

Economic Load Dispatch Using Firefly Algorithm

A Dissertation

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In

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CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled, "*Economic Load Dispatch Using Firefly Algorithm*", in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems* submitted in Electrical And Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of *Mr. Souvik Ganguli* and refers other researcher's work which are duly listed in the reference section.

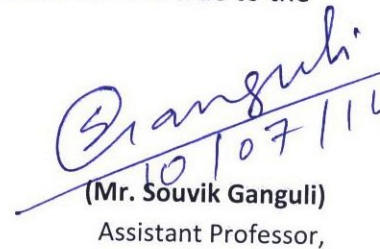
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ABSTRACT

In this work, we have applied the Firefly Algorithm (FA) for some non-linear benchmark functions to highlight the efficiency of algorithm. Generalized Economic Load Dispatch (ELD) problem is discussed and implemented with firefly algorithm optimization technique. Then, we have included the renewable sources in ELD problem, by estimating wind and solar power generation through probability density function including the overestimation cost and underestimation cost of wind and solar units. In this problem we have assumed that the renewable source units are located near the load, hence we are neglecting the transmission losses by renewable sources and considering them only for the thermal units. The problem is implemented on the four test cases with and without inclusion of renewable sources along with different combinations of renewable sources and validated them with experimental approach.

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Today, as an engineer it is always in concern to obtain a product at a minimum cost by reducing either the product operating cost or by reducing the raw or input cost to the production unit. Economic Load Dispatch (ELD) has a common meaning – the practice of operating a coordinated power system such that the lowest operating cost generators are used to the greatest extent and the highest operating cost generator are used to the lowest extent. Economic load dispatch problem is a constrained problem, several principles and strategies are already been developed in order to solve these problems, some of which are discussed in the later chapters. ELD has become a important fundamental function in operation and control of the power system. Several deterministic optimization approaches were proposed to solve the ELD problem, including lambda iteration method, gradient method, linear programming, non-linear programming, dynamic programming and quadratic programming. But these methods require enormous efforts in terms of computation.

Due to complexities of computing, therefore developing efficient algorithm to find optimal solution viz. genetic algorithm, particle swarm optimization, evolutionary programming, artificial bee colony optimization, and biogeography based optimization; bacterial foraging and also their variants came into picture. Bio-inspired meta-heuristic algorithms have recently shown the efficiency in dealing with many non linear optimization constrained problems for finding the optimal solution. In the same pipeline, a newly nature based optimization technique Firefly Algorithm (FA) is developed based on the flashing behavior of fireflies. FA, developed by Yang is used to solve constrained engineering problems. Until now many researches have been carried out to find the closest optimum result in determining the power generation of each generator using FA and it was inferred that the FA is more robust and efficient in determining the optimal load scheduling. Also the variants of firefly algorithm viz. modified firefly algorithm, self-adaptive modified algorithm

and hybrid of FA and ant colony optimization technique were applied on the ELD problem to obtain the optimal values of generation by generating units.

Wind power has vast possibility of expansion in India especially in the coastal plains. Winds in India are influenced by strong south-west summer monsoon in months of April to September where as are weakest in north-east winter monsoons. Total 1100 wind monitoring stations are established in India in 33 states/UTs, also it was estimated that 233 sites with annual average wind power density to be greater than 200 Watts/m². In future wind power growth in India is estimated to be around 1, 00,000 MW. Further there is a vast scope of the solar power generation in India due to the high solar irradiance index and also a very high estimated life of a solar power plant. Presently many projects are already in progress employing solar power generation in Rajasthan, Gujarat and other regions of the country. India currently has a grid connected power capacity of around 10,000 MW. After allowing 100% FDI in wind sector and providing Generation Based Incentives (GBI), wind power sector has boosted [1].

Distributed generation with renewable sources of energy has played a significant role in both industry and research of late. It reduces the emissions and provides the wider choice of power generation choices. Multi-energy generating systems are widely used applications for utilizing renewable sources which provides power by combining power outputs from different sources. Today wind and solar sources of power generation are faster growing renewable energy sources which are highly environment friendly. The hybrid system of power generation comprises different power sources including the traditional fossil fuel fired generators, wind energy conversion system and solar power generating system. Both these renewable power sources are weather and geographical conditions dependent. Probabilistic technique can be used to evaluate the variability of wind speed and solar irradiance. Modeling of wind speed and solar irradiance by probability density function provides key parameters which can illustrate the characteristics of wind speed and solar irradiance. The penalties are imposed on the over generation and under generation of power on the generating unit companies which are being included in the operating cost of renewable power generating units. This penalty varies from state to state and country to country depending upon the policies of that state or country. With the inclusion of renewable sources in load

dispatch problem along with conventional fossil fuel fired generating units reduces fuel cost, emission/pollution and transmission losses in the system. The proposed method in this dissertation will also encourage the utilization of renewable sources of energy.

1.2 OBJECTIVE OF WORK

The main objective of the electric utility company is to provide continuous electrical supply to the consumer without interruption. In such process, economic operation of the system and total demand fulfillment must attain such that the total demand must be equally shared among the units. Inclusion of renewable sources in the problem will share load with thermal units to reduce the load of generation on thermal generating units. Further the fuel cost will reduce with reduced transmission losses. The transmission losses by renewable sources are neglected and transmission losses with thermal units are only considered. Major considerations of fulfilling the objective function are

- Loss minimization
- Fuel cost minimization

1.3 AUTHORS CONTRIBUTION

Earlier the load allocation to the generators is performed using conventional methods, which is less efficient and cannot predict the exact load dispatch value of the units which increases the cost of production. Here in this dissertation we will calculate the minimum fuel cost by optimizing the objective function using firefly algorithm (FA). Moreover, we have considered renewable energy sources viz. solar and wind along with thermal units in the economic load dispatch problem so as to reduce the load sharing by thermal units. Probabilistic techniques can be used to evaluate the variability of the wind speed and solar irradiance. Modeling of wind speed and solar irradiance by probability density function provides key parameters which characterize wind speed and solar irradiance. The probability density function is used for the estimation of power output from solar and wind units for exact determination of availability of wind and solar power. The FA optimization technique applied to the objective function has already been reported and it is concluded that the algorithm determines the best optimal solution globally than the conventional techniques.

1.4 ORGANIZATION OF THESIS

The work of the dissertation is depicted in seven chapters. Chapter 1 highlights brief introduction to economic load dispatch and author's contribution to the proposed work.

Chapter 2 discusses the literature survey on the related topic of the problem.

Chapter 3 describes the economic load dispatch problem and also discusses the solution of problem with the different methods. The objective function of the problem is described with the inclusion of renewable sources of energy.

Chapter 4 discusses the basics of firefly algorithm, its structure and its variants. The standard benchmark functions are also discussed along with their results.

Chapter 5 details the results pertaining to economic dispatch utilizing firefly algorithm. The comparison of the result among different methods is also discussed.

Chapter 6 summarizes the dissertation work and also discussing scope of future work of economic load dispatch problem with firefly algorithm.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews economic load dispatch problem, including economic emission and economic power dispatch using firefly, modified firefly and hybrid firefly algorithm. The variants like modified firefly algorithm, self adaptive modified firefly algorithm

2.2 LITERATURE REVIEW

Theofanis *et al.* [2], developed firefly algorithm for the application of multi-objective problem of economic load dispatch with emission constraints. Further, the proposed method was applied for several load demand wherein they slightly modified the firefly algorithm in a 700 MW and 500 MW load demands to reduce the difference in the initial solutions. The results clearly showed the efficiency and effectiveness of the firefly algorithm over other stochastic nature inspired algorithms.

Xin she Yang *et al.* [3], proposed a novel approach to determine the optimal solution of economic load dispatch problem utilizing the firefly algorithm taking into account the non linear characteristics of power system viz. valve point loading effect, ramp rate limits and prohibited operating zones considering for three, thirteen and forty generating units. The FA results its robustness and effectiveness to solve complex optimization problem.

Sulaiman *et al.* [4], have proposed a paper on economic load dispatch problem solution by using the meta-heuristic firefly algorithm technique. They used 26 bus systems to show the effectiveness of firefly algorithm. Later on the FA result was compared with the continuous genetic algorithm and lambda iteration method for the cost minimization showing that FA is more robust and consistent.

Amoli *et al.* [5] presented the application of firefly algorithm to solve economic load dispatch with cubical and quadratic equation of fuel cost functions. Also they have compared

the simulation results with genetic algorithm, modified Particle Swarm Optimization (PSO), pattern search, dynamic programming and improved genetic algorithm with multiplier updating techniques. The simulation were carried out on 1400 MW load, and it was concluded that the FA works more efficiently than other mentioned methods in terms of better optimal solution while fulfilling the equality and inequality constraints.

Swarnkar [6] proposed the approach to solve economic load dispatch with reduced power losses using firefly algorithm, The author also introduced the Biogeography-Based Optimization (BBO) algorithm to solve the described problem. The effectiveness and the efficiency of the firefly algorithm was later compared with GA, PSO, Artificial Bee Colony optimization (ABC), BBO and Bacterial Foraging Algorithm (BFA) and other optimization techniques. BBO was found to be more capable for obtaining better quality solutions with higher computational efficiency and stable convergence characteristic.

Latifa et al [7], showed the efficiency and the feasibility of the firefly meet algorithm to resolve economic load dispatch problem with pollutant emission reduction. The proposed method was tested on IEEE 14 bus test system and on two thermal plant units. In one of the test cases the transmission loss and the pollutant emission were neglected, finally the results were compared with the PSO, to demonstrate the efficiency and the robustness of the firefly algorithm with lesser average CPU time.

Reddy et al. [8] proposed a novel method of economic load dispatch using the firefly algorithm which was then applied to various test systems and result were compared with the lambda iteration method. The 3 and 6 unit test system were used for testing and the results revealed that the firefly algorithm gave more reliable optimal solution than the lambda iteration method.

Rao et al. [9] proposed a comparative study of the Big Bang- Big Crunch (BB-BC) and firefly algorithm for solving the economic load dispatch problem. To test the effectiveness and quality if optimization method simulations were carried out on the ward hale 6 bus and modified IEEE 30 bus system networks were revealed that the firefly optimization gives optimal, fast and reliable solutions than the BB-BC optimization method.

Abedinia et al. [10] proposed a method to solve multi objective environmental economic dispatch using firefly algorithm technique. The Multi Objective Firefly Algorithm (MOFA) was validated and tested on the IEEE 30 bus and IEEE 118 bus test system and results were compared with other optimization techniques like Non-dominating Sorting Genetic Algorithm (NSGA), Niche Pareto Genetic Algorithm (NPGA) and Strength Pareto Evolutionary Algorithm (SPEA) which revealed that the MOFA gave lower cost with higher efficiency.

In another paper of **Sulaiman et al** [11], economic load dispatch problem was resolved with the Modified Firefly Algorithm (MFA) including practical operation constraints such as ramp rate limit, prohibited operating zones and generating limits. To demonstrate the effectiveness and the feasibility of MFA two well known test systems were evaluated and compared with other recently developed ELD problem solution techniques. Results revealed that the method found more economical solutions than those determined by other techniques.

Taher et al [12], proposed a new fast Self Adaptive Modified Firefly Algorithm (SAMFA) to solve the Reserve Constraint Dynamic Economic Dispatch (RCDED) where the self adaptive tuning parameter tuning and mutation strategy were utilized. In order to evaluate the proposed method, it was implemented and tested on four cases: 5, 10 30 and 100 units system and it was found that SAMFA converged towards more better optimal solution with higher computational efficiency and accuracy.

Mimoun Younes et al. [13] proposed an approach to solve the economic load dispatch including renewable energy using firefly algorithm. Solar and wind power were included as the sources of renewable energy, They had considered the emission constraints to reduce the emission pollution. The proposed method was tested on a 10 unit system and The inclusion of renewable power to the system reduces the generator fuel cost as well as the emission of pollutants in the environment.

Palaniyappan et al. [14] proposed a computational approach to solve economic load dispatch with reduction of CO₂ emission in thermal plant using firefly algorithm. It was concluded from the simulation of the six generating system that the proposed method reduce

the global warming by minimization of fuel consumption. Higher accuracy and lesser computational time of the method described its superiority to the existing Meta heuristic algorithms.

Subramanian *et al.* [15] proposed an efficient and reliable firefly algorithm to solve economic load dispatch problem. The proposed method was applied on six generating system and the results were compared with the other population based techniques like simulated annealing, genetic algorithm, differential evolution, particle swarm optimization, artificial bee colony optimization and biogeography- based optimization techniques. This method showed its higher quality of solutions with better computational efficiency and stable convergence characteristics.

Rama *et al.* [16] proposed applications of bacterial foraging and firefly optimization algorithms to solve economic load dispatch including valve point loading. The proposed methods were tested on 3 and 13 generator systems, for load demand of 850 MW, 900 MW and 1800 MW with inclusion and exclusion of valve point loading effect. The results obtained from bacterial foraging optimization algorithm were more dominating than FA in terms of efficiency, accuracy and speed.

Allairani *et al.* [17] proposed a method of solution of firefly algorithm for solution of economic load dispatch with emission constraints in various generation plants. The proposed method was implemented and tested on 3, 6 and 12 generating test systems. The results obtained were compared with the artificial bee colony and particle swarm optimization techniques and it was found that the FA fuel cost was less than the mentioned above algorithms. Moreover the quality of the solutions as well as the convergence rate were found to be higher than that of other techniques and gives promising approach for solving ELD problem.

In another paper of the **Allairani *et al.*** [18], the economic load dispatch with emission constraint in various generation plants were solved using firefly algorithm and compared with a artificial bee colony algorithm and particle swarm optimization. The proposed method was validated on the three generator system, six generator systems with emission constraints and ten generator systems. The results showed that firefly algorithm

proved more efficient, Thereby providing the more accurate solutions and converge more nearer to the global minimum in less search account.

Subramanian *et al* [19], presented the method to solve the economic load dispatch using the modified firefly algorithm for IEEE 3, 6, 13 and 15 generator test case systems. Later the results were compared with the GA, DE, PSO, ABC, BBO and BFO techniques. From the simulation it was found that the MFA gave better results of total cost minimization as compared with the other mentioned algorithms.

Chandrasekaran *et al* [20], proposed a new approach to solve the unit commitment problem using the Binary Real Coded Firefly Algorithm (BRCFF). The proposed BRCFF algorithm was validated on the test system viz. 3, 12, 17, 26, and 38 unit systems. The tanh function and the sigmoid functions were introduced to improve the flipping probability of the binary variables, Thereby increasing the quality of solution and reducing computational time. The proposed method was found more efficient and gave the more promising results as compared to other techniques.

Mimoun Younes [21] proposed a novel hybrid Firefly Algorithm – Ant Colony optimization (FA-ACO) for economic load dispatch approach, where he had clubbed the robustness of ACO with the convergence speed of the FA to create a new hybrid algorithm. The ACO was used for the global search while FA was used for the local search. The method was tested on modified IEEE 30 bus test system. Later the outcomes are compared with the other techniques like PSO, tabu search, improved evolutionary programming, DE, EP and non-linear programming. Case study reported that the proposed method was easy to apply, robust, having fast computational speed and require less number of iterations.

2.3 CONCLUSIONS

From the literature review it is found that not firefly algorithm but also, its variants like modified firefly algorithm, self adaptive modified firefly algorithm and hybrid firefly algorithms have already being applied to economic load dispatch problem efficiently.

In the subsequent chapter we will discuss the Economic load dispatch (ELD) including the generator operating cost, solution with the lambda iteration method, gradient method, and renewable power sources inclusion in economic power dispatching.

CHAPTER 3

ECONOMIC LOAD DISPATCH

3.1 INTRODUCTION

In this chapter we will discuss the basics of the Economic Load Dispatch (ELD) problem and solution methods. Furthermore, we will discuss inclusion of renewable sources in problem and formulate the mathematical expressions for the objective function definition with system constraints. Also, the methods of solving problem with conventional techniques will be discussed.

With large interconnection of power system, the increasing energy crisis and price hikes, it is very essential to reduce the operating cost of the electrical energy. Today the major problem for all a power utilities is just not to satisfy the consumer demand of power but also to do it in the most economic way with minimum cost. Any power system can consist of multiple generator units and stations, each of which has its own characteristic operating parameters. The operating cost of these generating units does not correlate with the output; therefore balancing of the load among generators is the main task to the power utilities with the maximum efficiency.

In a typical power system, several generators are implemented to provide enough total output to satisfy a given total consumer demand. Each of these generating units usually has a unique cost-per-hour characteristic for its output operating range. A station has incremental operating cost for fuel and maintenance; and fixed costs associated with the station itself that can be quite considerable in case of a nuclear power plant. When the transmission losses are considered then it is more complicated for the utilities to account.

The main aim of the power utilities has been identified as to provide smooth electrical energy to the consumers with the assurance of minimum cost of generation. Hence in order to achieve economic operation of system, the total demand must be appropriately shared among the units. This will minimize the total cost of generation for the system with the voltage level maintained at safe operating area.

Economic load dispatch can be defined as the process of distributing generation level to the power generating units in such a fashion such that load demand is fully supplied in the most economic way. The method of economic load dispatching for power generating units at different load demands must have total fuel cost at the minimum point. There are many conventional methods that are in use to solve the economic load dispatch problem such as Lagrange multiplier method, lambda iteration method, gradient search method and Newton's method etc. In conventional techniques, it is difficult to get the optimal solution of the problem, hence it is been required to compute the economic dispatch each time which consumes a lot of time for computation, thus advanced computing techniques for example the natural solving algorithms are becoming popular in solving complicated problems in economic load dispatch.

