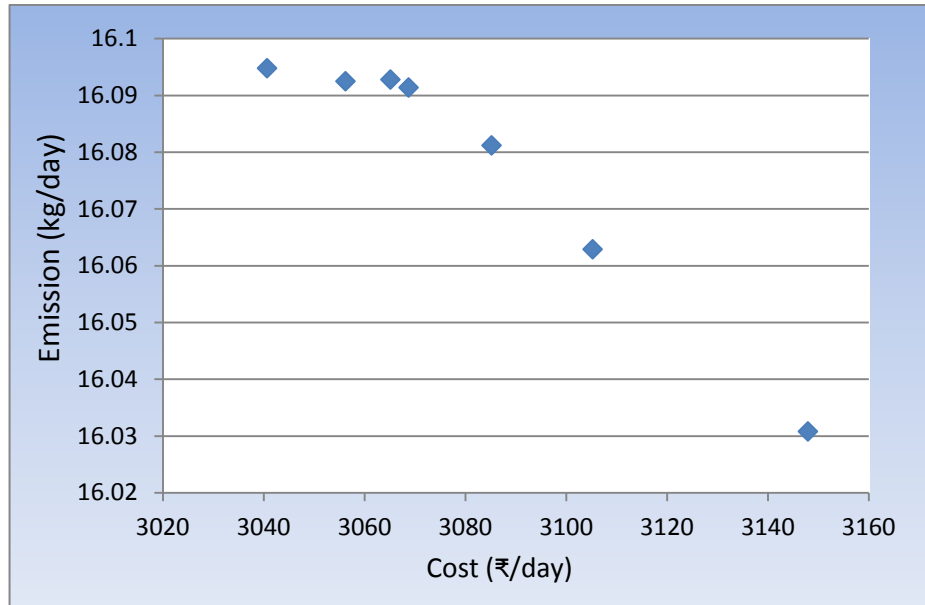


Fig. 5.13: Trade off between cost and emission.

5.2.5 Scenario 5: Multiobjective minimization of operational cost and emission level with battery

In this scenario, two conflicting objective functions that are operational cost and emission level are combined in a manner to get the optimized results with considering the battery storage device. Figure 5.14 shows the convergence of the multiobjective for scenario 5.

Table 5.8: Optimized operational cost and emission level for Scenario 5

	Load demand (kW)	Cost (₹/day)	Emission (Kg/day)	Mismatch (kW)
Without penalty function	179.2	3043.212156	16.0977	-
With penalty function	179.2	3100.7558	16.0927	0.0284

