Study and Application of Intelligent Control to Power System Scheduling

Submitted By

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<u>"Statement of Originality"</u>

I, **SUMAN KR DEY** registered on **the year of 2013** do hereby declare that this thesis entitled **"Study and Application of Intelligent Control to Power System Scheduling"** contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019", and the level of similarity as checked by iThenticate software is **<u>7</u> %**.

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DECLARATION

I, Sri Suman Kr Dey, hereby certify that the work "**Study and Application of Intelligent Control to Power System Scheduling**" submitted by me to Jadavpur University, Kolkata, India for the award of Ph.D. (Engineering) degree, has not been submitted previously in this university or any other University for the degree of Ph. D./D.Litt./D.Sc.

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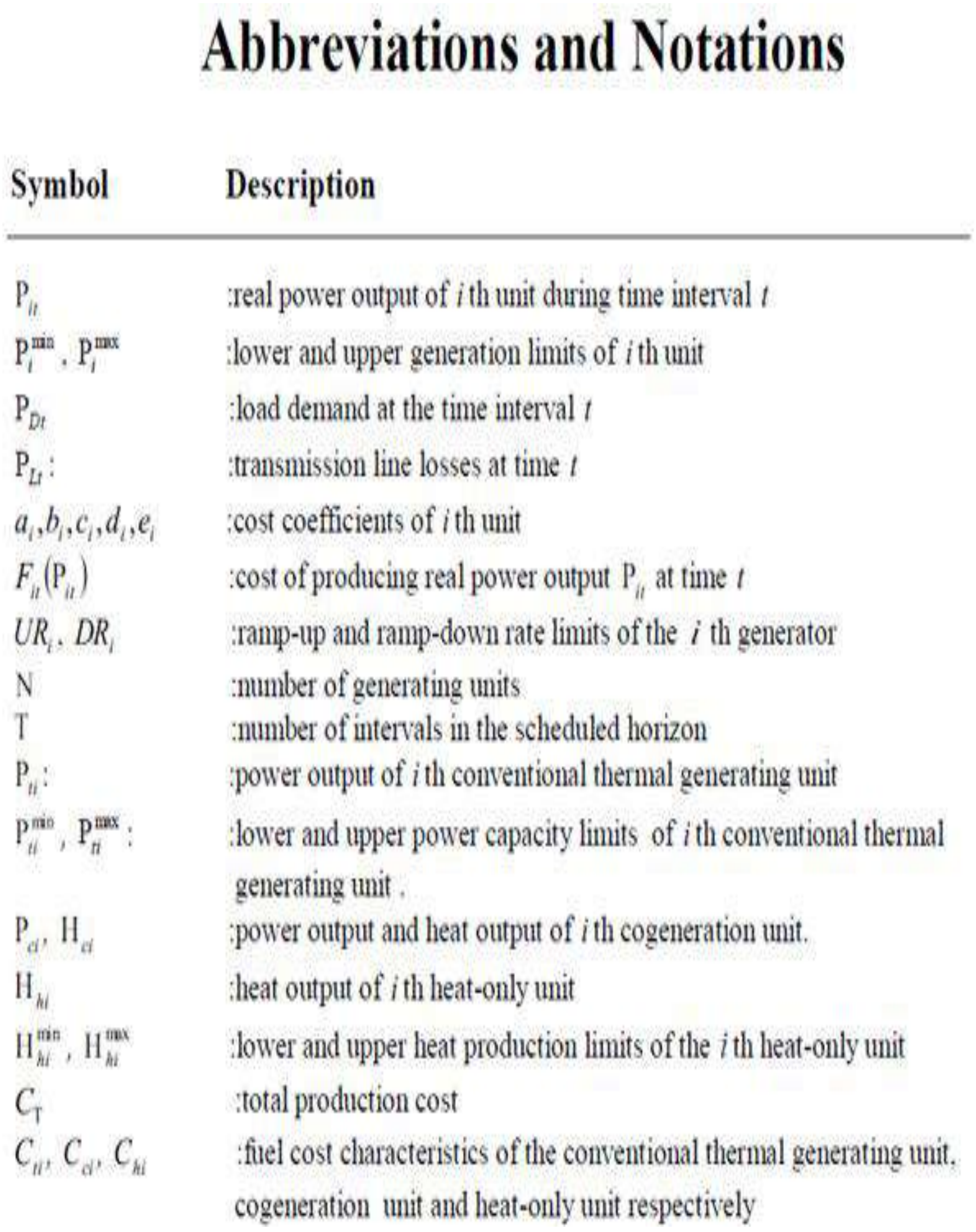
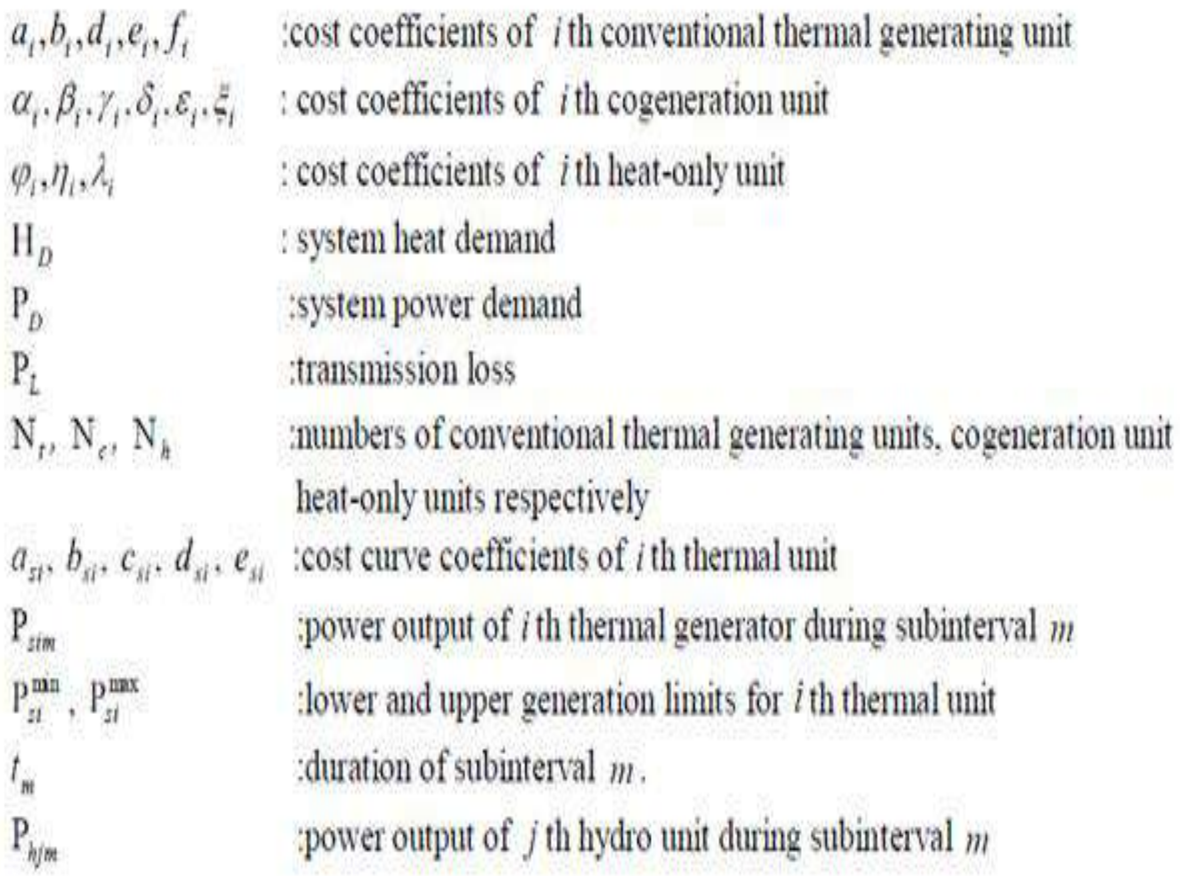