3.2 GENERALIZED ECONOMIC DISPATCH PROBLEM

The system in the figure 3.1 given below is a multi generator unit system [28] connected to a single bus-bar serving a electrical load of P_{load} . The input shown by F_i represents the cost rate of the i^{th} unit. The total cost of the system will be the sum of the costs of each individual unit. The most essential constraint on the operation of this system is that the sum of output powers must equal the load demand.

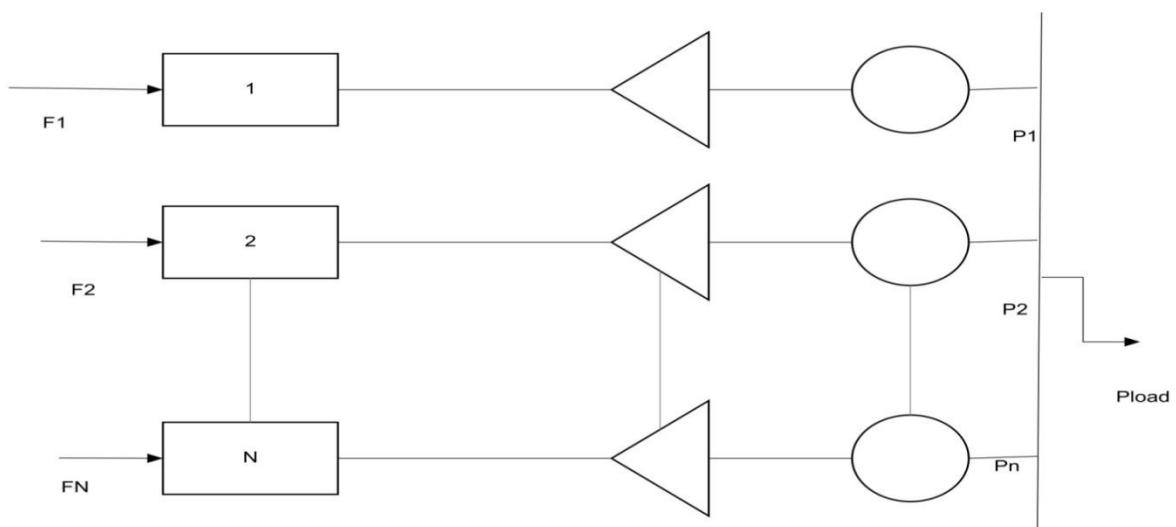


Figure 3.1 Total N thermal units connected to serve load of Pload.

3.2.1 GENERATOR OPERATING COST

The net cost of the generator includes mainly the fuel cost, labor cost and maintenance cost etc. [29]. The power output of fossil fuel plants is increased sequentially by opening of the steam valve to the turbines inlet. The throttling losses are quite large when open just opened and small when fully opened.

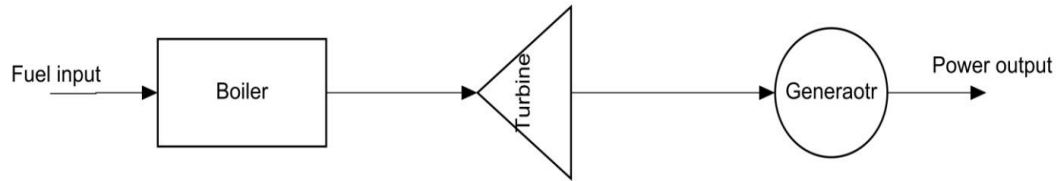


Figure 3.2 Simple model of the thermal power plant.

Figure 3.2 shows the simple model of the thermal power plant. The fuel cost is usually a quadratic function and can be given as:

$$F(P_{gi}) = a_i P_{gi}^2 + b_i P_{gi} + c_i \text{ Rs/Hr} \quad (3.1)$$

where, the a_i , b_i and c_i are the generator cost constant coefficients. This fuel cost increases with the increase in the energy production i.e. electrical output from the generator. This can be seen in the given figure 3.3

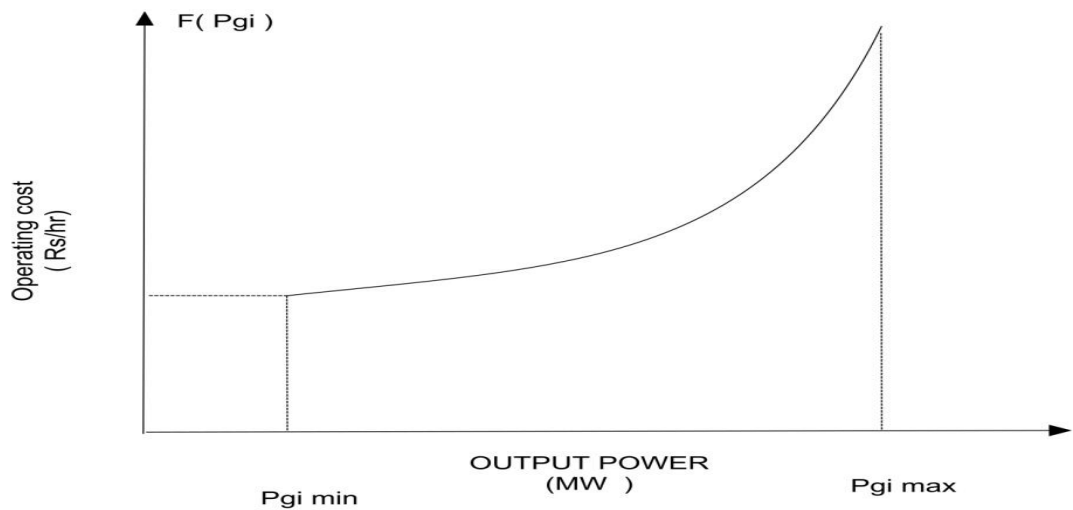


Figure 3.3 operating cost curve of Thermal Power Plant Generator.

The P_{gi}^{min} and P_{gi}^{max} are the minimum and the maximum limits of generation of the generator beyond which generation will be uneconomical (or may be infeasible). .

3.2.2 OBJECTIVE FUNCTION

From equation 3.1 $F_i (P_{gi})$ is the fuel cost of the i^{th} generating unit, expressed in the Rs/hr. the total cost rate of the system is the sum of the cost of the each of the individual units when there are N thermal units.

$$F_T = F_1 + F_2 + \dots + F_N \quad (3.2)$$

The objective function can be also being written as given below, this objective function is to be minimized for the best optimal values of the generation cost of the connected generator units to the network.

$$MIN F_T = \sum_{i=1}^N F_i(P_{gi}) \quad (3.3)$$

3.2.3 SYSTEM CONSTRAINTS

We can broadly classify the constraints into two categories:

1. Equality Constraints
2. Inequality Constraints

Equality constraints: The cost function is not affected by the reactive power demand, so the full attention is given to the real power balance in the system [29]. The power balance equation is thus given by:

$$P_d = \sum_{i=1}^N P_{gi} \quad (3.4)$$

In the above equation the transmission losses are neglected, but if we consider the transmission losses in the ELD problem then the equation 3.4 will get slightly modified as:

$$P_d + P_L = \sum_{i=1}^N P_{gi} \quad (3.5)$$

where, P_L is the transmission losses and P_d is the total load demanded.

Furthermore the transmission loss can be calculated as,

$$P_L = \sum_{i=1}^N \sum_{j=1}^N P_{gi} B_{ij} P_{gj} + \sum_{i=1}^N P_{gi} B_{0i} + B_{00} \quad (3.6)$$

where, the B_{ij} , B_{0i} and B_{00} are the B-coefficients of the Transmission losses.

Inequality constraints: The inequality constraints can be further classified into several ways for economic load dispatch problem.

a) Generator constraints: the KVA loading should not be exceed a pre defined value to avoid temperature rise to higher extents which may cause damage to the generator

- The maximum active power generation can be limited by thermal consideration and minimum power generation is limited by the flame intensity of the boiler. The power output should always be within the limits as shown in the Figure 3.2, due to generation limitations given by,

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad (3.7)$$

- Similarly the reactive power generation is also limited to avoid the overheating and of the rotor and stability loss. Hence ,

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad (3.8)$$

b) Transmission line constraints: the flow of the power through the transmission line is limited by the thermal capability of the circuit. The transmission loss should always be greater than zero.

$$P_L > 0 \quad (3.9)$$

3.3 SOLVING THE ELD PROBLEM WITH CONVENTIONAL METHODS

3.3.1 THE LAMBDA-ITERATION METHOD

In the Lambda iteration method [27], a variable λ (lambda) is introduced to solve the constraints optimization problem also referred as Lagrange multiplier. This method has the advantage of ability to solve problem manually by solving system equations using the iterative method. We can solve this problem by a graphical technique and then expanding into the area of computer algorithms. The basic algorithm for solving the problem with the lambda iteration method can be described with the help of the following steps:

- i. Assume a appropriate value of λ .
- ii. Compute the generation of the each unit individually.
- iii. Compute the transmission losses(P_L).
- iv. Compute $\Delta P = P_D + P_L - \sum_{i=1}^N P_{gi}$
- v. Check if $\Delta P \leq \varepsilon$ & program reached its maximum iteration, if true then GOTO step vii else modify the $\lambda_{new} = \lambda + \alpha \Delta P$, where α is the step size for increment.
- vi. Check again step iv, and increase the iteration and replace the $\lambda = \lambda_{new}$, and GOTO to step ii and repeat.
- vii. Check the generation limits, if violated then fix them else GOTO next step.
- viii. Compute the optimal Fuel cost and transmission loss
- ix. Stop

3.3.2 GRADIENT SEARCH METHOD

The lambda iteration method is sometimes does not give the optimal solution for the large power system problems with the complex cost function. So we can go for the gradient search [29] method to solve economic load dispatch problem. In this method minimum of the function $f(x)$ is been found by a series of steps in the downward direction. The process of solving the ELD problem with gradient method can be described as,

Let we have the objective function as given in the eq. 3.3, and the equality constraints being same as described above in the equation number 3.5.

The Lagrange function will be,

$$l = \sum_{i=1}^N F(P_{gi}) + \lambda(P_{load} - \sum_{i=1}^N P_i) \quad (3.10)$$

and the gradient of the function will be,

$$\nabla l = \begin{bmatrix} \frac{\partial l}{\partial P_1} \\ \frac{\partial l}{\partial P_2} \\ \frac{\partial l}{\partial P_3} \\ \cdot \\ \cdot \\ \frac{\partial l}{\partial \lambda} \end{bmatrix} = \begin{bmatrix} \frac{d}{dP_1} F_1(P_1) - \lambda \\ \frac{d}{dP_2} F_2(P_2) - \lambda \\ \frac{d}{dP_3} F_3(P_3) - \lambda \\ \cdot \\ \cdot \\ P_{load} - \sum_{i=1}^N P_i \end{bmatrix} \quad (3.11)$$

Now the initial value of the λ and P_1 , P_2 and P_3 are required. The gradient is found from the above equation and the new value can be found as,

$$X^1 = X^0 - (\nabla l)\alpha \quad (3.12)$$

Where X is a vector given by,

$$X = \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ \cdot \\ \cdot \\ \cdot \\ \lambda \end{bmatrix} \quad (3.13)$$

The only disadvantage of this approach is that with the new generated points, each step will lie on the surface, but this method requires less no. of iteration than the lambda iteration method.

3.4 ECONOMIC LOAD DISPATCH WITH RENEWABLE SOURCES

3.4.1 INTRODUCTION

The renewable sources of energy present in abundant quantity in nature or environment, as solar energy, wind energy, ocean energy, geothermal energy, biomass, tidal energy etc. These energy sources can be converted into various other form of useful energy, like electrical energy, mechanical energy, thermal energy, chemical energy etc. through various energy conversion systems. Mostly the electrical energy is the major demanded energy, and many researches are going on to extract more electrical energy from these renewable sources [30].

So far, economic load dispatching with the conventional power sources, such as thermal, hydro, diesel and nuclear have been carried out, but due to the increasing demand of the power and also reducing conventional sources of power, we need to rely on the renewable sources of power generation. The commitment of the units along with these renewable sources, like wind, solar, bio-fuel, geothermal, etc., is also an important point of consideration. We widely use wind power generation in the economic load dispatch due to large period availability of the wind and hence power. The wind provides power for the longer period comparing to the other renewable sources. In India the bio-Fuel is included in the research area for the economic load dispatch due to the availability of the cattle dung and agricultural waste as the raw material for the production of the bio-fuel.

Also there is a vast scope of the solar power generation in India due to the high solar irradiance index and also the high estimated life of a solar power plant. Presently many projects are already in progress of solar power generation in Rajasthan, Gujarat and other regions of the country [36]. India currently has a grid connected power capacity of around 10,000 MW

Wind power has vast possibility of expansion in India. Winds in India are influenced by strong south-west summer monsoon in months of April to September where as are weakest in north-east winter monsoons [37]. Total 1100 wind monitoring stations are established in India in 33 states/UTs, also it was estimated that 233 sites with annual average wind power density greater than 200 Watts/m². In future wind power growth in India is estimated to around 1, 00,000 MW.

3.4.2 ECONOMIC LOAD DISPATCH PROBLEM FORMULATION WITH RENEWABLE ENERGY SOURCES

The problem of economic load dispatch with the inclusion of the renewable power sources [23] will reduce the load of generation on the Thermal and other fossil fuel units. Here in the problem description we are considering only the Photo voltaic system (PVS) and wind energy conversion system (WECS) with the thermal units in the economic dispatch problem adding factors of both overestimation and underestimation of the available power of wind and solar. The hybrid system with PVS, WECS and Fossil fired system (FFS) is thus shown in the figure 3.3.

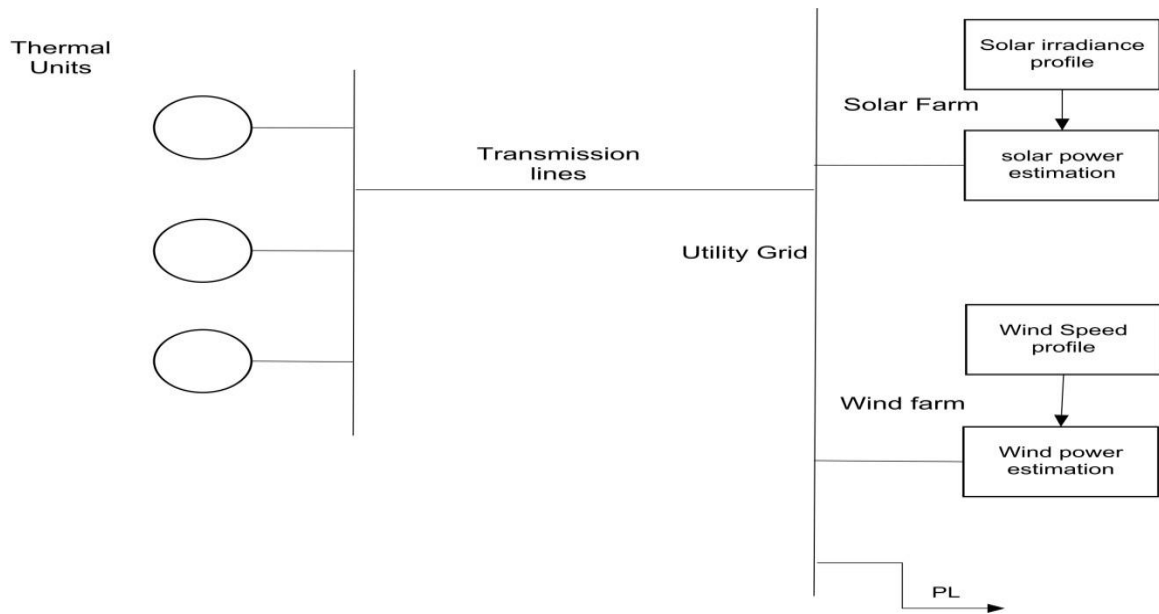


Figure 3.4 hybrid model of the PVS, WECS and FFS

3.4.3 MODELING OF RENEWABLE SOURCES

In the hybrid system [23] [24] that we have considered, both renewable energy systems are highly dependent on weather conditions and geographical locations. Probability based techniques can be utilized to express the variations in speed and solar irradiance distribution, determining thereby the performance and the feasibility of solar and wind

power. The probability density function (*pdf*) is expressed for the estimation of the wind speed via *Weibullpdf*.

3.4.3.1 HOURLY WIND SPEED AND WIND POWER OUTPUT MODELING

The *weibullpdf* [23] [38] is been used for the wind speed estimation, the probability of wind speed being v during any time interval can be stated as:

$$f_v(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad \text{for } 0 < v < \infty \quad (3.14)$$

where $f_v(v)$ is the distribution probability of the wind speed (v), c and k are the scale and the shape parameter respectively. These parameters are calculated by the mean and standard deviation as follows:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \quad (3.15)$$

$$c = \frac{v_m}{\Gamma(1+(1/k))} \quad (3.16)$$

The *weibull* distribution curve of wind varies with the values of k and c parameters. the value of k determines the shape of the curve and hence called as shape parameter. For $k=1$, the weibull distribution is called as exponential distribution and usually used for reliability studies. For $k \geq 3$, it behaves as a normal distribution and also called as Gaussian distribution or bell shaped distribution [38]. Usually the best appropriate values for k are between 1.5 to 2.5. For greater values of c , curve moves towards higher wind speeds. Thus, because of this shifting, it is called as scale parameter. The v_m is the mean wind speed and is the annual average speed, σ is the mode speed which is speed of wind most of time.