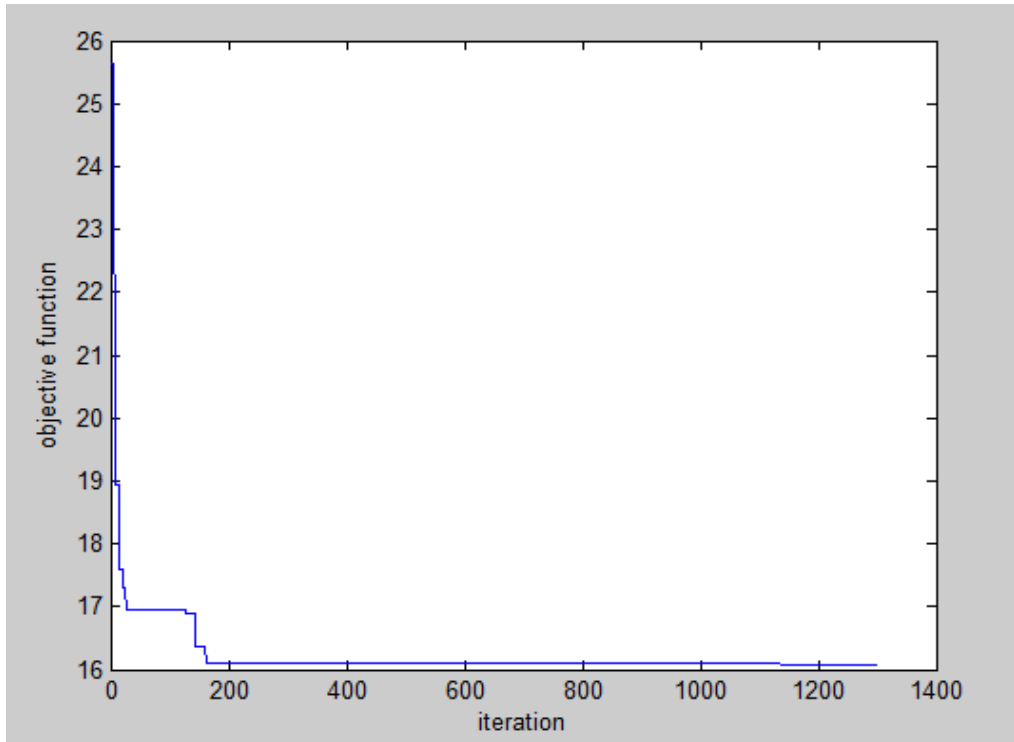


Fig. 5.14 Multiobjective optimization with battery storage device

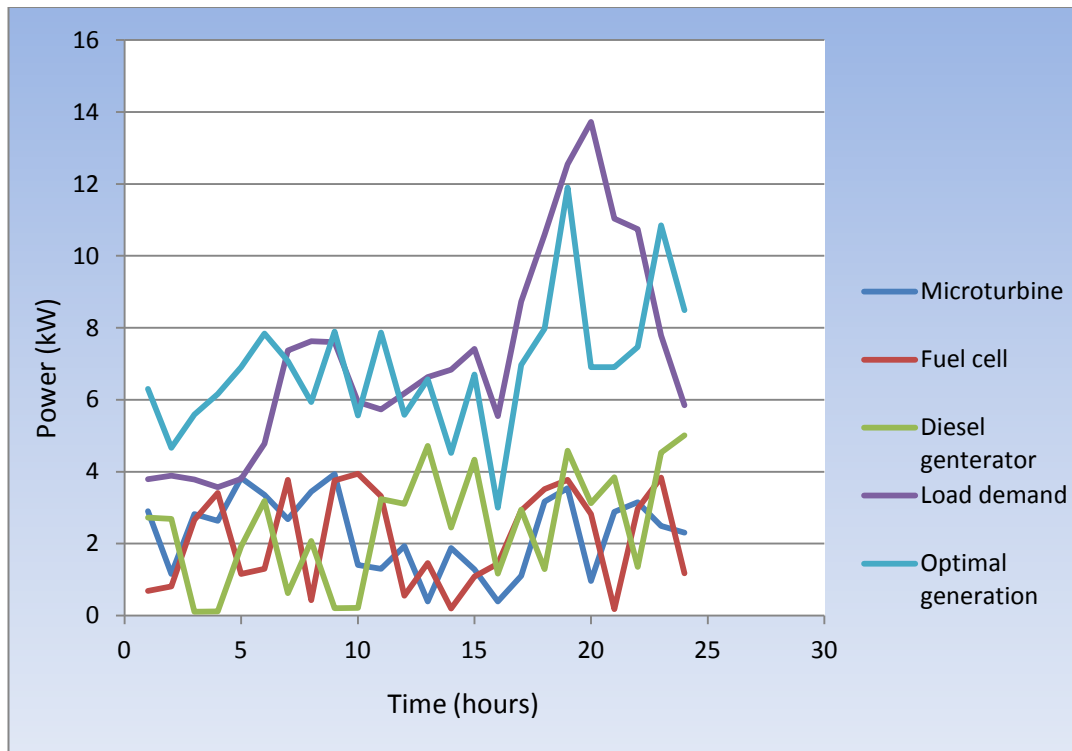


Fig. 5.15 Optimal generation without penalty function for scenario5.