Abbreviations and Notations

Symbol	Description
P_{it}	:real power output of i th unit during time interval t
P_i^{min}, P_i^{max}	:lower and upper generation limits of i th unit
P_{Dt}	:load demand at the time interval t
P_{Lt} :	:transmission line losses at time t
a_i, b_i, c_i, d_i, e_i	:cost coefficients of i th unit
$F_{it}(P_{it})$	:cost of producing real power output P_{it} at time t
UR_i, DR_i	:ramp-up and ramp-down rate limits of the i th generator
N	:number of generating units
T	:number of intervals in the scheduled horizon
P_{ti} :	:power output of i th conventional thermal generating unit
P_{ti}^{min} , P_{ti}^{max} :	:lower and upper power capacity limits of i th conventional thermal generating unit .
P_{ci}, H_{ci}	:power output and heat output of i th cogeneration unit.
H_{hi}	:heat output of i th heat-only unit
H_{hi}^{min} , H_{hi}^{max}	:lower and upper heat production limits of the i th heat-only unit
C_T	:total production cost
C_{ti}, C_{ci}, C_{hi}	:fuel cost characteristics of the conventional thermal generating unit, cogeneration unit and heat-only unit respectively



a_i, b_i, d_i, e_i, f_i	:cost coefficients of i th conventional thermal generating unit
$\alpha_i, \beta_i, \gamma_i, \delta_i, \varepsilon_i, \xi_i$	: cost coefficients of i th cogeneration unit
$\varphi_i, \eta_i, \lambda_i$	: cost coefficients of i th heat-only unit
H_D	: system heat demand
P_D	:system power demand
P_L	:transmission loss
N_t, N_c, N_h	:numbers of conventional thermal generating units, cogeneration unit heat-only units respectively
a_{si}, b_{si}, c_{si}, d_{si}, e_{si}	:cost curve coefficients of i th thermal unit
P_{sim}	:power output of i th thermal generator during subinterval m
$P_{si}^{\min}$, $P_{si}^{\max}$	:lower and upper generation limits for i th thermal unit
t_m	:duration of subinterval m .
P_{hjm}	:power output of j th hydro unit during subinterval m

Executive Summary

The current work examines and applies **intelligent control to the scheduling of power systems**. The work here focuses on various scheduling optimization methods for power systems. The power system is optimized for Economic Dispatch, Economic Emission Dispatch, Combined Heat and Power Economic Dispatch, Hydrothermal System, etc. using Intelligent Control such as Evolutionary Algorithm, Differential Evolution. For the aforementioned intelligent power system optimization strategies, many test platforms are used. The test results are compared to other outdated optimization strategies, and it is found that the proposed intelligent control methods produce superior outcomes.