Furthermore the *pdf* of wind power can be formulated as:

$$f_{pw}(P_w) = \begin{cases} \left(\frac{k v_i l}{c}\right) \left(\frac{(1+\rho l) v_i}{c}\right)^{k-1} \exp\left(-\left(\frac{(1+\rho l) v_i}{c}\right)^k\right) & ; \text{for } 0 < v < v_r \\ 1 - \exp\left[-\left(\frac{v_r}{c}\right)^k\right] + \exp\left[-\left(\frac{v_0}{c}\right)^k\right] & ; \text{for } v=0 \\ \exp\left[-\left(\frac{v_r}{c}\right)^k\right] - \exp\left[-\left(\frac{v_0}{c}\right)^k\right] & ; \text{for } v=v_r \end{cases} \quad (3.17)$$

Now the wind turbine generated power at different velocities is calculated as:

$$P_w = \begin{cases} 0 & \text{for } v < v_i \text{ and } v > v_0 \\ P_{wt} \left(\frac{v-v_i}{v_r-v_i} \right) & \text{for } v_i \leq v \leq v_r \\ P_{wr} & \text{for } v_r \leq v \leq v_0 \end{cases} \quad (3.18)$$

where the $\rho = v/v_r$ and $l = (v_r - v_i)/v_i$, v_i , v_r , and v_0 are the cut in, rated and the cut out speed for WECS system.

3.4.3.2 HOURLY SOLAR IRRADIANCE AND PV OUTPUT MODELING

The solar radiation that reaches on the earth depends on the geographical location and weather conditions of the area. Moreover the cloudiness factor affects the difference of values measured outside and inside the atmosphere horizon.

Here we are considering the clearness index *pdf* [23] [24] to model the hourly solar irradiance. The hourly clearness index (k_t) can be stated as the ratio of the irradiance on a horizontal plane I_t (kW/m²) to the extraterrestrial total solar irradiance I_0 (kW/m²). And can be calculated

$$k_t = \frac{I_t}{I_0} \quad (3.19)$$

$$f_{kt}(k_t) = c \left(1 - \left(\frac{k_t}{k_{tu}} \right) \right) \exp(\lambda k_t) \quad (3.20)$$

Where λ and c are the mean value of clearness index and maximum value of clearness index, and were calculated as,

$$c = \lambda^2 k_{tu} / (\exp(\lambda k_{tu}) - 1 - \lambda k_{tu}) \quad (3.21)$$

$$\lambda = ((2\gamma - 17.519) \exp(1.3118\gamma) - 1062 \exp(-5.0426\gamma)) / ((k_{tu})) \quad (3.22)$$

$$\gamma = \frac{k_{tu}}{k_{tu} - k_{tm}} \quad (3.23)$$

Now when the λ is determined corresponding value of c can be calculated from eq. 3.8. After this the solar irradiance can be calculated as ,

$$I_\beta = [Tk_t - T'k_t^2] \quad (3.24)$$

where T and T' depends on inclination angle , ground reflectance, latitude, hour angle, sunset hour angle.

$$T = \left[\left(R_b + \rho \frac{1 - \cos\beta}{2} \right) + \left(\frac{1 + \cos\beta}{2} - R_b \right) p \right] I_0$$

$$T' = \left(\frac{1 + \cos\beta}{2} - R_b \right) q I_0 \quad (3.25)$$

where β is the inclination angel, R_b is the ratio of the beam radiation on a tilted surface to the horizontal surface, ρ is the reflectance of the ground and p and q are the constants.

$$k = p - qk_t \quad (3.26)$$

Now from the above equation 3.26, sign of the T and T' will decide the probability density function for solar power [23] that has four different expressions but only two of them have the physical significance given as follows:

if $T > 0$ and $T' < 0$;

$$f_{pv}(P_{pv}) = \begin{cases} \frac{c(k_{tu} - 0.5(\alpha + \alpha'))}{k_{tu} A_c \eta T' \alpha'} \exp\left(\frac{\lambda(\alpha + \alpha')}{2}\right) & \text{if } P_{pv} \in [0, P_{pv}(k_{tu})] \\ 0; & \text{otherwise} \end{cases} \quad (3.27)$$

if $T > 0$ and $T' > 0$ then ,

$$f_{pv}(P_{pv}) = \begin{cases} \frac{c(k_{tu}-0.5(\alpha-\alpha'))}{k_{tu}A_c\eta T'\alpha'} \exp\left(\frac{\lambda(\alpha-\alpha')}{2}\right) & \text{if } P_{pv} \in [0, P_{pv}(k_{tu})] \\ 0; & \text{otherwise} \end{cases} \quad (3.28)$$

where, the α and α' are given by,

$$\alpha = \frac{T}{T'} \quad \alpha' = -\sqrt{\alpha^2 - \frac{4P_{pv}}{\eta T' A_c}} \quad (3.29)$$

3.4.4 ECONOMIC DISPATCH MODEL FOR RENEWABLE ENERGY SOURCES

The economic load dispatch problem is an important aspect in deciding the allocation of the generation to the generating units. Now the problem of ELD with the inclusion of the renewable sources [23] will be discussed, the probability density functions for both wind and solar has already been discussed in the previous section and we will now use that in this section for the cost function estimation. Here we also assume that the wind and the solar farms are near to the load center, so neglecting the transmission losses by the power generated from renewable sources, hence only the transmission losses due to thermal units is considered. The cost function includes the operating cost of the thermal units, wind and PV plants and penalty for cost due to imbalance between the actual and the scheduled power outputs of the wind and PV plants. The weighted cost method is considered in the formulation.

The objective function of the new ELD problem [23] with the renewable sources can be described as,

$$\text{minimize } F_t = \sum_{i=1}^N OC(P_{gi}) + \sum_{j=1}^M OC(P_{wj}) + \sum_{k=1}^S OC(P_{pvk}) \quad (3.30)$$

Subjected to,

$$P_D + P_L - \sum_{i=1}^N P_{gi} - \sum_{j=1}^M P_{wj} - \sum_{k=1}^S P_{pvk} = 0 \quad (3.31 \text{ a})$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad (3.31 \text{ b})$$

$$0 \leq P_{wj} \leq P_{wrj}^{max} \quad (3.31 \text{ c})$$

$$0 \leq P_{pvk} \leq P_{pvrk}^{max} \quad (3.31 \text{ d})$$

The first term of the eq. 3.30 is the operating cost of the thermal units $OC(P_{gi})$, second term is the operating cost of the wind farms $OC(P_{wj})$ and the last term is the operating cost of the PV system $OC(P_{pvk})$. Also, P_{gi}^{min} and P_{gi}^{max} are the minimum and maximum limits of the i^{th} thermal generator units, P_{wj} and P_{wrj} are the scheduled and rated power generation of the j^{th} wind farms, similarly P_{pvk} and P_{pvrk} are the scheduled and the rated power generation of the k^{th} solar system.

Furthermore the operating cost of the thermal units can be expressed as the quadratic function and will be same as eq. 3.1, but the operating cost of the wind and solar farms will be quite different with that of thermal unit.

The operating cost of the wind farm is the sum of the three components: first part is the weighted cost function based on the speed of the wind, second part is the penalty cost for not using the available power of wind and the third part is the penalty cost on the reserves which is due to that the actual wind power is less than scheduled wind power. The combination of the operating costs can be described as,

$$\sum OC(P_{wj}) = \sum_{j=1}^M C_{wj}(P_{wj}) + \sum_{j=1}^M C_{p,wj}(P_{wj,av} - P_{wj}) + \sum_{j=1}^M C_{r,wj}(P_{wj} - P_{wj,av}) \quad (3.32)$$

where,

$$C_{wj}(P_{wj}) = c_{wj} f_{pw}(P_w) P_{wj} \quad (3.33)$$

$$C_{p,wj} (P_{wj,av} - P_{wj}) = k_{p,wj} (P_{wj,av} - P_{wj}) \quad (3.34)$$

$$C_{r,wj} (P_{wj} - P_{wj,av}) = k_{r,wj} (P_{wj} - P_{wj,av}) \quad (3.35)$$

C_{wj} is the direct cost coefficient for the j^{th} wind unit, $f_{pw}(P_w)$ is the *pdf* of the wind from the eq. 3.17, $k_{p,wj}$ and $k_{r,wj}$ are the penalty cost coefficients of underestimation and reserve cost coefficient of overestimation of the available wind power and $P_{wj,av}$ is the available wind power for the j^{th} unit.

Similarly, the operating cost of the solar farm is the sum of the three components: first part is the weighted cost function based on the solar irradiance, second part is the penalty cost for not using all the available PV generated power and the third part is the penalty cost on the reserves which is due to that the actual solar power is less than scheduled PV system generated power. This combination can be described as,

$$\sum OC(P_{pvk}) = \sum_{k=1}^S C_{pvk} (P_{pvk}) + \sum_{k=1}^S C_{p,pvk} (P_{pvk,av} - P_{pvk}) + \sum_{k=1}^S C_{r,pvk} (P_{pvk} - P_{pvk,av}) \quad (3.36)$$

where,

$$C_{pvk} (P_{pvk}) = c_{pvk} f_{pvk} (P_{pv}) P_{pvk} \quad (3.37)$$

$$C_{p,pvk} (P_{pvk,av} - P_{pvk}) = k_{p,pvk} (P_{pvk,av} - P_{pvk}) \quad (3.38)$$

$$C_{r,pvk} (P_{pvk} - P_{pvk,av}) = k_{r,pvk} (P_{pvk} - P_{pvk,av}) \quad (3.39)$$

C_{pvk} is the direct cost coefficient for the k^{th} solar unit, $f_{pvk}(P_{pvk})$ is the *pdf* of the wind from the eq. 3.27 and 3.28 depending on the sign of the T and T', $k_{p,pvk}$ and $k_{r,pvk}$ are the penalty cost coefficients of underestimation and reserve cost coefficient of overestimation of the available PV power and $P_{pvk,av}$ is the available PV generated power for the k^{th} unit.

Furthermore, in test cases considered in the later chapter, we have taken the thermal with solar, thermal with wind and thermal with both solar and wind power units. So in that case we will consider only the respective operating cost of the included renewable source, i.e. if we go for the thermal and wind only then our objective function will be the sum of only thermal units and wind farm units operating costs, we will not consider the solar operating cost in the problem.

3.5 ECONOMIC DISPATCHING PROBLEM IN FUTURE

From the past 30 years, many optimization techniques have been developed. Many newly developed optimization techniques were applied to economic load dispatch problem like, evolutionary algorithms, genetic algorithm, particle swarm optimization, direct search algorithm, ant colony optimization, gravitational search algorithm optimization, firefly optimization, harmony search optimization, etc. It is been found that the these algorithms provides more better results comparative to the conventional methods described in the previous section with the higher efficiency and accuracy. The conventional methods are more time consuming due to fact that large number of iterations are required to get the optimal value, but such new techniques reduces the elapsed time to a considerable extent.

3.6 CONCLUSIONS

In this chapter we have discussed the economic load dispatch problem with system constraints, solution of the problem with lambda iteration method and gradient search method including the transmission losses. Also, the inclusion of the renewable sources in the ELD problem is been discussed considering the solar and the wind power of sources, with the probability density function analysis of the wind of the solar and wind. The problem description is defined with the equality and the inequality constraints, the operating cost of the wind and the solar were discussed and implemented in the problem of economic load dispatch.

4.1. INTRODUCTION

The Optimization techniques provide the best possible solution of objective function when all its constraints are satisfied. They can be classified into two main categories: deterministic and stochastic algorithms. Hill climbing approach is a deterministic approach which produces the same set of solutions if the iterations start with the same initial guess. Whereas the stochastic algorithm produces different solutions with same initial starting point, although the results differ slightly.

Deterministic algorithms are basically local search algorithms and are efficient in finding local optimal value [22]. A common practice is to introduce some stochastic component to an algorithm so that it becomes possible to jump out of such locality and find the global optima and in such case the algorithm is called as stochastic.

Stochastic algorithm has two components, deterministic and random component associated with it. The stochastic component can take many forms such as simple randomization by randomly sampling the search space or by random walks. Most stochastic algorithms can be considered as meta heuristic viz. Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Firefly Algorithm (FFA), Harmony Search Algorithm (HAS), etc.

Nowadays bio-inspired algorithms [22] are getting popular in the research field making an efficient way to deal with many optimization problems and non linear optimization constraint problem. Such algorithms are based on the biological natural phenomenon in order to reach at global optimal solution. Such population based nature inspired algorithms works as follows: a population of individual is randomly initialized where each of the individual represents a expected solution to the problem. The quality of each solution is then estimated using a fitness function. Thereafter, a selection procedure is applied in order to form a new population. The searching process is biased towards the better

individuals to increase their chances of being included in the new population. The process is repeated until convergence rules are met.

Firefly Algorithm (FA) [33] is a new nature inspired algorithm developed by Xin-She Yang in the year 2007, based on the flashing behavior of the fireflies. The flashing signifies the signal to attract other fireflies, where the objective function is associated with the flashing light or the light intensity which helps the fireflies to move to brighter and more attractive locations to achieve optimal solution.

4.2 BIOLOGICAL FOUNDATION

The fireflies are the most charismatic species among the insects and their spectacular display have inspired the poets, writers and scientists. Today more than 2000 species exists and the flashings of the fireflies can be seen in the summer sky in the tropical and temperate regions with warm weather and most active in the nights [35]. These fireflies produce the short rhythmic patterns of flashing lights and these patterns of flashes are unique in species to species, and the flashing light is produced by a bioluminescence process. Moreover flashing is produced to attract their partners; the first signalers are flying males who tries to attract the females on ground. In response females also emit flashing lights and move towards the brightest firefly. However the flashing lights obey certain physical rules, the light intensity I decrease with the increase of distance r according to the term $I \propto 1/r^2$ [34]. Also the flashing is produced for communication purpose among each other and also to attract prey, but still the flashing behavior is a topic of discussion among scientists.

4.3 STRUCTURE OF FIREFLY ALGORITHM

The firefly algorithm [33] has three idealized rules or assumptions which are been developed to define the characteristics of fireflies:

- All fireflies are unisex and they move towards the more attractive and brighter one irrespective of their sex.

- The level of attraction of firefly is proportional to brightness which reduces with the increase in the distance between two fireflies since air absorbs the light.

If there is no brighter or more attractive firefly than a particular one, it will then move randomly.

- The brightness or light intensity is determined by the value of the objective function of a given problem and it is proportional to the light intensity for a maximization problem.

4.4 CHARACTERISTICS OF FIREFLY ALGORITHM

The proper designing of the firefly algorithm can be defined on two important issues: the variation of the light intensity and the formulation of the attractiveness.

4.4.1 Attractiveness: In the FA the attractiveness follows a monotonically decreasing function given by

$$\beta(r) = \beta_0 \exp(-\gamma r^m), \text{ with } m \geq 1 \quad (4.1)$$

where, r is the distance between the two fireflies, β_0 is the initial attractiveness at $r = 0$, and γ is the absorption coefficient to control the decrease of the light intensity.

4.4.2 Distance: The distance between any two fireflies i and j at position x_i and x_j respectively is defined by the Cartesian distance as follows:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^d (x_{i,k} - x_{j,k})^2}, \quad (4.2)$$

where $x_{i,k}$ is the k^{th} component of the spatial coordination x_i of the i^{th} firefly and d is the number of dimensions we have, for $d=2$, we have

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (4.3)$$

4.4.3 Movement: The movement of the firefly i which is attracted by the firefly j is given by the following equation:

$$x_i = x_i + \beta_0 * \exp(-\gamma r_{ij}^2) * (x_i - x_j) + \alpha * (rand - 0.5) \quad (4.4)$$

where the first term is the current position of a firefly, the second term defines a firefly's attractiveness to light intensity seen by the adjacent firefly and the third term is for the random movement of a firefly if no brighter firefly is left. The coefficient α is a randomization parameter, and $rand$ is a random number generator uniformly distributed over the space $[0, 1]$. Now when $\gamma \rightarrow 0$ then attractiveness becomes $\beta = \beta_0$ i.e. the attractiveness is constant at every point in space, which is the special case of the particle swarm optimization (PSO). When $\gamma \rightarrow \infty$, the second term gets eliminated from the eq. no. 4.4 and the firefly movement becomes a random walk or random search method, which is the parallel version of the simulated annealing.

4.5 PSEUDO CODE FOR FIREFLY ALGORITHM

Step 1. Define objective function $f(x)$.

Step 2. Input the algorithm parameters- randomness(α), attractiveness(β), light absorption coefficient(γ), random reduction parameter(δ), number of fireflies (n), maximum iterations, and stopping criteria.

Step 3. Generate initial population of fireflies x_i ($i = 1, 2, 3, \dots, n$) randomly generated.

Step 4. Evaluate the light intensity I_i or function value at x_i by value of $f(x_i)$.

Step 5. While ($t \leq$ Max. Generation)

for $i = 1 : n$ % for all fireflies

for $j = 1 : n$ % for all fireflies

If $I_i < I_j$ where $i, j = 1:n$, then move the firefly i towards firefly j using equation 4.4

$$x_i = x_i + \beta_0 * \exp(-\gamma r_{ij}^2) * (x_j - x_i) + \alpha * (rand - 0.5)$$

Attractiveness varies with distance r_{ij} via $\exp(-\gamma r_{ij})$.