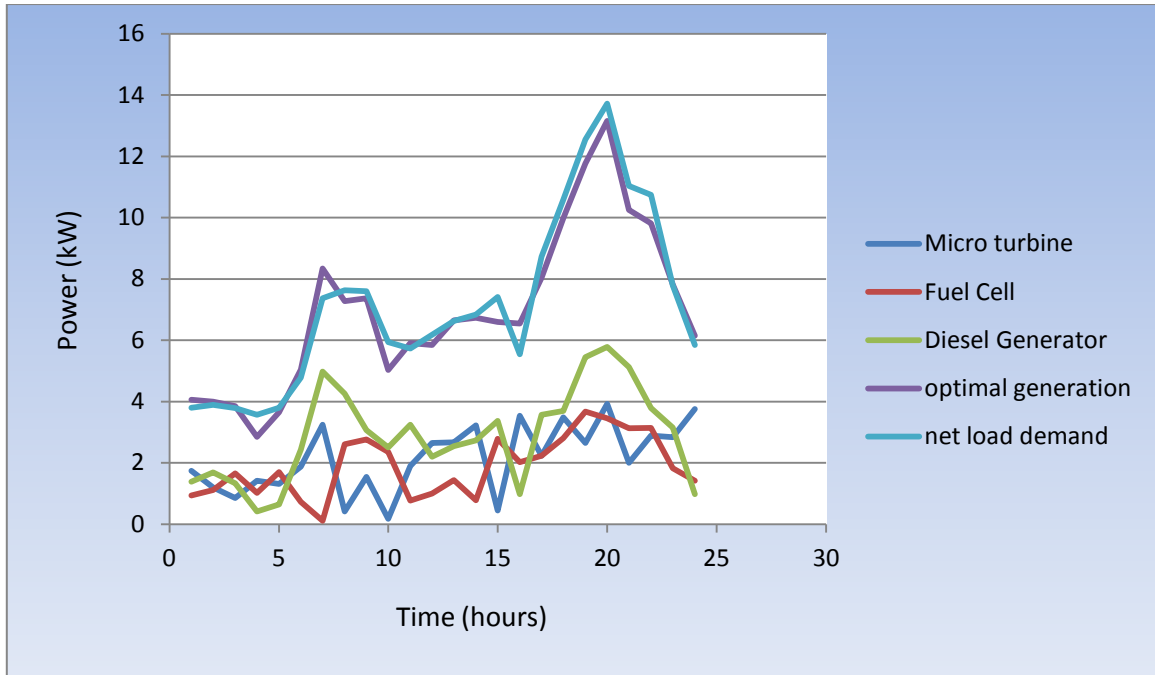


Fig. 5.16 optimal generation of microgrid with penalty function for scenario 5.

Figure 5.16 shows the optimal generation from microsources for 24 subinterval of complete one day. If the generation is not sufficient to meet the load, the required power is purchased from the main grid. Similarly if generation exceeds the load demand, the excess power is sold to the utility grid which is considered as revenue. The trade off between emission and cost for scenario 5 is shown below.