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Chapter-1

Introduction

1.1 General Introduction

The fundamental goal of an electric power system is to gather the demand forced on it in an optimal approach. The choice of optimal criteria is always a subjective one since one may have to decide first as to what shall be understood to be the optimum in each particular problem. Once the optimality criterion is decided it is then possible to proceed for mathematical formulations and solutions. Optimal operations involving various degrees of complexities are in vogue in power system. The optimum economic operation and development of electric power system always have to play a significant role in power system operation and control. The area of minimization of production cost has warranted a great deal of attention from engineers through the years.

The demand of economic operation have been and will go on to remain the most powerful force in utility arrangements in the face of steady rise in fuel charge ever-growing order for energy and the fast-reducing nature of fossil fuels. Although the effective function of optimization performances has a lengthy history in the power system operation and control, yet tangible enhancements can still be accomplished through more accurate formulation of the constraints and implementation of more strong solution system. This study attempts to discuss how such improvements can be achieved by way of exploiting Artificial Intelligence (AI) techniques for constrained nonlinear economic load dispatch.

Economic load dispatch (ELD) is an important daily optimization development whereby the whole mandatory production is circulated among the committed generating divisions with the purpose of diminishing a chosen cost criterion subject to fulfillment of system demand and other operational constraints such that not only the constraints forced are fulfilled but also the energy prerequisite in terms of BTU/hr or Rs/hr is diminished. Traditional classical dispatch algorithms employing calculus and Lagrangian multiplier require that the incremental cost curves of the participating units to be of monotonically increasing or of piece-wise linear nature. This implies that the cost curves are approximated by polynomial functions, usually quadratic curves. But there has been a lot of development in the design of more energy efficient thermal plants but they have added more non-linearties in the cost characteristics of the units.

A Dynamic Economic Dispatch (DED) process can cope up both with the ramp rate limits of dispatch units and modified the cost of balancing state to extra fuel consumption and the power can be delivered to the competitive price for customers. The key to the Dynamic Economic Dispatch method to make the generation dispatch which will meet the load. Otherwise, the loss in generation which will meet the load demand in real power plant may occur if the production of power is not dispatch properly. Such problems occur due to less amount of ramp rate and regulation capacity.

Presently, there is an increased attention towards the environmental pollution of thermal power plants as subject of much roar to combat air pollution. The production of electricity from fossil fuels releases several contaminants into atmosphere. Atmospheric pollution affects not only human beings but also other life-forms such as animals, birds, fishes, plants. Also, unless the air is clean, there will be tarnishing of materials, reducing visibility and global warming. Due to the increasing concern of the society over environmental considerations. In particular, at the implementation of Clean Air Amendment Act of 1990, emission control has become one of the most important operational objectives. Thus, the objectives are non-commensurable and conflicting with each other. This will give rise to many optimal solutions instead of one optimal solution. The obvious approach to handle both economic dispatch and environmental emission as competing objectives is called Economic Emission Load Dispatch (EELD) [6-14], which need to be solved simultaneously. Nowadays, the objective that is more focused is minimizing pollution by reason of popular claim for hygienic air. Each plant is directly related to Environmental pollution. Inspire of all these it has been acknowledged the Coal-based generating stations are critically accountable to produce atmospheric contamination by adding into the climate the high attention of pollutants controlled in their discharge. In EELD, process may be minimum cost or minimum discharge stage of power scheme. The conservative economic emission dispatch is formulated into a multi-objective optimization problem.

The Multi-Region Combined Heat and Power Economic Dispatch (MRCHPED) algorithm indicates the generation of heat with power simultaneously which is minimizing production cost along with all operational constraints. Various methods have already been proposed for the solution of CHPD. In balancing state, heat stability, and production boundary with interconnection limit with different fuel sources are the primary objective of MRCHPED. CHP systems are giving electrical force as well as warmth to the clients and also it decides for producing electrical as well as heat. Integration of heat and electrical energy in the form of dynamic economic emission dispatch is detailed with the goal to decide the unit power and heat creation so the framework's creation cost and discharge are at the same time limited, while the power and heat requests and different limitations are met.

In another side multi-region dynamic economic emission dispatch is an expansion of multi-region static economic emission dispatch issue. It plans a wide range of online generator yields, and exchange power between zones with the anticipated burden requests over a specific timeframe to such an extent that absolute expense and discharge level in all territories are upgraded at the same time while fulfilling different limitations.

Increasing demand of prices of oil that indicates the minimization of fuel source as well as increasing the electrical energy and the global scenario of air pollution and the environmental protection, so the use of the Renewable Energy (RE) resources has more attention of researchers in recent years. Such sources are taken as environmentally friendly and have no operational cost.