Generate and evaluate the new solutions and update light intensity.

End for j loop

End for i loop

check the ranges of the given solutions and update them as appropriate

Rank the fireflies find and display the current best

End of while loop

Step 6. Post process results and visualization

Step 7. Find the firefly with the highest light Intensity among all fireflies

Step 8. Plot the increase of Light intensity with time / iterations.

Step 9. Plot the objective with respect to time. % best solution with time.

Step 10.End of Algorithm.

By following these steps in MATLAB or in any of the programming tool, firefly algorithm can be implemented based on defined objective function. The stopping criterion of algorithm is usually the constraints limits subjected to objective function. In this problem of ELD, generation limits of generator are the stopping criterion of algorithm. FA has the main advantage of ease of implementation.

4.6 FLOW CHART OF FIREFLY ALGORITHM

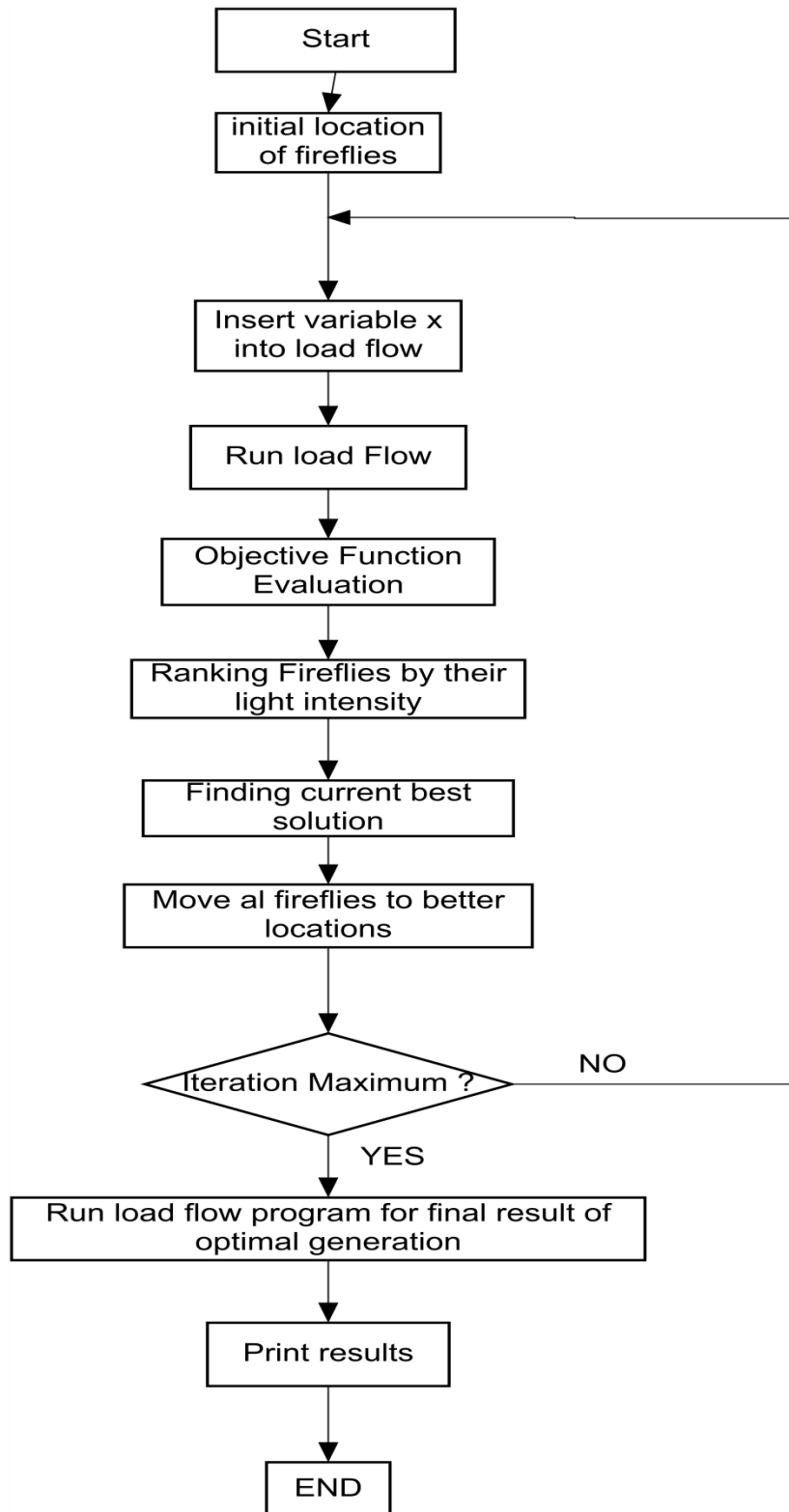


Figure 4.1 Flow chart for the FFA

4.7 VARIANTS OF FIREFLY ALGORITHM

Several variants of firefly algorithm [33][34] have so far been developed. The classification of the variants is done to distinguish the firefly algorithms according to the setting of their control parameter. Usually there are two ways to seek parameters of algorithm properly, one way is tuning the parameters and the other is to modify them while runs. The classical firefly is divided into modified and hybrid. Several papers are available on the modified and hybrid forms of the firefly algorithm with ant colony optimization and several others. The modified firefly algorithm can be done in the direction of development of the elitist, binary, Gaussian, Levi flights, chaos, and parallel firefly algorithms. The binary firefly algorithm has emerged for solving the different set of problems with constraints, like economic load dispatch problem. The taxonomy of firefly algorithm variants is shown in figure 4.2.

The improvement in the solutions can be made by reducing the randomness by,

$$\alpha = \alpha_{\infty} + (\alpha_0 - \alpha_{\infty})e^{-t} \quad (4.5)$$

where, $t \in [0, t_{max}]$ is the pseudo time for simulation and t_{max} is the maximum number of generations. α_{∞} and α_0 are the final and initial values of the randomness parameter. We can also use the similar function to the geometrical annealing schedule. That is

$$\alpha = \alpha_0 \theta^t \quad (4.6)$$

where, $\theta \in [0,1]$ is the randomness reduction constant.

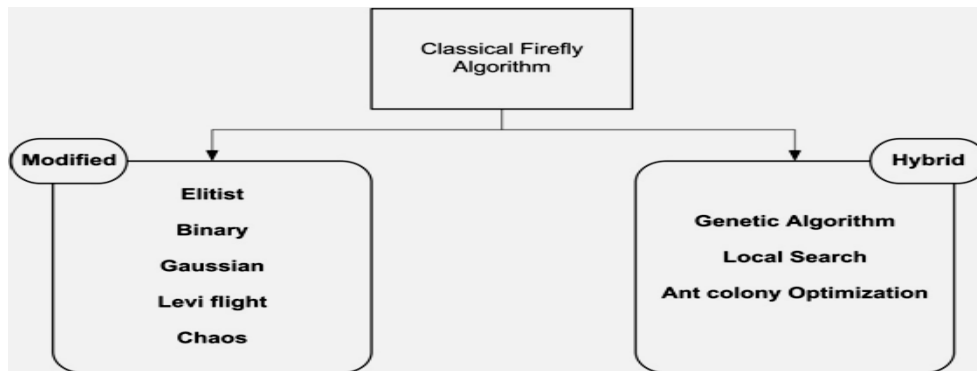


Figure 4.2 Taxonomy of Firefly Algorithm variants

4.8 ADVANTAGES OF FIREFLY ALGORITHM

The reasons behind making firefly algorithm [34] so popular and successful are depicted below:

- FA automatically divides its population into subgroups, because of the fact that local attraction is stronger than long distance attraction.
- FA does not use historical individual best and explicit global best. This reduces the potential drawbacks of premature convergence. Also it does not use the velocities hence problems associated with velocities in PSO is automatically eliminated.
- FA has an ability to its mobility and possibility to control the parameter such as γ .

Hence it can be clearly seen that the firefly algorithm is more efficient in respects of controlling parameters, local search ability, robustness and elimination of premature convergence.

4.9 APPLICATION AREAS OF FIREFLY ALGORITHM

Today, Firefly Algorithm and its variants have been applied to solve many optimization and several engineering problems and practices [33]. The taxonomy of the FFA has been shown in figure (4.3). In addition to this, it has been used in the machine learning, data mining, neural networks, data clustering, economic load dispatch, scheduling and traveling salesman problem, chemical phase equilibrium, nonlinear engineering optimization problems and constrained optimization problem. In Real time applications, firefly algorithm often converge quickly, however there is no useful to use theories of dynamical system. there are a few important open problems concerning all meta-heuristic algorithms. Finally the firefly algorithm is used in almost all branches of engineering. In this context, we can focus on the following engineering areas: image processing, wireless sensor networks, industrial optimization, antenna design, business optimization, robotics and civil engineering.

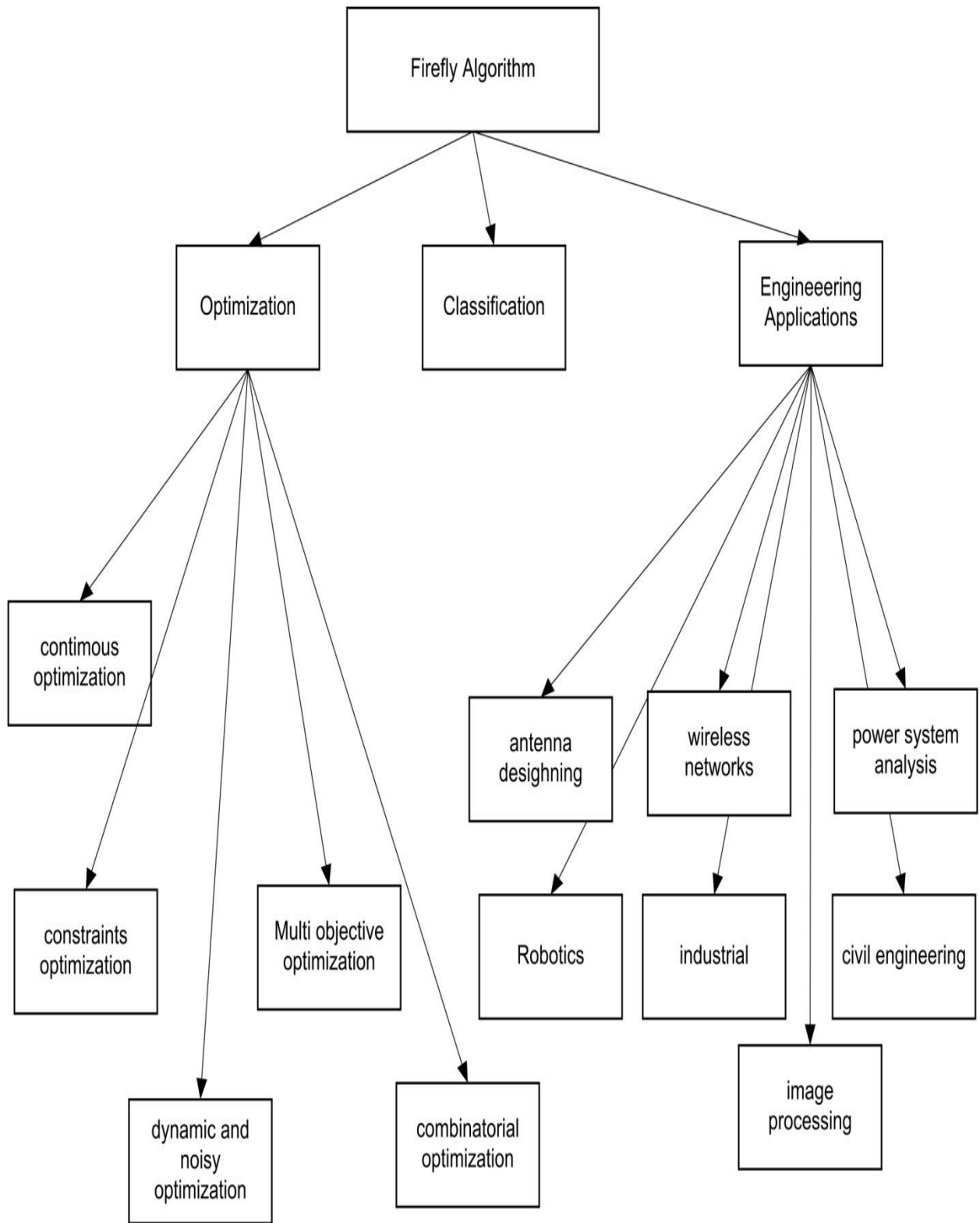


Figure 4.3 Taxonomy of the Firefly Algorithm Application

4.10 VALIDATION OF ORIGINAL FIREFLY ALGORITHM

Firefly Algorithm has been tested on several standard benchmark test functions for its validation [33] viz. sphere function, Greiwank's function, Rotated Hyper Eelipsoid fuction, Ackley function.

4.10.1 Sphere function

This function is also know as De jong's function and is one of the simplest benchmark functions. The three dimensional plot for the function and function values per iteration are shown in figure 4.4 and 4.5 respectively. This function is unimodal, continuos and convex. It can be defined as:

$$f(x) = \sum_{i=1}^N x_i^2$$

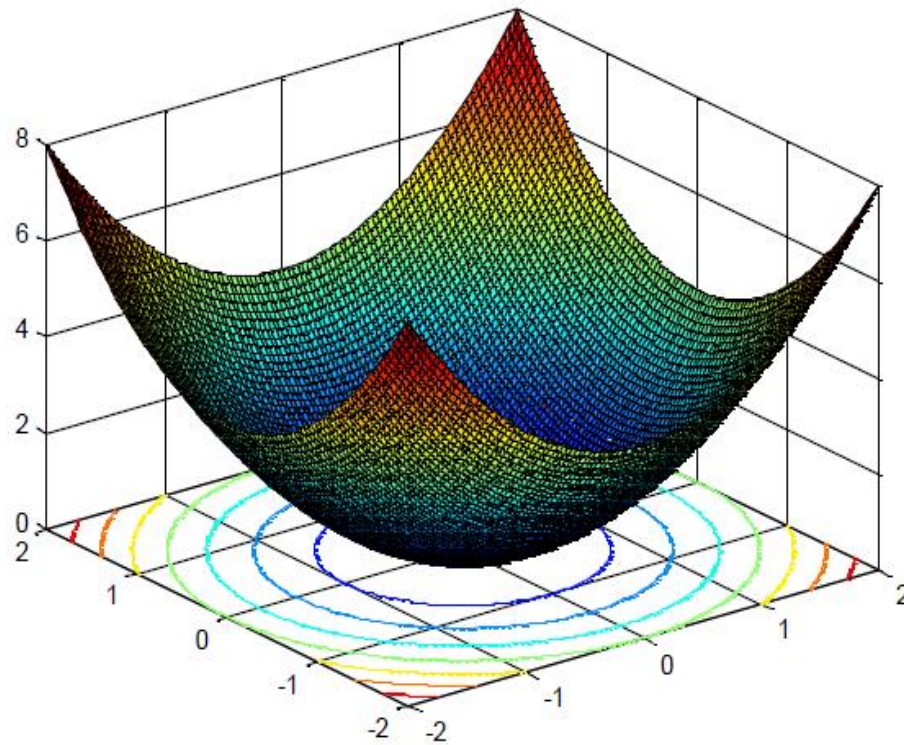


Figure 4.4 Three dimensional plot for Sphere function

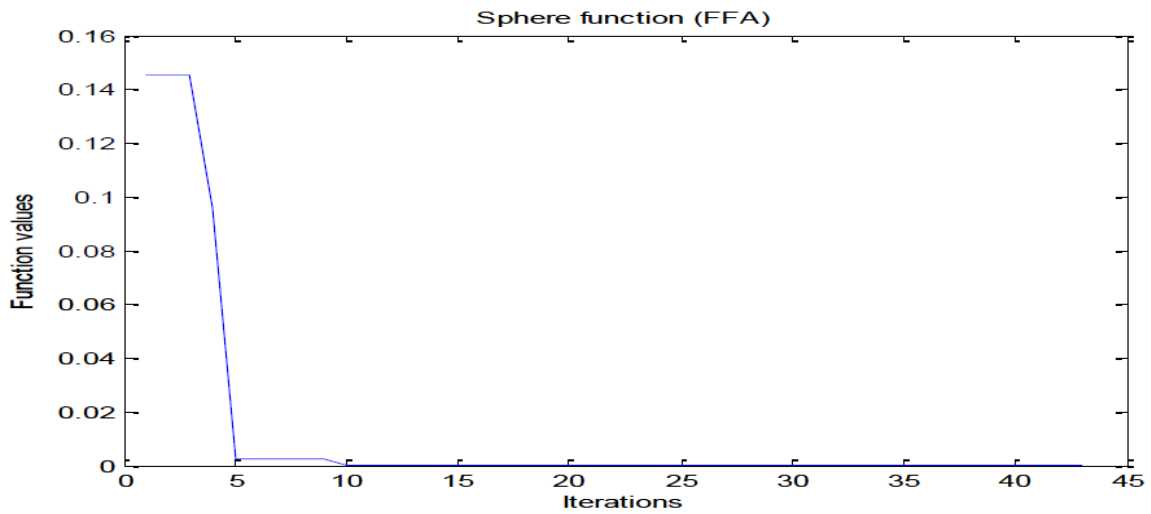


Figure 4.5 Variation of function values for sphere function per iteration.