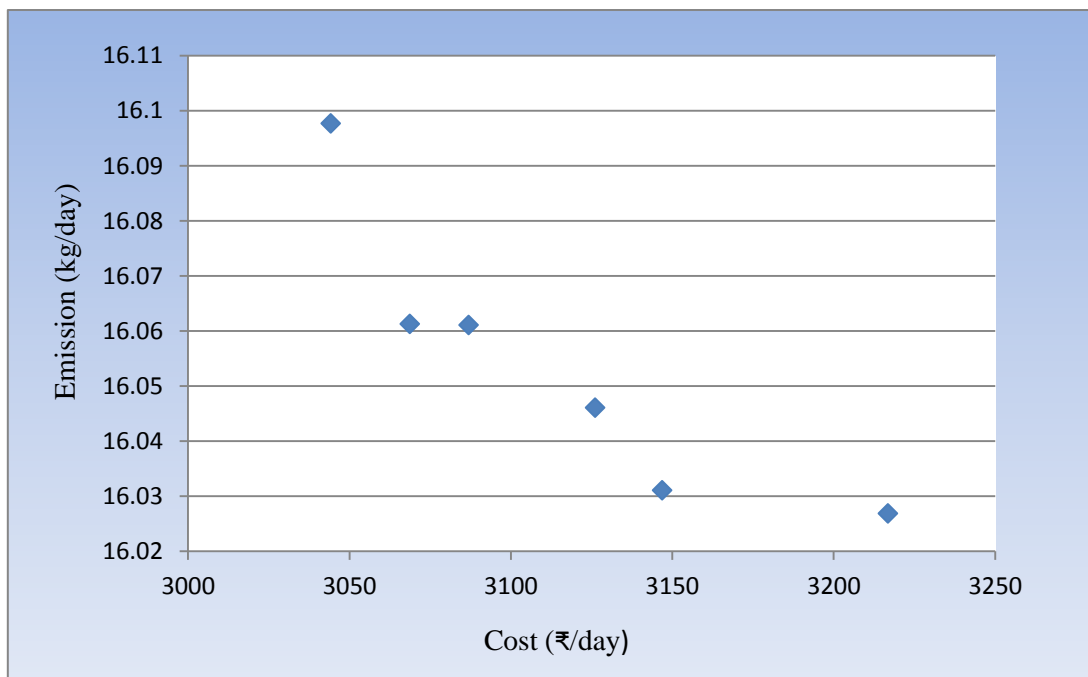


Fig. 5.17 trade off between emission and cost.

The obtained results are shown in table 5.2 for both scenarios 4 and 5. The results show that the cost and emission is somewhat greater than the results obtained as a single objective due to the conflicting nature of the objectives.

It can also be concluded that, there is not much increase in emission level when it is considered to be conflicting with the operational cost.

6.1 CONCLUSION

The optimal generation from the microsources is obtained which provide a reasonable result of operating cost (₹/day) and emission level (kg/day). The operating cost and emission curves for the microgrid, clearly shows that the optimization technique works very well and also shows the effectiveness of the this approach while satisfying all the equality and inequality constraints. It can be observed that load was served properly.

6.2 FUTURE SCOPE

- The proposed technique can be applied for different load demand and for more number of days.
- Same problem can be tested with improved BSA or with different mutation techniques.
- Problem can also be tested with different purchased and sold tariff, to see the effect of tariff on the operational cost.
- The proposed system can be applied with exponential charging and discharging function of battery storage device.

REFERENCES

- [1] R.H Lasseter, "MICROGRID," in *proc. IEEE Power Eng. Soc. Winter meeting*, vol. 1, pp. 305-308, January 2002.
- [2] J.A.P. Lopes, C.L. Moreira, and A.G. Madureira, "Defining control strategies for MicroGrids islanded operation," *IEEE Transactions on Power Systems*, vol. 21, pp. 916-924, 2006.
- [3] M. R Vallem, D. Jensen and J. Mitra, "Reliability evaluation and need based storage assessment for surety microgirds," in *Proc. North Amer. Power Symp.*, pp. 29-33, September 2006.
- [4] R. Firestone and C. Marney, "Energy manager design for microgrids," CERTS, Calif. Energy Comm., Sacremento, CA, LBNL-54447, 2005.
- [5] R. Lasseter, "Microgrids [distributed power generation]," *IEEE Power Engineering Society Winter Meeting, 2001.*, vol. 1, pp. 146–149, February 2001.
- [6] Y. Zoka, H. Sasaki, N. Yorino, K. Kawahara, and C.C. Liu, "An interaction problem of distributed generators installed in a microgrid," In *Proc. of IEEE on Electric Utility Deregulation, Restructuring and Power Technologies Conference*, vol. 2, pp.795 – 799, April 2004.
- [7] A. Arulampalam, M. Barnes, A. Engler, A. Goodwin and N. Jenkins, "Control of Power Electronic Interfaces in Distributed Generation Microgrids," *International Journal of Electronics*, vol. 91, no.9, pp. 503-523, 2004.
- [8] A. Meliopoulos, "Challenges in simulation and design of μ Grids," *IEEE Power Engineering Society Winter Meeting. Conference Proceedings*, 2002.
- [9] G. Venkataramanan and M. Illindala, "Microgrids and sensitive loads," In *Proc. IEEE Power Eng. Soc. Winter Meeting*, vol. 1, pp. 316 – 322, 2002.
- [10] J. M. Correa, S. Chakraborty, M. G. Simoes, and F. A. Farret, "A single phase high frequency ac microgrid with an unified power quality conditioner," In *Proc. IEEE Industry Applications Conference*, vol. 2, pp. 956 – 962, October. 2003.
- [12] S. Rao, " *Engineering optimization*," Hoboken, N.J.: John Wiley & Sons, 2009.
- [13] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans and W. D'haeseleer, "Distributed generation: definition, benefits and issues", *Energy Policy*, vol. 33, no. 6, pp. 787-798, 2005.
- [14] P. Civicioglu, "Backtracking Search Optimization Algorithm for numerical optimization problems", *Applied Mathematics and Computation*, vol. 219, no. 15, pp. 8121-8144,