An integration of hydro, wind and solar energy generation systems which will be penetrated into the different systems [46]. The total unit is very complex and the authors are taking all the security constraints RE systems.

Normal assets are a type of value, and they are known as regular capital. Biofuel, or vitality produced using inexhaustible natural items, has picked up pervasiveness as of late as an elective vitality source to non-renewable assets, for example, coal, oil, and gaseous petrol. Despite the fact that costs are as yet higher for biofuel, expanding shortage and the powers of market interest will bring about more significant expenses for non-renewable energy sources, which will make the cost of biofuel progressively serious. Other inexhaustible assets incorporate oxygen and sun-based vitality. Wind and water are likewise used to make sustainable power source. For instance, windmills outfit the breeze's common force and transform it into vitality. Inexhaustible assets have become a point of convergence of the natural development, both strategically and financially. Vitality got from sustainable assets puts substantially less strain on the constrained stock of non-renewable energy sources, which are non-renewable assets. The issue with utilizing inexhaustible assets for a huge scope is that they are exorbitant and, much of the time, more research is required for their utilization to be savvy.

Recently, it is observed that the electrical engineers are motivated to employ various soft computing methods to different optimization algorithms in electrical field. Presently available soft computing methods are categories as follows:

(i) NSGA II

(ii) Artificial Bee Colony (ABC)

(iii) Whale Optimization Algorithm (WOA)

(iv) SPEA 2

(v) RCGA

EAs are capable of finding near global optimum value for highly non-convex objective functions but the solution quality depends on the number of iterations an evolution process is allowed to continue. NSGA II has been found to be very efficient and reliable for on-line economic dispatch calculation. An integrated approach for EED with renewable sources and CHPD with renewable sources using NSGA II has the ability to accommodate the online demands of Economic Emission load Dispatch and also Combined Heat and Power Dispatch.

1.2 Literature Survey

Evolutionary algorithms (EA) [1]-[2] are search algorithms based on the simulated evolutionary development of natural collection and heredity. Genetic algorithm (GA) [3] belongs to a class of evolutionary computation techniques [4]-[5] based on model of biological growth. The main difficulty of GA is its binary representation which occurs when commencing with unceasing search space having extensive dimensional.

Optimal scheduling dispatch allots the energy requirement of a certain period of amidst the devoted production system commercially but gratifying different restrictions. DED is an augmentation of SED, decides the optimum division of changeable power requirement a midst the dedicated systems. DED is the greatest precise expression of the SED, however, the trickiest to resolve due to its bigger dimension. Recently, Optimization methods such as differential evolution

(DE) [15],[18], harmony search algorithm [16], particle swarm optimization (PSO) [17] are effectively used to resolve DED. Due to difficulties of binary representation when dealing with nonstop search space with large extent, real-coded genetic algorithm (RCGA) [19]-[20] has been employed.

Harmonic search algorithm (HS) has been projected for implementing the CHPED problem. The enhanced HS methods have gained better result quality than the unique one. However, the convergence quality of the HS has exposed that the method is still slow for getting optimal solution. Various heuristic methods like genetic algorithm (GA) [27], group search optimization (GSO) [28], cuckoo search algorithm (CSA) [30], integrated civilized swarm optimization (CSO) and Powell's pattern search (PPS) method [31] have been used for solving the CHPED problem.

An innovative ED model comprising of a Wind Energy Conversion System (WECS) was adapted in [21] to be deployed in an integrated renewable energy producing unit. The researchers employed a Weibull probability density function [22] to determine wind velocity in place of short-term anticipating of climate positions. The wind velocity distribution is then transformed to wind power distribution by applying the linear wind power equation. In [21], a two-fuel and two-wind generator system was applied and the research article focuses on many instances of coefficient alteration on which the proposed scheme depends. Chen [24] proposed a hybrid method thatcorrelatethewindandthermalgenerationschedulingproblemforfunctioning as a reliable and efficient hybrid power system.

In thermal balancing state all the particles' atoms can be converted to heat in the form of transmission, convection and emission. In every step of the planned process is implemented with equal prospect throughout an whole search method. The all procedure of three phases is calculated in such a way that the search space can be explored during the first half cycle and then it will be calculated the second half cycle. The maximization and minimization problem in optimizing fixed head hydrothermal system is defined by Michalewicz [32].

1.3 COMPARISON BETWEEN AI TECHNIQUES AND CONVENTIONAL METHODS

Artificial intelligent (AI) techniques like various computational systems, fuzzy systems and neural networks differ from conventional search optimization. The AI techniques mainly the following characteristics:

(i) SC method indicates can use the earlier facts for the way out of a difficulty and its activities under different situation while finding fresh results.

(ii) In the process of search, SC method indicates size of population is called potential solutions. This helps to perform parallel processing. But, Conventional method states that move from one point to other points without any parallelism.

(iii) SC method indicates the fitness information in lieu of function derivatives to the conventional method which uses the higher order cost function.

(iv) SC paradigms use probabilistic transition rules rather than deterministic one as in the case of conventional paradigms.