4.9.2 Greiwank's function

This function has many regularly distributed widespread local minima. The three dimensional plot for the function and function values per iteration are shown in figure 4.6 and 4.7 respectively. The function is defined as,

$$f(x) = \frac{1}{4000} \sum_{i=1}^N x_i^2 - \prod_{i=1}^N \cos\left(\frac{x_i}{\sqrt{i}}\right) + 1$$

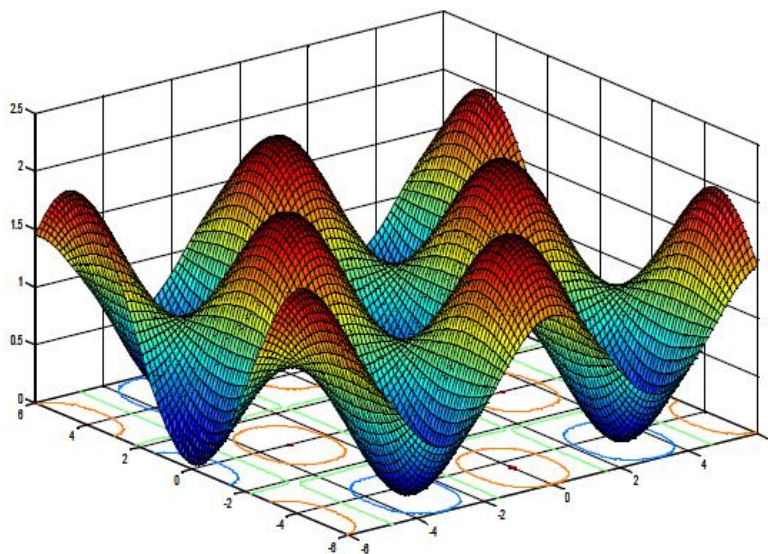


Figure 4.6 Three dimensional plot for Greiwank's function

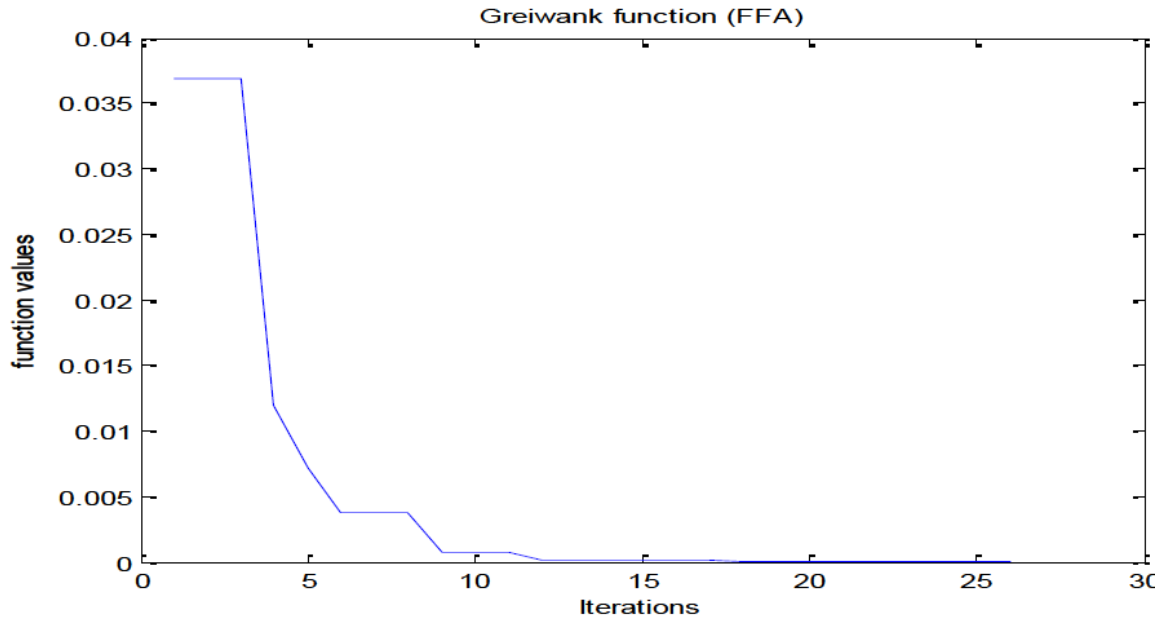


Figure 4.7 Variation of Greiwank's function values per iteration

4.10.3 Rotated Hyper Ellipsoid function

This function gives the rotated hyper- ellipsoids, as the function is continuous, convex and unimodal in nature. The three dimensional plot for the function and function values per iteration are shown in figure 4.8 and 4.9 respectively The function has the following definition:

$$f(x) = \sum_{i=1}^N (\sum_{j=1}^i x_j)^2$$

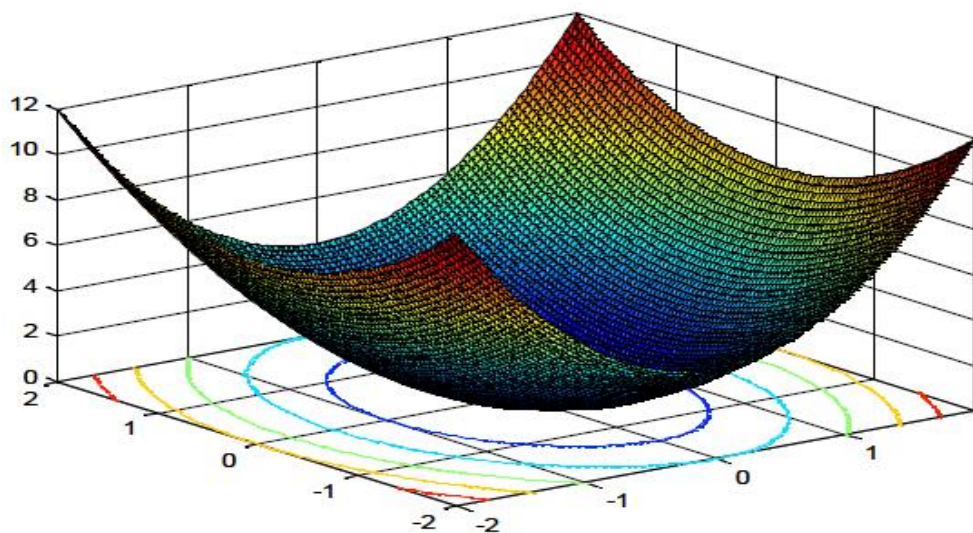


Figure 4.8 Three dimensional plot of Rotated Hyper Ellipsoid function

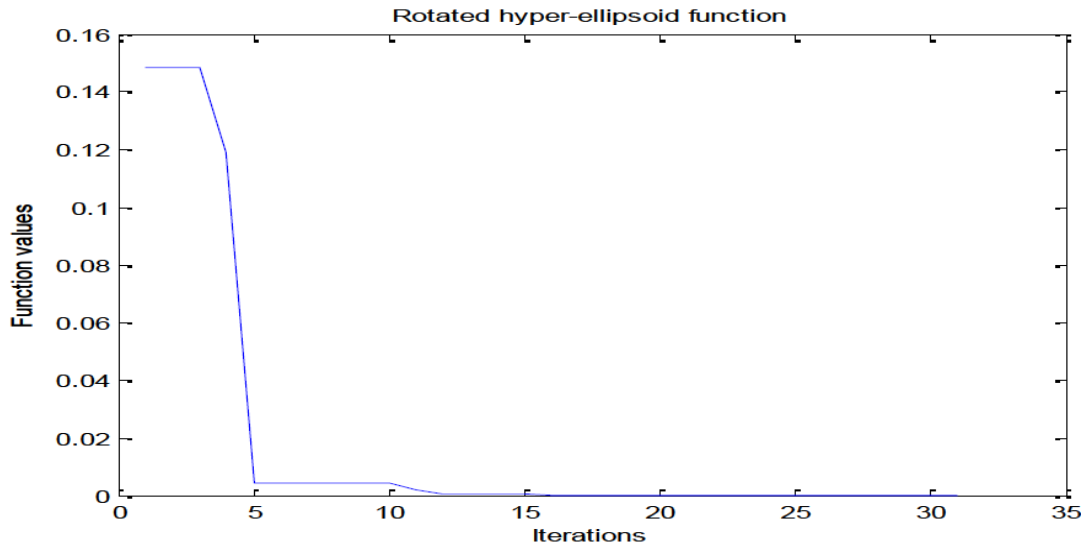


Figure 4.9 Variation of Rotated Hyper Ellipsoid function values per iteration

4.10.4 Ackley function

This function is widely used and is most difficult function to optimize. The three dimensional plot for the function and function values per iteration are shown in figure 4.10 and 4.11 respectively The function can be stated as:

$$f(x, y) = -20 \exp\left(-0.2 \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2}\right) - \exp\left(\sqrt{\frac{1}{N} \sum_{i=1}^N \cos(2\pi x_i)}\right) + 20 + \exp(1)$$

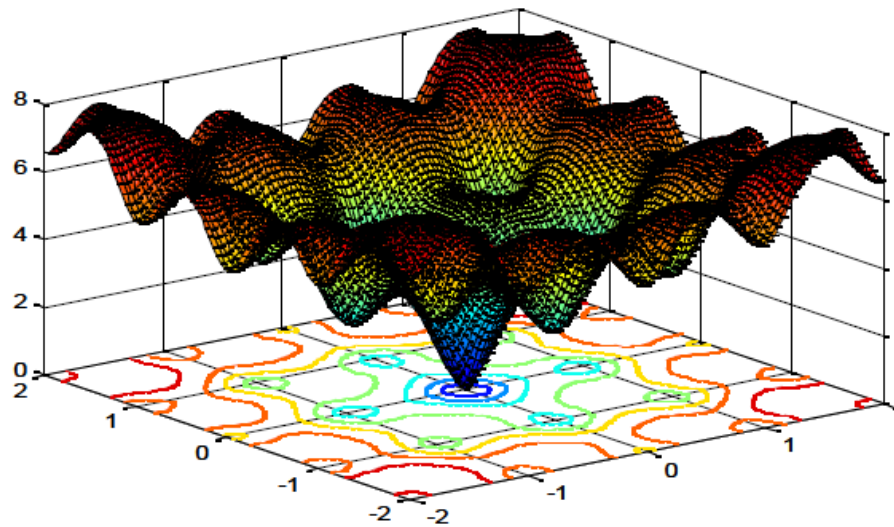


Figure 4.10 Three dimensional plot of Ackley Function

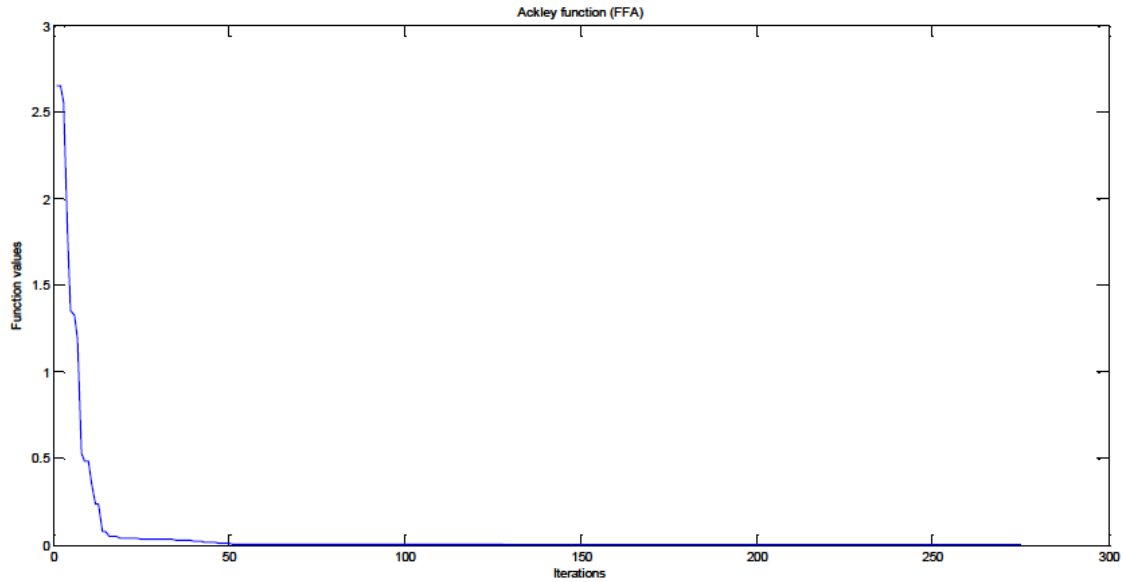


Figure 4.11 Variation of Ackley function values per iteration

4.11 CONCLUSIONS

In this chapter we have studied the firefly algorithm and its variants. The original algorithm is applied to various benchmark functions viz. Sphere, Greiwank, Roatated Hyper Ellipsoid and Ackley functions. Thus we conclude that the algorithm provides the best optimal value of the given test function in lesser number of iterations and execution time. In the forthcoming chapter, economic load dispatch problem is handled using standard firefly algorithm.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

The different techniques of economic load dispatch discussed in the previous chapters will now be applied to the problems using renewable energy sources. In this chapter we are going to discuss problem described in the previous chapter on four test cases, with and without the inclusion of the renewable sources of power in consideration. Moreover we will discuss the results and compare them with respect to fuel cost, transmission loss and elapsed time. The four test cases taken up in this chapter includes-

- i. Economic Load Dispatch with 3 thermal units system.
- ii. Economic Load Dispatch with 3 thermal units and 2 WECS systems.
- iii. Economic Load Dispatch with 3 thermal units and 2 PV systems.
- iv. Economic Load Dispatch with 3 thermal units and 1 PV and 1 WECS system.

In all three test cases we are calculating only fuel cost of the thermal units, since the fuel cost of the renewable energy sources is zero and operating cost is only considered for the renewable farms. Further, the renewable sources are considered to be located near the load center, so that the transmission loss are due to power transfer from thermal units to the load center is considered.

5.2 CASE STUDY-1: THREE THERMAL UNITS SYSTEM

The three thermal generating units considered are having different characteristics [39]. Their characteristic cost function is given below by following equations,

$$F1 = 0.00816 P_{g1}^2 + 7.02P_{g1} + 200 \quad Rs/hr$$

$$F2 = 0.00900P_{g2}^2 + 6.35P_{g2} + 180 \quad Rs/hr$$

$$F3 = 0.00782 P_{g3}^2 + 6.97P_{g3} + 140 \quad Rs/hr$$

Only active power constraints are considered among the inequality constraints. The operating limits of the generator are different for each unit which is enlisted below:

$$10 \text{ MW} \leq P_1 \leq 85 \text{ MW}$$

$$10 \text{ MW} \leq P_2 \leq 80 \text{ MW}$$

$$10 \text{ MW} \leq P_3 \leq 70 \text{ MW}$$

The transmission losses are calculated by knowing the loss coefficients. The loss coefficients are taken from [39].

$$B_{ij} = \begin{matrix} 0.000218 & 0.000093 & 0.000028 \\ 0.000093 & 0.000228 & 0.000017 \\ 0.000028 & 0.000017 & 0.000179 \end{matrix}$$

$$B_{0i} = 0.0003 \quad 0.0031 \quad 0.0015 \quad \text{And} \quad B_{00} = 0.030523$$

A. SOLVING ECONOMIC LOAD DISPATCH USING LAMBDA ITERATION METHOD

In the lambda iteration method [28][30], lambda is calculated from the derivative of the cost function. Also, the value of the lambda is initially introduced to solve the constraints optimization problem also referred as Lagrange multiplier method. This method has the advantage of ability to solve problem manually by solving system equations using the iterative method. For the better convergence of the problem the delta lambda should be small and here we have taken it as 0.0001 and the step size is taken as 0.002. The results obtained from the following method is shown in Table 5.1 It is been observed that if the value of the lambda is not selected in appropriate range then the fuel cost does not converge. Also, the elapsed time to converge depends on the lambda selection and value of the delta lambda. The problem converges in 1000-2000 iterations.