2013.

- [15] T. Ackermann, G. Andersson and L. Soder, "Distributed generation: a definition", *Electric Power Systems Research*, vol. 57, no. 3, pp. 195-204, 2001.
- [16] D. Fouskakis and D. Draper, "Stochastic Optimization: a Review", *International Statistical Review*, vol. 70, no. 3, pp. 315-349, 2002.
- [17] H. Nikkhajoei and R. Lasseter, "Distributed Generation Interface to the CERTS Microgrid", *IEEE Trans. Power Delivery*, vol. 24, no. 3, pp. 1598-1608, 2009.
- [18] L. Mariam, M. Basu and M. Conlon, "A Review of Existing Microgrid Architectures", *Journal of Engineering*, vol. 2013, pp. 1-8, 2013.
- [19] P. Piagi and R. Lasseter, "Autonomous control of microgrids", *IEEE Power Engineering Society General Meeting*, 2006.
- [20] G. Stavrakakis and G. Kariniotakis, "A general simulation algorithm for the accurate assessment of isolated diesel-wind turbines systems interaction., A general multimachine power system mode", *IEEE Trans. On energy Conversion*, vol. 10, no. 3, pp. 577-583, 1995.
- [21] F. Mohamed and H. Koivo, "System modelling and online optimal management of MicroGrid using Mesh Adaptive Direct Search", *International Journal of Electrical Power & Energy Systems*, vol. 32, no. 5, pp. 398-407, 2010.
- [22] A. Wood and B. Wollenberg, "Power generation operation and control" 2nd edition', *Fuel and Energy Abstracts*, vol. 37, no. 3, pp. 195, 1996.
- [24] S. Obara, "Fuel cell micro-grids," London: Springer, 2009.
- [25] J. Smith, M. Nehrir, V. Gerez and S. Shaw, "A broad look at the workings, types, and applications of fuel cells," *IEEE Power Engineering Society Summer Meeting*, 2002.
- [26] M. Ellis, M. Von Spakovsky and D. Nelson, "Fuel cell systems: efficient, flexible energy conversion for the 21st century", *Proc. IEEE*, vol. 89, no. 12, pp. 1808-1818, 2001.
- [27] F. Barbir, "Efficiency and economics of proton exchange membrane (PEM) fuel cells", *International Journal of Hydrogen Energy*, vol. 21, no. 10, pp. 891-901, 1996.
- [28] T. Kreutz and J. Ogden, "Assessment of hydrogen-fueled proton exchange membrane fuel cells for distributed generation and cogeneration," In *Proc. of the 2000 US DOE Hydrogen Program Review*, United States Department of Energy, 2000.
- [29] C. Sharma, "Modeling of an island grid," *IEEE Transactions on Power Systems*, vol. 13, no. 3, pp. 971-978, 1998.
- [30] W. Scott, "Micro-turbine generators for distribution systems", *IEEE Ind. Appl. Mag.*,