Most of the classical conventional systems the optimization method generates a sequential of higher order cost function. The system can be generated sequentially and asymptotically converge for getting optimal solution. They move from one point in the decision hyperspace to another using some deterministic rule. These means repeatedly fall short to execute sufficiently when arbitrary perturbations are forced on the cost characteristics. Accordingly AI method new population size will be generated which will balance the number of generation. So maximization or minimization can be developed in same time to reduce the local minimum.

The various Swarm Intelligence techniques and Evolutionary strategy such as PSO, Bacterial Foraging Algorithm (BFA) [17], Ant Colony Optimization (ACO) [18], Artificial Immune System (AIS) and Differential Evolution (DE) have received much attention of the power engineering community from the perspective of reliability and efficiency. The PSO method was developed to know the social and cognitive characteristics, but the algorithm was applied in different engineering problems. In general, PSO method computes the traditional capability of human societies and to know the different steps through interaction, cooperation and social learning. The BFA is a new member of SI that exploits the seek and optimal foraging decision-making of animals in solving engineering problems. In recent times, the social foraging conduct of E.Coli micro organism has been used to resolve optimization troubles. The Artificial immune scheme is a verity of cells, molecules and organs which are able to doing several obligations, like sample reputation, studying, memory acquisition, distributed detection and optimization.

According to on immunological law, new computational algorithms are developed to solve the engineering problems. These strategies generate sequences that asymptotically converge to local optimum.

The intelligent algorithms, which are population based stochastic methods are conventional which indicates the solution of population size instead of single size solution, independence of first variables which are close to success rate variables and robustness of real-world solution.

1.4 Solution Methodology:

Mathematical optimization methods are being widely used over the years in solving power system problems on planning, operation and control. These techniques aim at finding the optimum solution of continuous and differentiable functions. But, the algorithms of these techniques are not green in managing proposals having discrete parameters. Also, they can't be correctly implemented on parallel technology. However, these techniques may be classified into three categories, viz. calculus based, enumerative and random search. Calculus based methods make use of the derivatives. They are excellent for unimodal and continuous functions. But, in case of multi-modal functions, these methods can only find the local minima. Now, most of the real life problems have multiple peaks or discontinuous search spaces or both. As a result these calculus based methods are not satisfactory for most of the real life problems. For enumeration technique, the values of the functions to be optimized are found out at every point of the search space. But, for practical problems having too large search spaces, enumeration techniques turn out to be very inefficient and sometimes even incapable. Random search algorithms are not in any way better than the enumeration techniques. To be specific, the conventional search techniques are not at all that robust to be advocated for wide acceptance.

There are a wide range of mature mathematical programming topologies, viz. Linear Programming (LP) [9], Interior Point (IP) method [10], Quadratic Programming (QP) [11], etc. Some of these strategies aren't accomplished of fixing optimization issues with a non-convex, discontinuous and fairly nonlinear result area. Other procedure turns out to be ineffective given that they require too many computational ideas to offer precise results for massive electric power framework. The current progress in computation as well as the search for higher consequences of complicated optimization issues has resulted in the improvement of practice identified as

Evolutionary Algorithms.

Global optimization techniques of the past decades are Genetic Algorithms (GA) [12], Tabu Search (TS) [13], and Artificial Neural Networks (ANN) [14] are all probabilistic heuristic set of rules and that they were efficaciously used to triumph over the non-convexity issues of the constrained ELD. Amongst these the GA scheme is most efficient because of its parallel seek strategies which imitate usual genetic operations.

Recently, Artificial Intelligence (AI) [15] is the most recent addition to the heuristic algorithm. It comes forward as a fast and strong optimization means in achieving remarkable success in solving various complex real-world power system optimization problems. Swarm systems are characterized as multiple lower level competences, ability to change environment, limited time to act, autonomous with no explicit control provision and problem solving through collective cooperation along with emphasis on reaction and adaptation.

In the present research work, the NSGA II and SPEA 2 techniques was useful to different problems such as Economic Emission Dispatch with renewable sources and also Multi Region Combined Heat and Power Dispatch with renewable sources for different test systems of dispatch solution and comparisons between them.

1.5 Aim of the recent approach:

The aim of the contributed approach mainly for developing the solution of producing power dispatch problem using soft computing methods. The targeted problems are:

(i) the performance and characteristics of solution procedures for EED of a thermal and wind energy power system to allocation of production cost of running units , NO_x extraction status and SO_2 extraction status whilst gratifying each and every experimental constraint using NSGA-II for issue of different systems.

(ii) the performance and characteristics of solution procedures for EED of a hydrothermal and wind energy power system to allocation of production cost of running units , NO_x extraction and SO_2 extraction status whilst gratifying of all constraint using NSGA-II for issue of different systems.

(iii) to develop and to study the performance of solution procedures for EED of a thermal with solar and wind energy power system to allocation of production cost of running units , NO_x extraction and SO_2 extraction status whilst satisfying all constraint using NSGA-II for issue of different systems.

(iv) to develop and to study the performance of solution procedures for Multiple-Area of Combined Heat and Power Economic Emission Dispatch whilst satisfying all constraint using NSGA-II for issue of different systems.

(v) to develop and to study the performance of solution procedures for MRCHPEED with solar and wind power system whilst satisfying all constraint using NSGA-II for issue of different systems.