Table 5.1 Results for Lambda iteration method

| Sr. no. | Load demand (MW) | Thermal Units | | | Fuel cost | Transmission loss | Elapsed Time |
|---------|------------------|---------------|----------|----------|-------------|-------------------|--------------|
| | | P1 (MW) | P2 (MW) | P3 (MW) | FC (Rs/hr) | (MW) | (sec) |
| 1. | 50 | 11.83862 | 25.11042 | 13.46771 | 888.7431753 | 0.718523234 | 0.848719 |
| 2. | 100 | 23.80078 | 50.28902 | 27.39688 | 1231.63755 | 1.486767959 | 0.502648 |
| 3. | 125 | 32.46016 | 57.87446 | 36.74929 | 1422.159458 | 2.084005739 | 0.404189 |
| 4. | 150 | 41.15784 | 65.50033 | 46.1556 | 1625.4586 | 2.813864755 | 0.438529 |
| 5. | 200 | 58.67056 | 80.87586 | 65.13323 | 2022.155835 | 4.679717947 | 0.597678 |

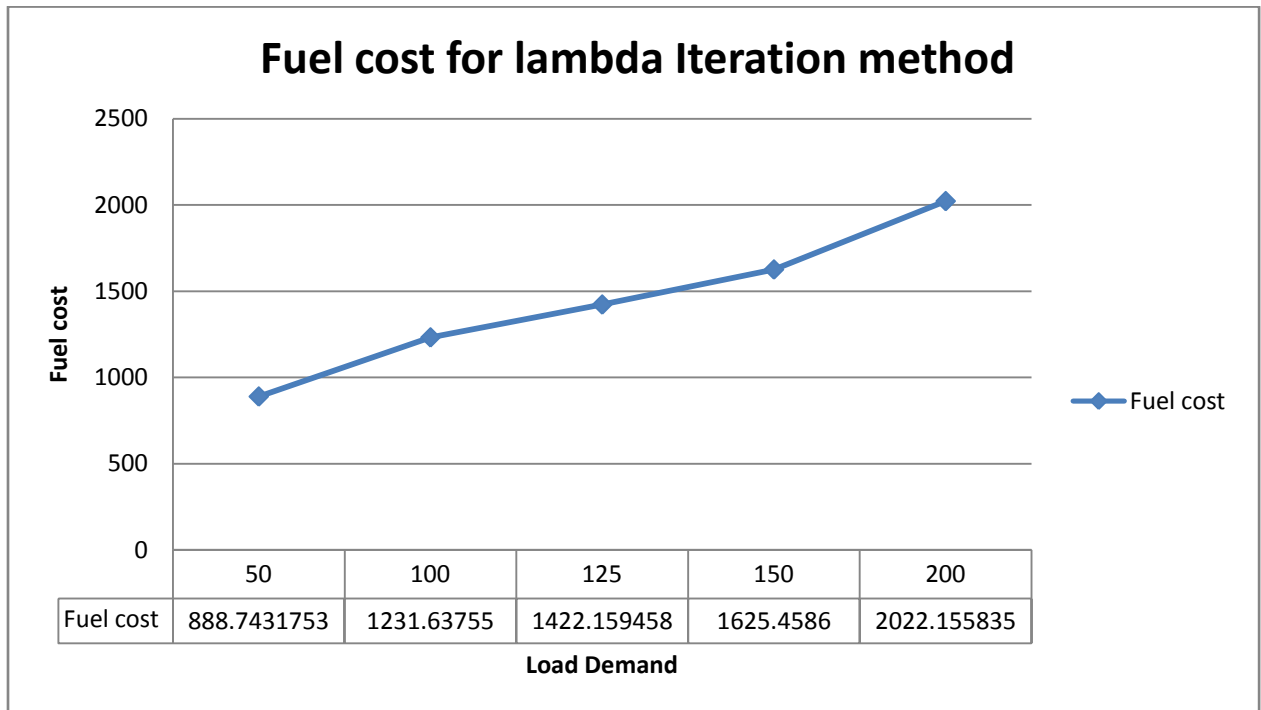


Figure 5.1 Fuel cost v/s load demand curve

B. SOLVING ECONOMIC LOAD DISPATCH USING FIREFLY ALGORITHM

In this method, the initial solution is generated randomly within the feasible range. The parameters of firefly algorithm used in problem are given in Table 5.2. The results are shown in the Table 5.3. The plots of fuel cost for different load demands is shown in the given below figures 5.2

Table 5.2 Parameters Used In Firefly Algorithm

| Sr. no. | Parameter | Parameter value |
|---------|--|-----------------|
| 1. | Total no of fireflies | 50 |
| 2. | Maximum no. of iterations | 100 |
| 3. | Randomness parameter (α) | 0.9 |
| 4. | Attractiveness parameter (β) | 0.5 |
| 5. | Absorption coefficient (γ) | 1 |
| 6. | Attractions at $r = 0$, (β_0) | 2.5 |

Table 5.3 Results for ELD with Firefly Algorithm.

| Sr. no. | Load demand (MW) | Thermal units | | | Fuel cost | Transmission loss | Elapsed Time |
|---------|------------------|---------------|----------|----------|-------------|-------------------|--------------|
| | | P1 (MW) | P2 (MW) | P3 (MW) | FC (Rs/hr) | PL (MW) | (sec) |
| 1. | 50 | 11.83862 | 25.11042 | 13.46771 | 865.0531503 | 0.417351908 | 2.706780 |
| 2. | 100 | 22.89661 | 49.11576 | 29.33646 | 1230.858158 | 1.349369266 | 1.42682 |
| 3. | 125 | 31.09317 | 56.60587 | 39.26521 | 1421.561972 | 1.964774407 | 2.00838 |
| 4. | 150 | 40.27854 | 64.22711 | 48.21578 | 1616.921725 | 2.721760653 | 2.360528 |
| 5. | 200 | 63.25846 | 76.72877 | 64.66465 | 2022.791132 | 4.652667582 | 2.366778 |

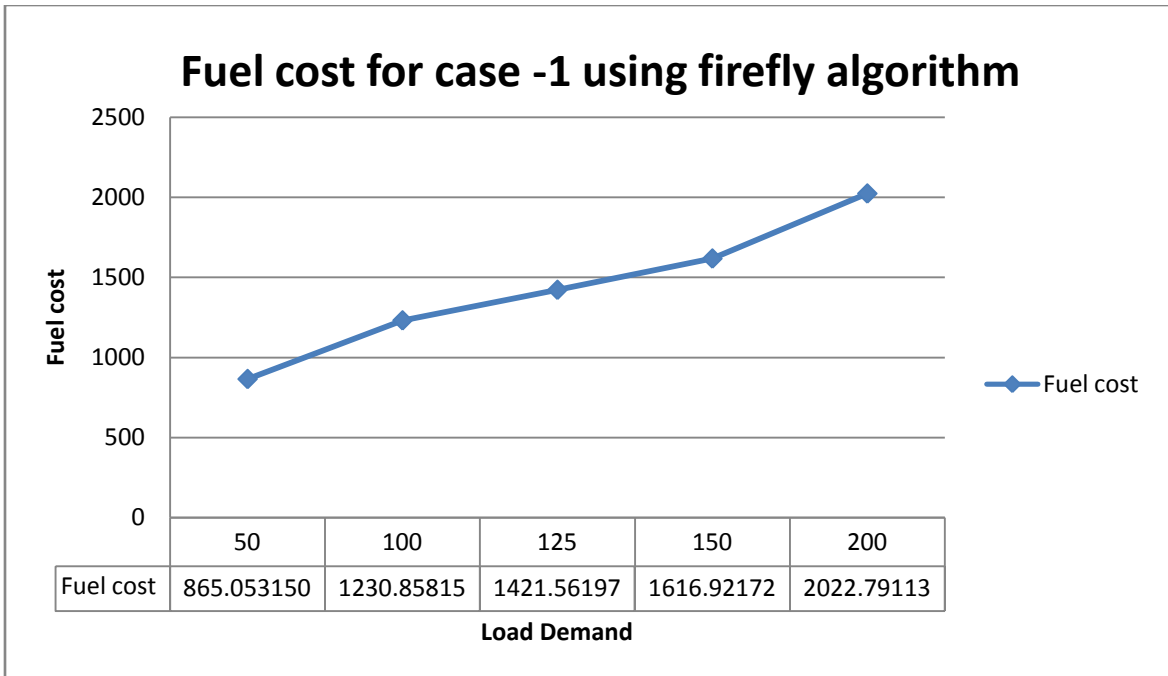


Figure 5.2 Fuel cost v/s load demand curve

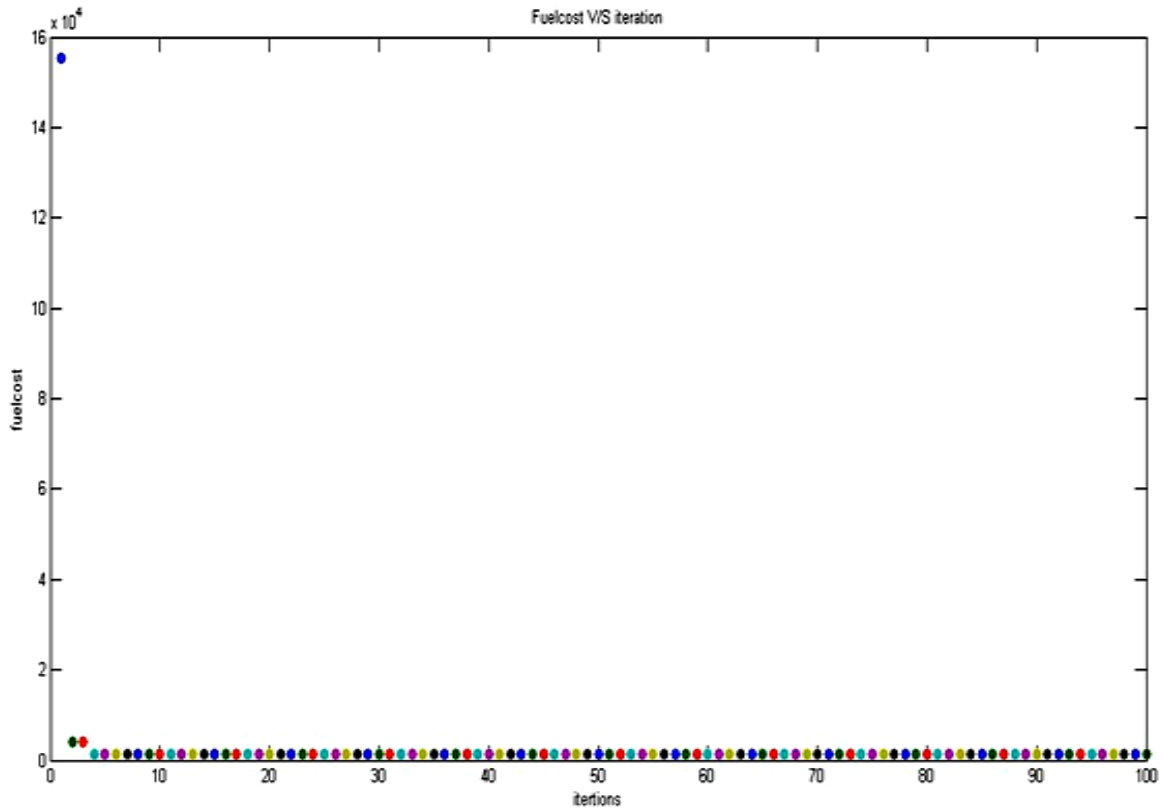


Figure 5.3 Fuel Cost v/s iteration curve for 100 MW

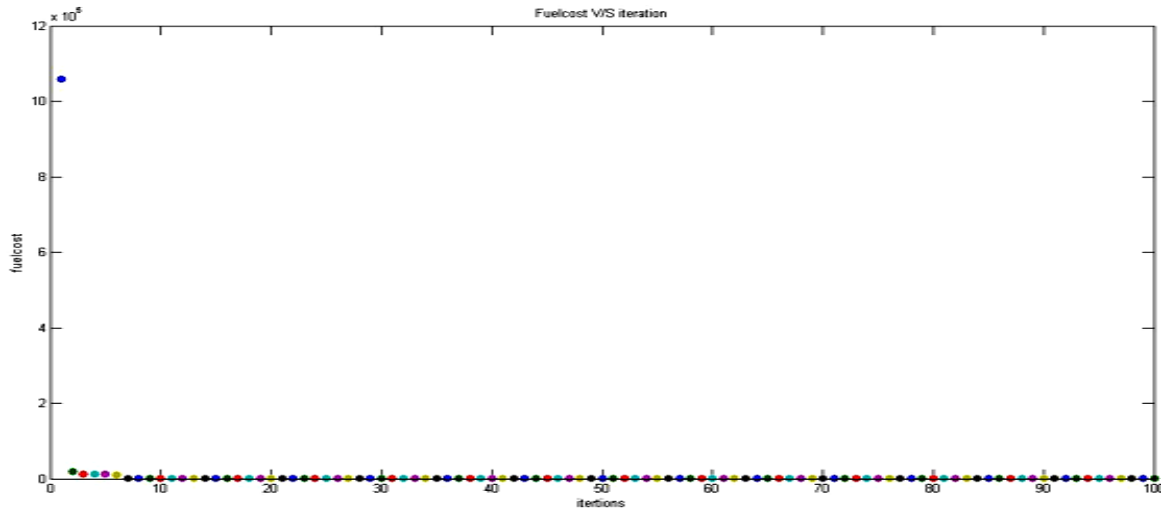


Figure 5.4 Fuel Cost v/s iteration curve for 200 MW

From the Table 5.1 and 5.3 it is been found that fuel cost for the different load demand in lambda iteration method is less than that of firefly algorithm, hence the firefly algorithm is more convergent and gives optimal values then lambda iteration method. Also, the firefly algorithm converges in 10 to 20 iterations where as lambda iteration method converges in 1000-2000 iterations.

5.3 CASE STUDY-2: ECONOMIC LOAD DISPATCH WITH 3 THERMAL UNITS AND 2 WIND UNITS USING FIREFLY ALGORIHTM

In this case, we are considering the three thermal units with same cost functions and generator constraints as in the case study-2 along with two wind farm units. The operating cost of the wind farm is given by the equation 3.17, the direct cost coefficient of wind power, penalty cost coefficient and reserve cost coefficient for the wind power are 4.89Rs/KW, 17.280 Rs/KWh and 12.280 Rs/KWh respectively. The Each Wind unit capacity is 30 MW. The result with the different load demand is shown in the Table 5.4. The parameter values for the firefly algorithm is been kept same as that for the test case 1. The cut in speed cut out speed and the rated speed of the wind turbine units are 3.5 m/s, 25 m/s and 15 m/s respectively. The notations of the various other parameters are given in appendix A. The fuel

cost for different load demands are shown in figure 5.5 and fuel cost per iteration is shown in figure 5.6 and 5.7 for 100MW and 125 MW load demands respectively.

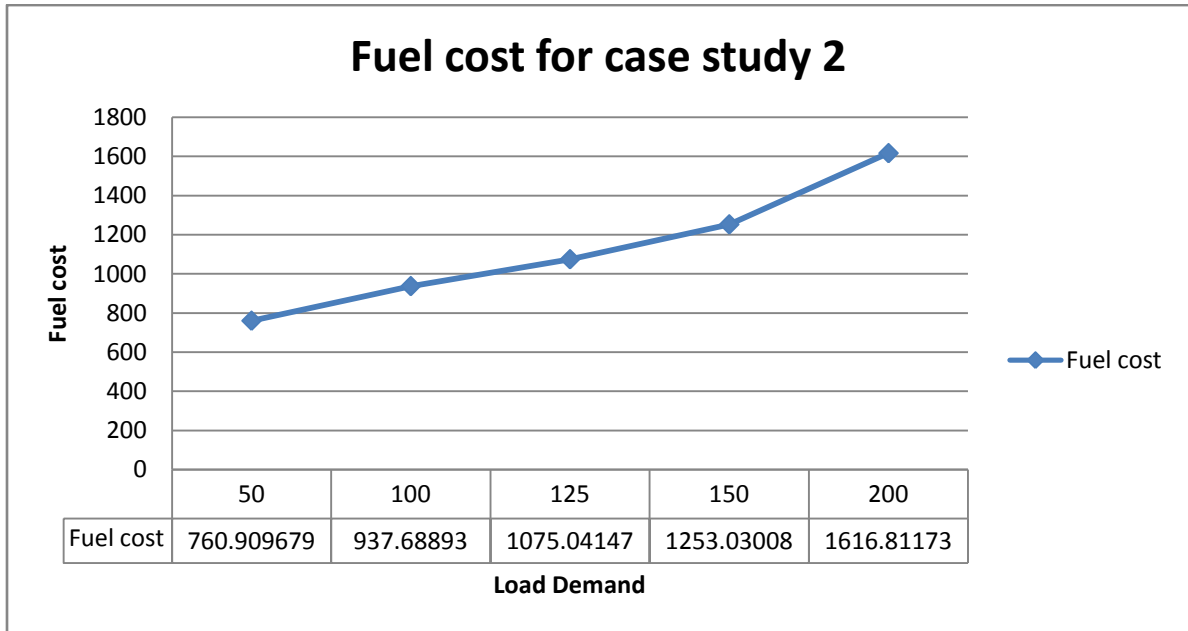


Figure 5.5 Fuel cost v/s load demand curve

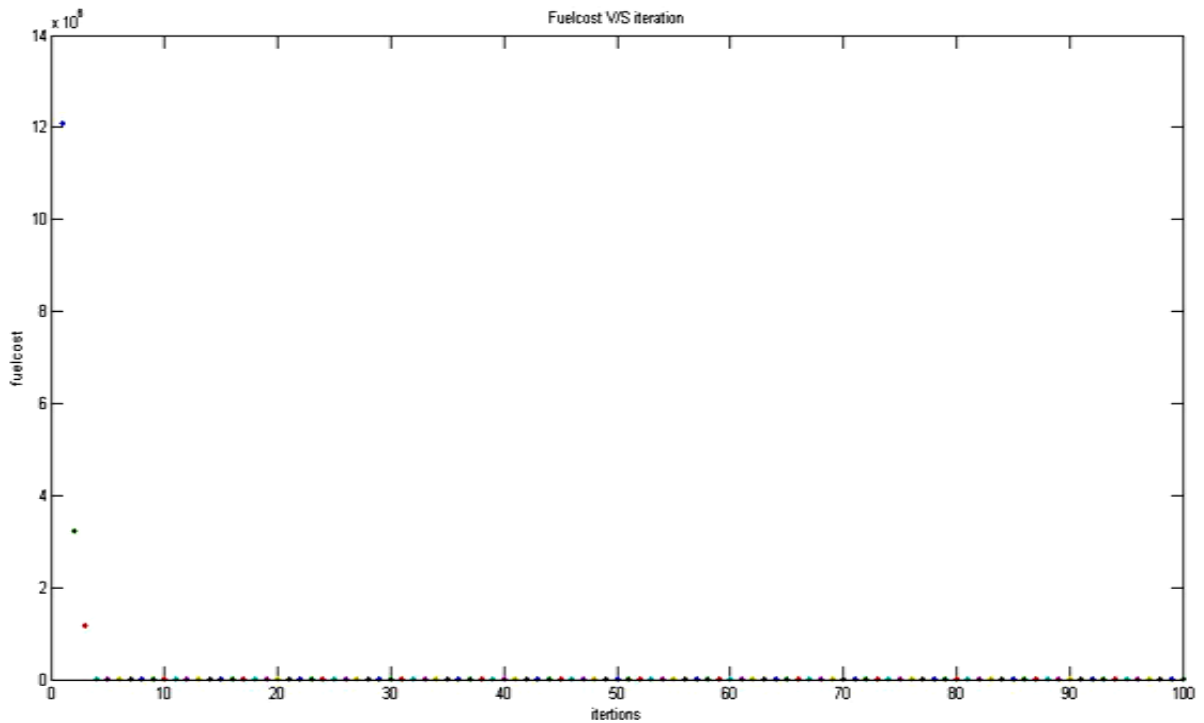


Figure 5.6 Fuel Cost v/s iteration curve for 100 MW

Table 5.4 results of the Economic Load Dispatch with Thermal and WECS system.