- vol. 4, no. 3, pp. 57-62, 1998.
- [31] S. Haugwitz, “Modelling of microturbine systems,” *Master’s thesis, Department of Automatic Control*, Lund Institute of Technology, Lund, Sweden, May 2002.
- [32] T. Ackermann, “Wind power in power systems,” Chichester, West Sussex, England: John Wiley, 2005.
- [33] R. Chedid, H. Akiki and S. Rahman, “A decision support technique for the design of hybrid solar-wind power systems”, *IEEE Trans. On energy Conversion*, vol. 13, no. 1, pp. 76-83, 1998.
- [34] M. Marwali, M. Haili, S. Shahidehpour and K. Abdul-Rahman, “Short term generation scheduling in photovoltaic-utility grid with battery storage”, *IEEE Transactions on Power Systems*, vol. 13, no. 3, pp. 1057-1062, 1998.
- [35] [online]. available: [www.nooutage.com/pdf/swwp_ air403_ landman.pdf](http://www.nooutage.com/pdf/swwp_air403_landman.pdf). Technical report.
- [36] M. Pipattanasomporn, “A Study of Remote Area Internet Access with Embedded Power Generation.” *PhD thesis, Faculty of the Virginia Polytechnic Institute and State University, Alexandria, Virginia*, December 2004.
- [37] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, and G. Strbac “Embedded Generation.” *The Institution of Electrical Engineers*, UK, 2000.
- [38] F. Farret and M. Simoes, “Integration of alternative sources of energy,” [Piscataway]: *IEEE Press*, 2006.
- [39] M. Patel, “Wind and solar power systems,” Boca Raton: CRC Press, 1999.
- [40] B. Lindgren, “A Power Converter for Photovoltaic Applications.” PhD thesis, Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 2000.
- [41] E. Gavanidous and A. Bakirtzis, “Design of a stand alone system with renewable energy sources using trade off methods”, *IEEE Trans. On energy Conversion*, vol. 7, no. 1, pp. 42-48, 1992.
- [42] F. Lasnier and T. Gan Ang, “Photovoltaic engineering handbook,” Bristol, England: A. Hilger, 1990.
- [43] A. Azmy and I. Erlich, “Online Optimal Management of PEM Fuel Cells Using Neural Networks”, *IEEE Trans. Power Delivery*, vol. 20, no. 2, pp. 1051-1058, 2005.
- [44] C. Deckmyn, T. Vandoorn, M. Moradzadeh and L. Vandeveldel, “Multi-objective optimization for environomic scheduling in microgrids,” *IEEE PES General Meeting / Conference & Exposition*, 2014.

- [45] "Emission rates for new dg technologies," Tech. Rep., www.raponline.org/docs/RAPDGEmissions200105.pdf.
- [46] P. Civicioglu, "Backtracking Search Optimization Algorithm for numerical optimization problems." *Applied Mathematics and Computation*, vol. 219, no. 15, pp. 8121-8144, 2013.
- [47] J. Nanda, D. Kothari and K. Lingamurthy, "Economic-emission load dispatch through goal programming techniques", *IEEE Trans. On energy Conversion*, vol. 3, no. 1, pp. 26-32, 1988
- [48] J. Nanda, "Economic emission load dispatch with line flow constraints using a classical technique", *IEE Proceedings - Generation, Transmission and Distribution*, vol. 141, no. 1, p. 1, 1994.
- [49] J. Andersson, "A survey of multiobjective optimization in engineering design," Department of Mechanical Engineering, Linköping University, Sweden.
- [50] C. Hernandez-Aramburo, T. Green and N. Mugniot, "Fuel Consumption Minimization of a Microgrid", *IEEE Transactions on Industry Applications*, vol. 41, no. 3, pp. 673-681, 2005.
- [51] M. Elmusrati, R. Jantti and H. Koivo, "Multiobjective Distributed Power Control Algorithm for CDMA Wireless Communication Systems", *IEEE Transactions on Vehicular Technology*, vol. 56, no. 2, pp. 779-788, 2007.
- [52] F. Mohamed, H. Koivo, "System modelling and online optimal management of microgrid with battery storage," International conference on renewable energies and power quality (ICREPQ'07), 26–28 March 2007, Sevilla, Spain.
- [53] W. Zhang and Y. Liu, "Multi-objective reactive power and voltage control based on fuzzy optimization strategy and fuzzy adaptive particle swarm", *International Journal of Electrical Power & Energy Systems*, vol. 30, no. 9, pp. 525-532, 2008.
- [54] A. Barin, L. Pozzatti, L. Canha, R. Machado, A. Abaide and G. Arend, "Multi-objective analysis of impacts of distributed generation placement on the operational characteristics of networks for distribution system planning", *International Journal of Electrical Power & Energy Systems*, vol. 32, no. 10, pp. 1157-1164, 2010.
- [55] F. Mohamed and H. Koivo, "System modelling and online optimal management of MicroGrid using Mesh Adaptive Direct Search", *International Journal of Electrical Power & Energy Systems*, vol. 32, no. 5, pp. 398-407, 2010.