1.6 Motivation behind the work

The valve-point impact, restricted working regions, ramp rate limits and different imperatives transform the choice space into disjoint subsets, changing the a large portion of the power framework into difficult non-smooth, non-convex optimization problems. The analytics based strategies neglect to address these sorts of issues. The dynamic programming strategy has no limitations on the state of the target work and can take care of these sorts of issues. Be that as it may, this strategy experiences the scourge of dimensionality or nearby optimality. Present day intelligent calculations are promising choices for the arrangement of complex force framework improvement issues. Keeping this in mind, this work mainly focuses on complex power system optimization by using various intelligent control methods.

CHAPTER-2

Multi-objective Economic Environmental Dispatch of Variable Hydro-Wind-thermal Power System

2.1. Introduction:

Electricity generation from fossil fuel releases various types of pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x) and carbon dioxide (CO_2), which are discharged in the air. Hence, reducing the air pollution is one of the major challenges for electric utilities. The 1990 Clean Air Act is aimed at decreasing acid rain and green house gases. This also necessitate that the fossil-fired electric power plants must reduce its sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emission level. Nowadays, the modern civilization requires adequate and secure electricity at economical cost as well as at minimized echelon of pollution.

Various methods have been suggested in the literature to bring down the environmental pollution [32].This considers the installation of switching device that maintains the emission level, use of low emission fuels, replacement of the old burners with new ones and dispatching with emission consideration. The three initial methods require the setting up of new equipments and/or alteration of the existing equipments that involves significant funds disbursement. Therefore, the last method is more recommended. Diverse techniques [33] - [37] have been discussed related to the Economic Emission Dispatch (EED) problem. However, these techniques cannot handle the non-linear fuel cost and emission level functions.

Earlier, various researches have already discussed regarding the growth of multiobjective optimization methods such as Strength Pareto evolutionary algorithm[36], Non-dominating sorting genetic algorithm-II[37], multi-objective evolutionary algorithm[38], multi-objective particle swarm optimization[39], fuzzy clustering-based particle swarm optimization[40], multi-objective differential evolution[41], cultural quantum-behaved particle swarm optimization[42]. Various classical techniques [37, 46 & 45] have been effectively utilized for solving the hydrothermal scheduling problem since a number of decades. However, the Stochastic search algorithms are very faster, accurate such as simulated annealing [46], genetic algorithm [47], evolutionary programming technique, differential evolution [49], particle swarm optimization [50], clonal selection algorithm [51], teaching learning based optimization [51], modified chaotic differential evolution [52],ant lion optimization[53], real-coded genetic algorithm based on improved Muhlenbein mutation [54] and improved harmony search algorithm [55] etc. In addition, various other evolutionary algorithms [56]-[58] are deployed for resolving the economic environmental dispatch of hydrothermal power system.

Due to the complicated operational restrictions associated with hydro, thermal, and wind power generating units, it is discovered that the integration of hydrothermal scheduling with wind energy i s a non-linear and extremely hard optimization problem. The economic environmental dispatch of hydro-wind-thermal power system the three objectives i.e. cost, NO_x emission and SO_2 emission are to be considered at the same time to find the most favorable dispatch while satisfying all the equality and inequality constraints.

This paper demonstrates a NSGA-II for economic environmental dispatch of hydro-wind-thermal power system where three objectives i.e., cost, sulfur dioxide (SO_2) emission and nitrogen oxides (NO_x) emission are simultaneously optimized while considering the wind power uncertainty, cascaded hydro plant with water transport delay, reservoir limits, dynamic water discharge limits, hydraulic balance constraints, valve point effect of thermal generating units, power balance and capacity limits of hydro-wind-thermal power generating units. Real-Coded Genetic Algorithm (RCGA) [59]-[61] has been utilized in order to get rid of the cumbersome binary notation of dealing with continuous search space with large dimensions. Moreover, the Simulated Binary Crossover (SBX) and polynomial mutation is employed in the current proposition.

Extensive experiments have been carried out for validating the proposed scheme by pertaining it on Test System 1 and Test System 2. The results reported from the investigation on NSGA-II is compared and analyzed to that obtained from SPEA2.

2.2. Problem Formulation

The hydro-wind-thermal system's Economic Emission Dispatch (EED) is offered as a way to simultaneously optimize the three objective functions of cost, SO2 emission, and NOx emission while adhering to operational restrictions. Below is a discussion of the purpose and limitations that are used in the current study.