| Sr. no. | Load demand (MW) | Thermal units | | | Wind Farm Units | | Fuel cost Ft (Rs/Hr) | Transmission loss (MW) | Elapsed Time (sec) |
|---------|------------------|---------------|----------|----------|-----------------|----------|----------------------|------------------------|--------------------|
| | | P1 (MW) | P2 (MW) | P3 (MW) | P4 (MW) | P5 (MW) | | | |
| 1. | 50 | 11.34008 | 11.41744 | 12.23306 | 7.546139 | 7.674855 | 760.9097 | 0.48560685 | 2.082560 |
| 2. | 100 | 20.50356 | 21.14625 | 18.34094 | 19.51166 | 21.02793 | 937.6889 | 0.8027887 | 2.137497 |
| 3. | 125 | 23.01455 | 29.64393 | 26.34379 | 23.60459 | 23.25979 | 1075.041 | 1.14066378 | 1.178443 |
| 4. | 150 | 29.82921 | 40.55632 | 32.9725 | 23.7666 | 24.27653 | 1253.03 | 1.674578933 | 1.238223 |
| 5. | 200 | 52.37243 | 56.95001 | 42.31272 | 25.26034 | 25.92256 | 1616.812 | 3.091949405 | 2.273712 |

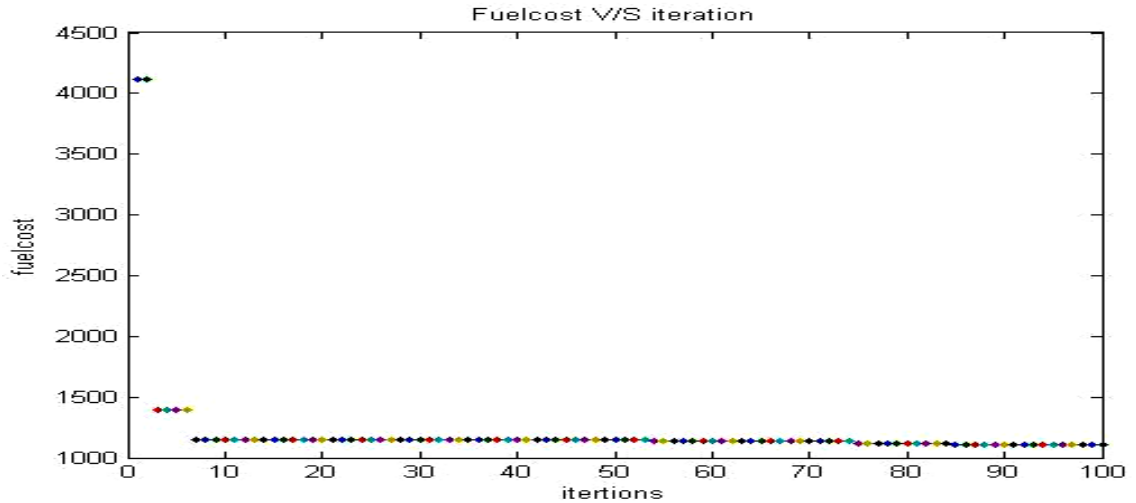


Figure 5.7 Fuel Cost v/s iteration curve for 125 MW

The result shows that the fuel cost decreases with the inclusion of the renewable sources in the dispatching methods. Moreover, the transmission losses are also decrease due to reduction in load sharing by the thermal generating units. The results are more dominating than that obtained for the 3 thermal units alone. The fuel cost converges in smaller no iterations as shown in the figure 5.6, 5.7. This indicates higher convergence rate of the firefly algorithm.

5.4 CASE STUDY-3: ECONOMIC LOAD DISPATCH WITH 3 THERMAL UNITS AND 2 PV UNITS USING FIREFLY ALGORITHM

In this case, we are considering the three thermal units with same cost functions and generator constraints as in the case study 2. And two solar farm units. The operating cost of the solar farm is given by equation 3.21, the direct cost coefficient of solar power, penalty cost coefficient and reserve cost coefficient for the solar power are 7.86 Rs/KW, 17.80Rs/KWh and 12.28 Rs/KWh respectively. The Each PV unit capacity is 30 MW. The result with different load demand is shown in the Table 5.5. The notations of the parameters in the probability density function, like PV efficiency, ground reflectance and other parameters are given in appendix A. The fuel cost per iteration for 125 MW and 200 MW is shown in figure 5.9 and 5.10 respectively.

Table 5.5 Result of the Economic Load Dispatch with Thermal and PV system.

| Sr. no. | Load demand (MW) | Thermal units | | | | Solar Farm Units | | Fuel cost Ft (Rs/Hr) | Transmission loss (MW) | Elapsed Time (sec) |
|---------|------------------|---------------|----------|----------|----------|------------------|----------|----------------------|------------------------|--------------------|
| | | P1 (MW) | P2 (MW) | P3 (MW) | P4 (MW) | P5 (MW) | | | | |
| 1. | 50 | 10.98689 | 11.74848 | 11.29873 | 8.233376 | 7.939959 | 753.8376 | 0.204921526 | 2.380974 | |
| 2. | 100 | 19.76804 | 19.33529 | 19.90568 | 20.21284 | 21.28841 | 931.8654 | 0.51105775 | 1.409495 | |
| 3. | 125 | 23.5109 | 28.74328 | 27.58915 | 22.60856 | 23.41388 | 1081.215 | 0.86644477 | 1.415576 | |
| 4. | 150 | 30.34574 | 39.57384 | 33.10726 | 23.61905 | 24.75173 | 1251.412 | 1.396535 | 1.667739 | |
| 5. | 200 | 49.62634 | 56.90616 | 45.3739 | 26.08046 | 24.79429 | 1618.327 | 2.779728254 | 1.380076 | |

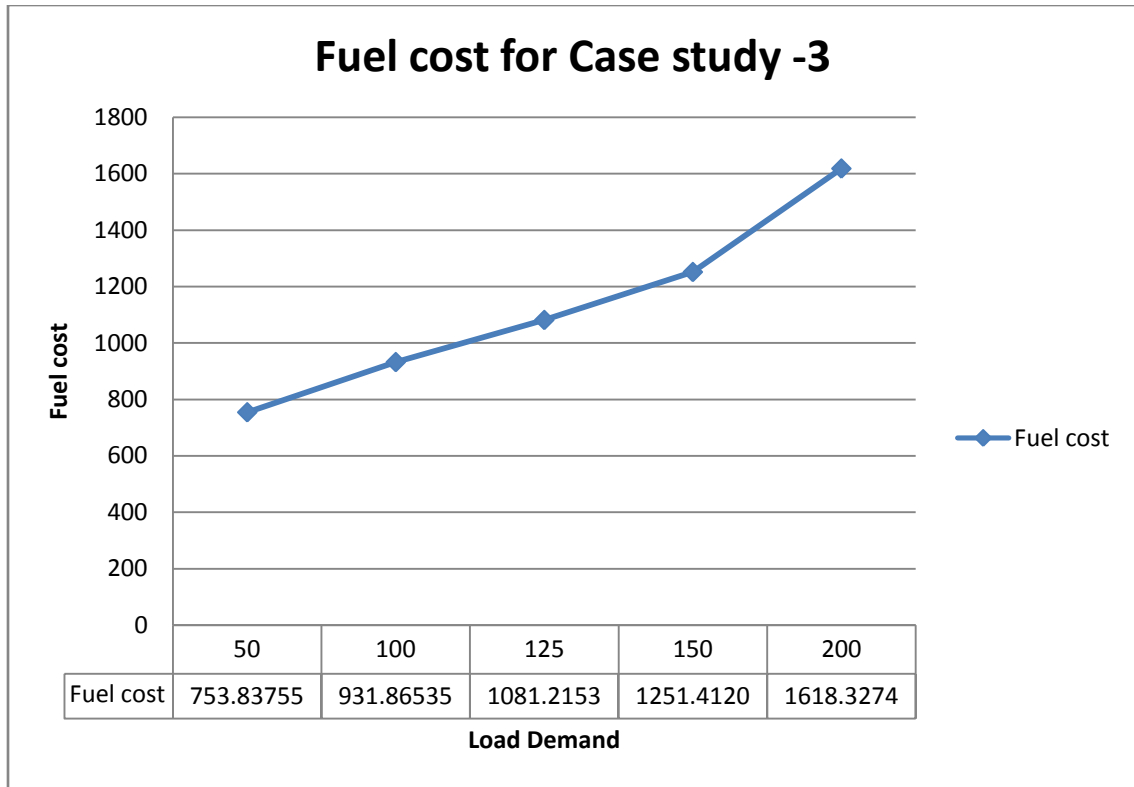


Figure 5.8 Fuel cost v/s load demand curve

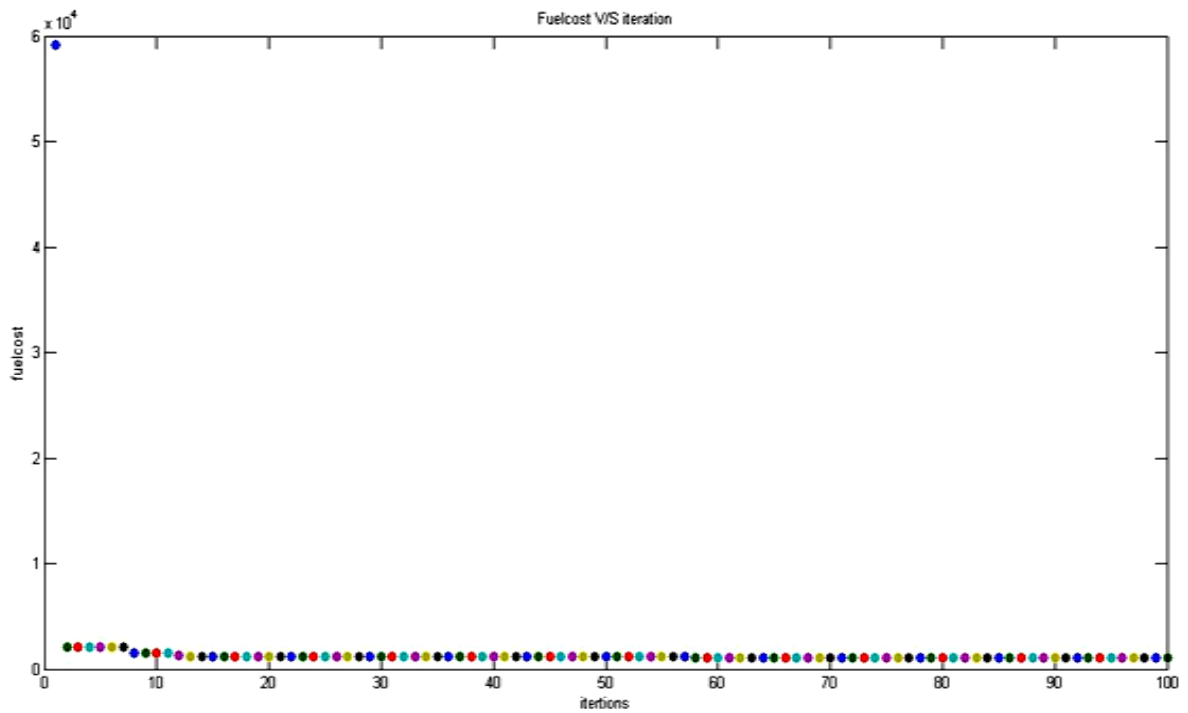


Figure 5.9 Fuel Cost v/s iteration curve for 125 MW

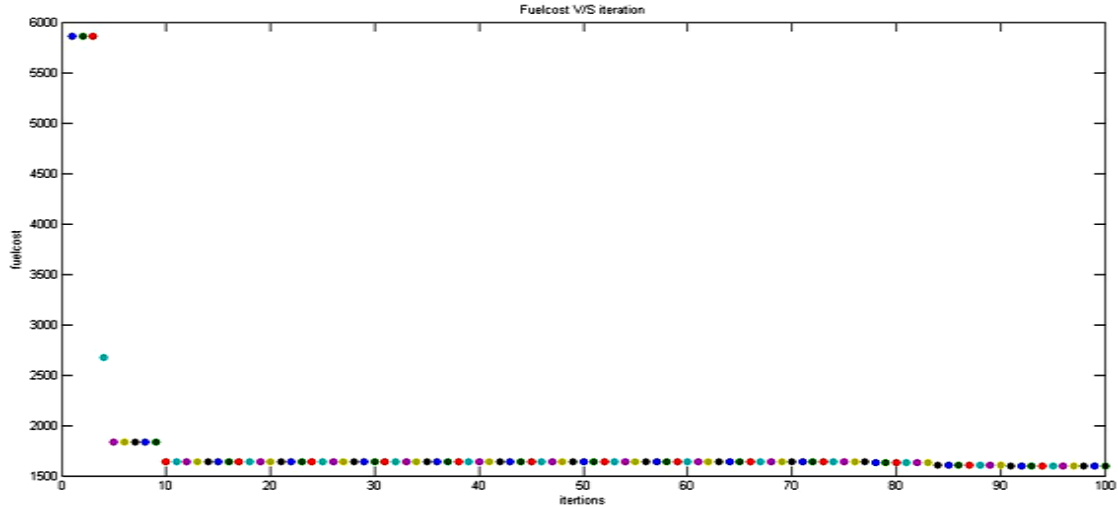


Figure 5.10 Fuel Cost v/s iteration curve for 200 MW

From the result it can be clearly seen that the solar power not only reduce the load sharing of the thermal generating units but also reduce the fossil fuel consumption in the thermal power plants. This shows that the economic load dispatching with the renewable sources is more efficient and modern way to fulfill future demand with reduced cost.

5.5 CASE STUDY-4 ECONOMIC LOAD DISPATCH WITH 3 THERMAL UNITS, 1 PV FARM UNIT AND 1 WIND FARM UNIT USING FIREFLY ALGORITHM

In this case study we have combined both the above cases study 3 and 4 discussed in the previous section, but here we are taking one unit each of 30 MW from both the renewable systems, i.e. one unit of solar farm and one unit of wind farm. The objective function of this case is described in the equation 3.15 and the operating cost of the wind and solar units is shown in equation no. 3.17 and 3.21 respectively. The direct cost coefficient, penalty cost coefficient and the reserve cost coefficient of wind and solar are same as in the previous cases. Furthermore, the parameter values of the solar and wind units are kept same as that for the previous test case studies. The result is shown in the Table 5.6 for the different load demands. Also, the fuel cost for different load demands is shown in figure 5.11 and fuel cost per iteration for 125 MW and 200 MW are shown in figures 5.12 and 5.13 respectively.