- [56] F. Mohamed and H. Koivo, "Multiobjective optimization using Mesh Adaptive Direct Search for power dispatch problem of microgrid", *International Journal of Electrical Power & Energy Systems*, vol. 42, no. 1, pp. 728-735, 2012.

APPENDIX-I

1. Wind turbine data

Output power coefficients of wind turbine.

S.No.	a	b	C
1	3.4	-12	9.2

Wind speed and rated power.

S.No	Cut in wind speed (m/s)	Cut out wind speed (m/s)	Rated speed (m/s)	Rated power of wind turbine (W)
1	3.5	18	17.5	130

Actual wind speed for 24 hours.

Hour	Actual wind speed (m/s)	Hour	Actual wind speed (m/s)
1	10.7	13	11.6
2	10.62	14	11.9
3	11.3	15	11.5
4	10.9	16	11.3
5	11.5	17	11.5
6	11.6	18	11.7
7	10.65	19	12.1
8	10.90	20	11.7
9	10.1	21	11.5
10	10.4	22	11.3
11	10.7	23	11.3
12	11.6	24	11.3

2. Photovoltaic cell data

S.No	Maximum module power (W)	Irradiance at standard test conditions (m/s^2)	Cell temperature ($^{\circ}C$)	Temperature coefficient
1	83	1000	25	0.0038

Input irradiance and reference temperature

Hour	Input irradiance (m/s^2)	Reference temperature ($^{\circ}C$)	Hour	Input irradiance (m/s^2)	Reference temperature ($^{\circ}C$)
1	0	15	13	820	20
2	0	15	14	850	21
3	0	14	15	690	21
4	0	13	16	600	21
5	100	14.5	17	250	21
6	210	14.9	18	210	21
7	250	15	19	160	20
8	470	17	20	80	19
9	640	17	21	50	18
10	690	17.5	22	0	17
11	810	18	23	0	16
12	850	19	24	0	15.5

3. Load demand

Hour	Load demand (kW)	Hour	Load demand (kW)
1	4	13	7
2	4	14	7.3
3	4	15	7.9
4	4	16	6
5	4.2	17	9
6	5	18	11
7	7.8	19	12.9

8	8	20	14
9	8	21	11.3
10	6.2	22	11.1
11	6	23	8
12	6.5	24	6

4. Maximum and minimum limits of DG, MT and FC.

	Minimum limit (kW)	Maximum limit (kW)
Diesel generator	0	7
Microturbine	0	4
Fuel cell	0	4

5. Startup cost for DG, MT and FC.

	Start up cost (\$)
Diesel generator	0.40
Microturbine	0.16
Fuel cell	0.12

6. Operating and management cost coefficient of DG, MT and FC

	Operating and management cost coefficient (\$/kWh)
Diesel generator	0.01258
Microturbine	0.00419
Fuel cell	0.00587

7. Cost coefficient of diesel generator

S.No	D	E	f
1	0.4333	0.2333	0.0074

8. Purchased tariff = 0.12 \$/kWh

9. Sold tariff = 0.07 \$/kWh