2.2.1. Objectives

(i) Cost

The prepared expense of a thermal-wind-solar system involves the raw material rate for coal-based units alongside the expense of wind energy creating entity. The complete expense can be expressed as:

$$F_C = \sum_{i=1}^{\mathrm{N}_s} f_{si}\left(\mathrm{P}_{si}\right) + \sum_{k=1}^{\mathrm{N}_w} f_{wk}\left(\mathrm{P}_{wk}\right) \tag{2.1}$$

The raw material charge capacity of every coal based unit, thinking about the valve point impact, is articulated like.

$$f_{si}\left(\mathrm{P}_{si}\right)=a_{si}+b_{si}\mathrm{P}_{si}+c_{si}\mathrm{P}_{si}^{2}+\left|d_{si}\times\sin\left\{e_{si}\times\left(\mathrm{P}_{si}^{\min}-\mathrm{P}_{si}\right)\right\}\right| \tag{2.2}$$

The expense of wind power incorporates three segments - an immediate fuel charge, an under estimation penalty fuel charge and a spare fuel charge due to over estimation of wind control. Henceforth, the charge related to wind energy conversion of ith generated entity at mth time is figured as [77]

$$f_{wk}=\left\{\left(d_{k}\times\mathrm{P}_{wk}\right)+C_{pk}\left(W_{k,av}-\mathrm{P}_{wk}\right)+C_{rk}\left(\mathrm{P}_{wk}-W_{k,av}\right)\right\} \tag{2.3}$$

$$C_{pk}\left(W_{k,av}-\mathrm{P}_{wk}\right)=\mathrm{K}_{\mathrm{P}k}\left(W_{k,av}-\mathrm{P}_{wk}\right)=\mathrm{K}_{\mathrm{P}k}\times\int_{\mathrm{P}_{wk}}^{\mathrm{P}_{wrk}}\left(w-\mathrm{P}_{wk}\right)f_{w}(w)\,dw \tag{2.4}$$

$$C_{rk}\left(\mathrm{P}_{wk}-W_{k,av}\right)=\mathrm{K}_{rk}\left(\mathrm{P}_{wk}-W_{k,av}\right)=\mathrm{K}_{rk}\times\int_{0}^{\mathrm{P}_{wk}}\left(\mathrm{P}_{wk}-w\right)f_{w}(w)\,dw \tag{2.5}$$

$$f_{w}(w)=\frac{k_{s}hv_{in}}{\mathrm{P}_{wr}c}\left[\frac{\left(1+\frac{hw}{\mathrm{P}_{wr}}\right)v_{in}}{c}\right]^{k_{s}-1}\times\exp\left\{-\left[\frac{\left(1+\frac{hw}{\mathrm{P}_{wk}}\right)v_{in}^{k_{s}}}{c}\right]\right\} \tag{2.6}$$

The wind power categorization is ended via employing Weibulpdf, $f_{w}(w)$. At this point $h=\frac{v_{r}}{v_{in}}-1$ .Detail description can be found in [46] and [47].

(ii) NO$_x$ Emission

Since NOx emissions from thermal power plants are produced from a variety of sources, they are challenging to mimic. NO$_x$ emission is not simple to represent since they are highly nonlinear and

[62] proposed NO_x emission to be a combination of quadratic and exponential function which can be stated as:

$$D_{NO_x} = \sum_{i=1}^{N_s} \left[\alpha_{ni} + \beta_{ni} P_{si} + \gamma_{ni} P_{si}^2 + \eta_{ni} \exp\left(\delta_{ni} P_{si} \right) \right] \tag{2.7}$$

(iii) SO_2 Emission

The SO2 emission of a thermal power plant is proportional to the fuel consumption of the thermal unit, and it can be expressed as a quadratic function [63] of generator power output.

$$D_{SO_2} = \sum_{i=1}^{N_s} \left[\alpha_{si} + \beta_{si} P_{si} + \gamma_{si} P_{si}^2 \right] \tag{2.8}$$

2.2.2. Constraints

(i) Power balance constraint

The complete active power production must adjust the anticipated power request in addition to active power losses in the transmission lines.

$$\sum_{i=1}^{N_s} P_{sim} + \sum_{j=1}^{N_h} P_{hjm} + \sum_{k=1}^{N_w} P_{wkm} - P_{Dm} - P_{Lm} = 0, \quad m \in M \tag{2.9}$$

In general, the hydro plant power output can be expressed in terms of the turbine discharge rate and storage, which is mathematical represented as [33]

$$P_{hjm} = C_{1j} V_{hjm}^2 + C_{2j} Q_{hjm}^2 + C_{3j} V_{hjm} Q_{hjm} + C_{4j} V_{hjm} + C_{5j} Q_{hjm} + C_{6j}, \; j \in N_h \; m \in M \tag{2.10}$$

The total transmission loss P_{Lm} can be calculated by using B-coefficient, which is stated as:

$$P_{Lm} = \sum_{i=1}^{N_t} \sum_{j=1}^{N_t} P_{im} B_{ij} P_{jm} + \sum_{i=1}^{N_t} B_{0i} P_{im} + B_{00} \tag{2.11}$$

Where, B_{ij}, B_{0i} and B_{00} are B-coefficients. Here, total number of plants $\mathrm{N}_t = \mathrm{N}_s + \mathrm{N}_h + \mathrm{N}_w$ and P_{im} and P_{jm} are the respective thermal, hydro and wind power generation.