Table 5.6 Result of the ELD with Thermal units and renewable sources combined

| Sr. no. | Load demand (MW) | Thermal units | | | Wind units | Solar units | Fuel cost | Transmission loss | Elapsed time |
|---------|------------------|---------------|----------|----------|------------|-------------|-----------|-------------------|--------------|
| | | P1 (MW) | P2 (MW) | P3 (MW) | | | | | |
| 1. | 50 | 10.90107 | 12.33091 | 11.14279 | 7.359671 | 8.476098 | 755.9367 | 0.20966767 | 2.663824 |
| 2. | 100 | 21.12639 | 19.82454 | 18.78448 | 20.70715 | 20.08377 | 936.8157 | 0.52383516 | 2.428631 |
| 3. | 125 | 23.18308 | 30.96212 | 26.06724 | 21.52108 | 24.16408 | 1083.305 | 0.89684504 | 1.569667 |
| 4. | 150 | 34.07808 | 40.65528 | 28.38547 | 23.45696 | 24.87344 | 1252.756 | 1.44612158 | 1.388910 |
| 5. | 200 | 47.63106 | 61.01115 | 42.06096 | 25.08687 | 27.00843 | 1607.551 | 2.798475 | 1.392367 |

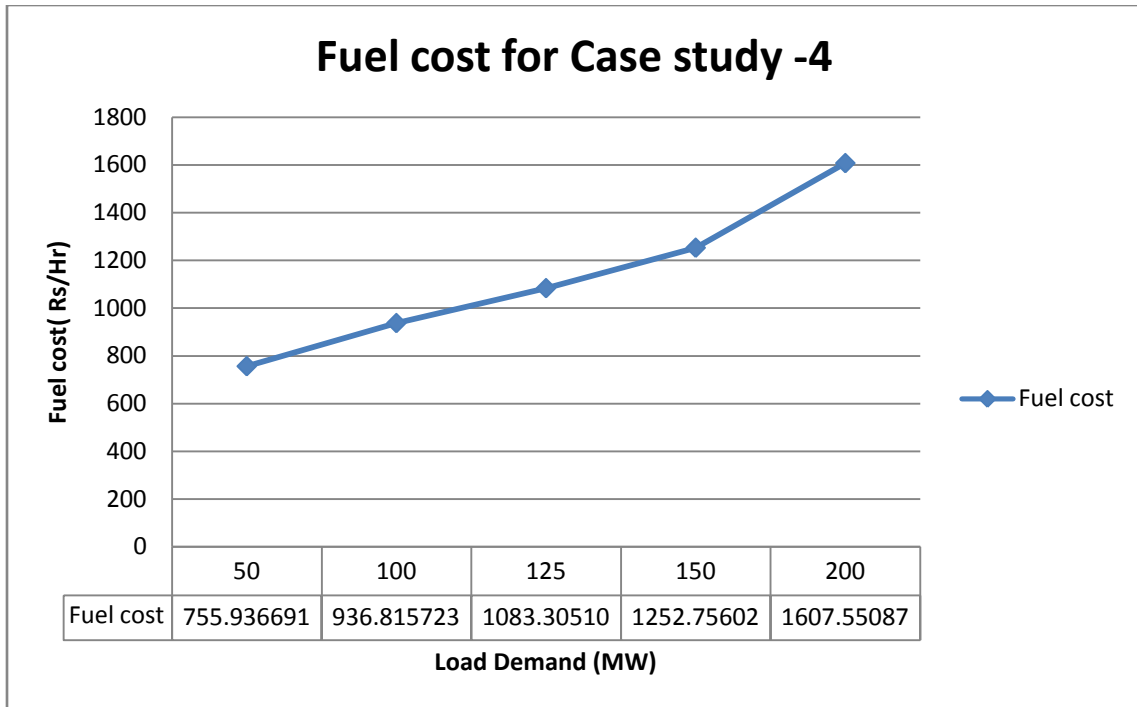


Figure 5.11 Fuel cost v/s load demand curve

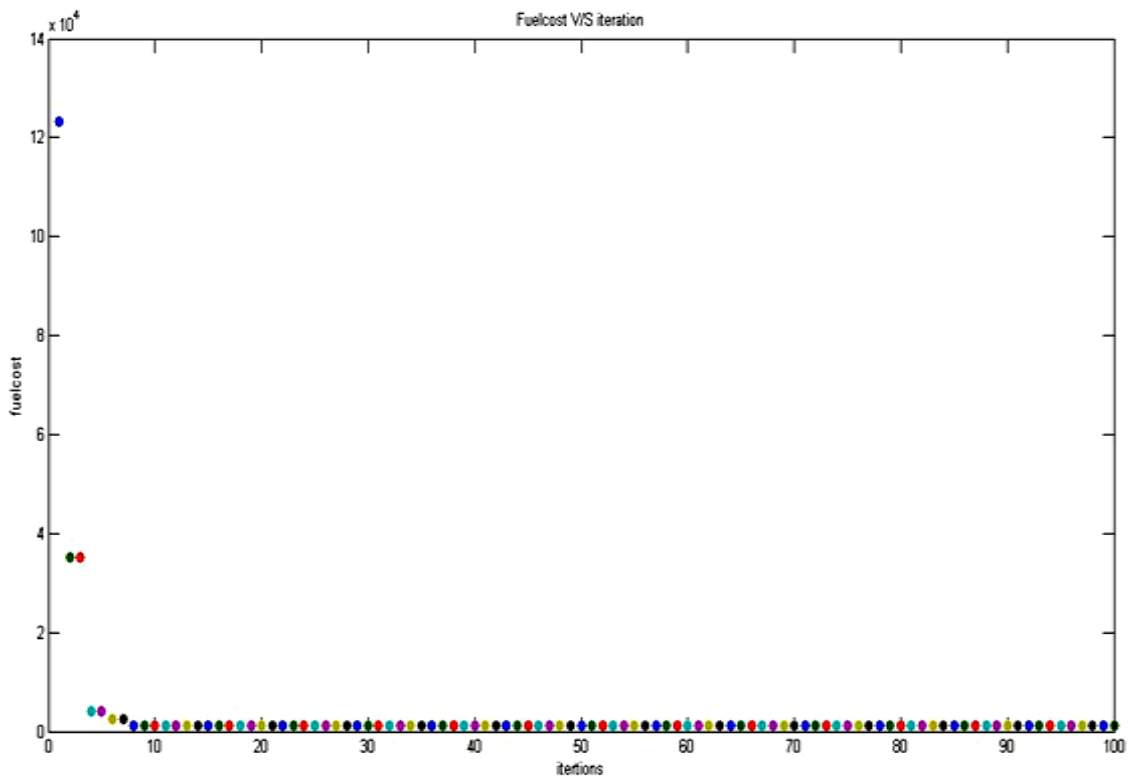


Figure 5.12 Fuel Cost v/s iteration curve for 125 MW

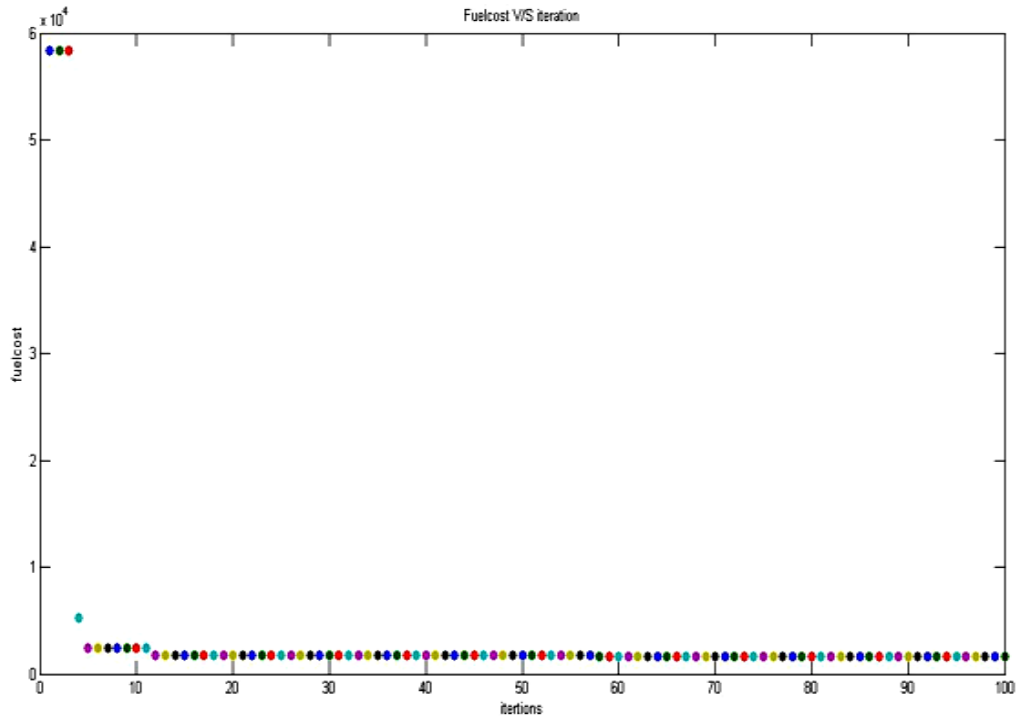


Figure 5.13 Fuel Cost v/s iteration curve for 200 MW

From Table 5.6 it is found that the fuel cost for thermal units reduces with the inclusion of the solar farms in the ELD problem, as the load sharing by thermal units reduces which in turn reduces the fuel consumption by thermal units. The fuel cost converges in 10-20 iterations which can be seen in figure 5.13.

5.6 COMPARISON OF FUEL COST FOR VARIOUS TEST CASES

A comparative study can be made among test cases results regarding fuel cost. It has been found that fuel cost concluded from test case 4 is lowest among all the other test cases for 200 MW, 150 MW and 50 MW. The comparison plot is shown in figure 5.14. Furthermore, while comparing the result from case 1 using firefly algorithm and case study 4 it is found that the fuel cost is reduced by 415.24 Rs /hr for 200 MW load test case which clearly indicates that the fuel cost of thermal power generation reduces to a good extent.

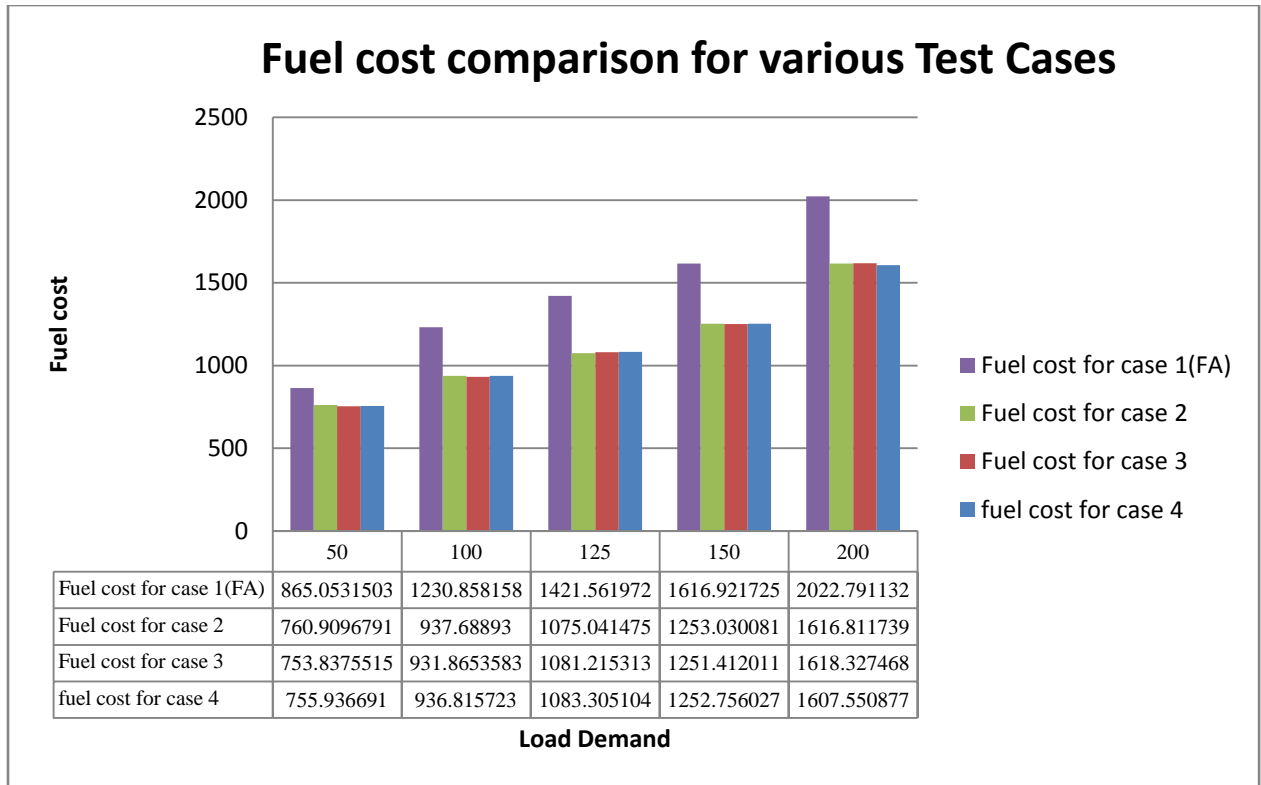


Figure 5.14 fuel cost comparison for different case studies.

5.5 CONCLUSIONS

In the chapter various test cases were implemented with the different load demands, and it has been concluded that after including the renewable sources with thermal units into the economic load dispatch problem the fuel cost and the transmission losses are reduced to a higher extent. The transmission loss due to the power transfer from renewable farms to load center is assumed to be negligible, since they are situated near to the load center. The entire test were performed on the MATLAB 2011b.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

The firefly algorithm developed by Yang works on the flashing behavior of the fireflies and widely has been applied on different benchmark functions to find the accuracy and the efficiency of algorithm. For various load demands of four different test cases considered, simulations were performed to solve the constrained optimization ELD problem with and without inclusion of renewable sources of energy for obtaining optimal value of power generation. From the results it can be inferred that firefly algorithm gives better optimal solution than lambda iteration techniques. From the simulations it was also seen that proper selection of population size, the number of iterations and the absorption coefficient for the convergence of the algorithm is important as this heavily depends on objective function of the problem.

With the inclusion of renewable sources of energy in the problem, the dispatching of load demand was simulated and it was concluded that the fuel cost of the thermal generating units and transmission losses (due to power transfer from thermal units to load center) both reduces. This was due to the sharing of load demand by the renewable sources, the power generation by thermal units reduces and finally fuel cost reduces keeping the energy balance and other constraints within limits. A proper estimation of solar and wind probability density function should be made to determine actual probability of wind and solar power generation. The penalty cost and reserve cost coefficients however depend from state to state and country to country and their policies. These should be taken for the place for which the power estimation of wind and solar is to be made.

6.2 FUTURE SCOPE

The results of firefly algorithm depend upon the best solution within a swarm. Therefore, improvising solution will be possible to improve the search power within the swarm. The binary coded firefly algorithm showed the application of firefly algorithm to problem with binary representation. Several variants of firefly algorithm viz. Gaussian, levy

flight, chaos firefly algorithm, parallel firefly algorithm, can be used to improve the tuning of parameters and for higher converging rate. The hybridization of firefly algorithm with others can also made be possible to make local searches more pronounced. The solution of ELD problem with hybrid firefly algorithm may also provide better optimal solution with higher convergence rate and lower elapsed time.

In India renewable power generation has a vast scope in future, various renewable energies like tidal energy, geothermal, bio energy, hydro energy and many more can be used for power generation. Since majority of population depends on agricultural farming for their livelihood and large amount of agricultural waste is produced which can also be utilized to produce electrical energy which further can be dispatched to grids or to local load centers. Moreover, in rural areas the bio organic waste can also be used to produce power for their local power demand requirements. Moreover, power from other renewable sources like tidal, geothermal etc. can be dispatch to the grid, or can be directly consumed to fulfill the load demands. Such practices may reduce the power generation from fossil fuel fired generating plants. The ELD problem with the inclusion of above mentioned resources of energy can be possible and then it will reduce the fuel cost of fossil fuel fired generating units and transmission losses due to power transfer from these units to the load center.

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Appendix A

| | |
|-------------------------------------|---|
| $F(P_{gi})$ | Fuel cost for i^{th} generating unit (Rs/hr) |
| a_i, b_i and c_i | Generator constants for i^{th} unit. |
| F_T | Total Fuel cost (Rs/hr). |
| P_d | Load demand (MW) |
| P_L | Transmission loss (MW). |
| B_{00}, B_{0i} and B_{ij} | Transmission loss Coefficients. |
| P_{gi}^{\min} and P_{gi}^{\max} | Minimum and maximum real power generation limit by i^{th} generator respectively (MW). |
| Q_{gi}^{\min} and Q_{gi}^{\max} | Minimum and maximum reactive power generation limit by i^{th} generator respectively (MW). |
| P_{wrj}^{\max} | Maximum power generated by j^{th} wind unit (MW). |
| P_{pvrk}^{\max} | Maximum power generated by k^{th} solar unit (MW). |
| k | Scale parameter. |
| c | Shape parameter. |
| v, v_i, v_o and v_r | Wind speed, cut in speed, cut out speed and rated speed of wind (m/s). |
| v_m and σ | Mean wind speed and standard deviation respectively (m/s). |
| $f_{pw}(P_w)$ | Probability density of wind power. |
| I_t | Irradiance at horizontal plane (kW/m^2). |
| I_o | Extraterrestrial total solar irradiance (kW/m^2). |
| k_t | Hourly clearness index. (kW/m^2) |
| k_m | Mean clearness index in (kW/m^2) |

| | |
|------------------|--|
| k_{tu} | Maximum clearness index (kW/m^2). |
| β | Inclination angle in degree. |
| p, q | Arbitrary constants. |
| R_b | Ratio of beam radiation on tilted surface to horizontal surface. |
| ρ | Ground reflectance (dimensionless). |
| $f_{pv}(P_{pv})$ | Probability density function of solar power. |
| A_c | Surface area of solar array in m^2 . |
| η | Solar panel efficiency (dimensionless). |
| δ | Declination angle (°) |
| ω | Solar hour angle (°) |
| ω_s | Sunset hour angle (°) |
| φ | Latitude angle (°) |
| c_{wj} | Direct cost coefficient for wind farm for j^{th} unit. (Rs/ KW) |
| $k_{p,wj}$ | Penalty cost coefficient for j^{th} wind farm unit. (Rs/ KWh) |
| $k_{r,wj}$ | Reserve cost coefficient for j^{th} wind farm unit. (Rs/ KWh) |
| $P_{wj,av}$ | Available wind power from j^{th} wind farm unit. (MW) |
| c_{pvk} | Direct cost coefficient for solar farm for k^{th} unit. (Rs/ KW) |
| $k_{p,pvk}$ | Penalty cost coefficient for k^{th} solar farm unit. (Rs/ KWh) |
| $k_{r,pvk}$ | Reserve cost coefficient for k^{th} solar farm unit (Rs/ KWh) |
| $P_{pvk,av}$ | Available wind power from k^{th} solar wind farm unit. (MW) |