(ii) Generation limits

$$\mathrm{P}_{hj}^{\min} \le \mathrm{P}_{hjm} \le \mathrm{P}_{hj}^{\max} \quad j \in \mathrm{N}_h \; m \in \mathrm{M} \tag{2.12}$$

$$\mathrm{P}_{si}^{\min} \le \mathrm{P}_{sim} \le \mathrm{P}_{si}^{\max} \quad i \in \mathrm{N}_s, \; m \in \mathrm{M} \tag{2.13}$$

$$\mathrm{P}_{wk}^{\min} \le \mathrm{P}_{wkm} \le \mathrm{P}_{wk}^{\max} \quad k \in \mathrm{N}_w, \; m \in \mathrm{M} \tag{2.14}$$

(iii) Hydraulic network constraints

In addition to the bounds for storage reservoir, the hydraulic constraints also include the water balance equations for each hydro unit. The physical reservoir, plant limitations and the multipurpose necessity of the hydro system are the deciding factors of the storage limits. These constraints comprise of the following:

(iii)(a) Physical limitations on reservoir storage volumes and discharge rates

$$V_{hj}^{\min} \le V_{hjm} \le V_{hj}^{\max} \quad j \in \mathrm{N}_h, \; m \in \mathrm{M} \tag{2.15}$$

$$Q_{hj}^{\min} \le Q_{hjm} \le Q_{hj}^{\max} \quad j \in \mathrm{N}_h, \; m \in \mathrm{M} \tag{2.16}$$

(iii)(b) The continuity equation for the hydro reservoir network

$$V_{hj(m+1)} = V_{hjm} + \mathrm{I}_{hjm} - Q_{hjm} - S_{hjm} + \sum_{l=1}^{R_{uj}} \left(Q_{hl(m-t_{lj})} + S_{hl(m-t_{lj})} \right), \; j \in \mathrm{N}_h, \; m \in \mathrm{M} \tag{2.17}$$

2.3 Principle of Multi-Objective Optimization:

Multi-target optimization issue involving various destinations and constraints like primary and secondary may be expressed like:

Minimize $f_i(x)$, $\boldsymbol{i}$ =1,…..,N$_{\text{obj}}$ (2.18)

area under discussion $\begin{cases} g_k(x) = 0 & k = 1,....,\mathrm{K} \\ h_l(x) \leq 0 & l = 1,....,L \end{cases}$ (2.19)

Where f_i is the i $^{\text{th}}$ intent function, x is a assessment vector.

2.4. Nondominated Sorting Genetic Algorithm-II:

To deal with multi-target optimization issues, NSGA has been proposed in the year of 1995. Non-domination is utilized to offer position to arrangements, and strength contribution is profited in support of expansion command over in the investigation area. Because of not highly susceptible to fitness sharing parameters of NSGA,[65] have instigated NSGA-II as it produce more authentic and dependable solution speedy than its precursor. Because of word constraints, the fact depiction of NSGA-II isn't given in the paper. The progression of occasions in 'NSGA-II' is introduced in Figure.I after given all the section one by one.

i) Fast nondominated sorting procedure

To accumulate way out of the initial nondominated the face in a inhabitants of dimension, each answer be able to be matched up to all extra answer inside the inhabitants to unearth if it's far conquered. By the side of the particular step, all community inside the first nondominated the front are created. In order to unearth the individuals inside the next nondominated front, the solutions of the first front are marked down for the time being and every answer of the residual populace can be matched as much as each different answer of the residual inhabitants to unearth if it is to governed.

Accordingly the entire particular inside the next nondominated face are created. This is right for creating third and higher tiers of nondomination.

In support of every way out two components are computed: a) dominion count n_q, the quantity of arrangements which overwhelm the arrangement q, and b) S_q, a lot of arrangements that the arrangement overwhelms. The approach for the rapid nondominated category can be stated as:

So as to uncover the people in the following nondominated front, the arrangements of the principal front are discounted for the present and every arrangement of the lingering populace can be coordinated up to each other arrangement of the remaining populace to uncover on the off chance that it is ruled. In this manner all people in the subsequent nondominated face are made. This is directly for making third and more elevated degrees of non-domination.

The algorithm for the fast nondominated category can be stated as:

Algorithm 1: Fast non dominated category

```
For each $p \in P$
  $S_p = \phi$
$n_p = 0$
for each $q \in P$
if $(p \prec q)$ then                if $p$ dominates $q$
$S_p = S_p \cup \{q\}$               add $q$ to the set $p$
else if $(q \prec p)$ then
$n_p = n_p + 1$                      augmentation of $p$
if $n_p = 0$ then                    $p$ fit in to the initial face
$P_{rank} = 1$
$F_1 = F_1 \cup \{p\}$
```

Every one inhabitants is given a grade identical to its nondomination degree or the face wide variety (1 for the exceptional stage and 2 for the following-great degree and so forth).

ii) Fast crowded distance estimation procedure

To collect an estimation of the concentration of answers contiguous a specific clarification within the populace, the common space of spots on both part of this thing beside all the targets is computed. This number provides as an estimation of the outer limits of the cuboid primarily based by the use of the closest pals because the vertices which may defined as crowding distance. This computation necessitates categorization of the populace in keeping with every goal feature fee in rising array of significance. Subsequently, in favor of every goal characteristic, the boundary populations (populations among nominal and biggest characteristic standards) are provided especially excessive distance fuel rate in order that boundary elements are constantly chosen. All different transitional inhabitants are supplied a distance price identical to the fixed regularized distinction inside the function standards of adjoining inhabitants. This computation is kept on with added goal capabilities. The crowding-distance assessment is computed because the total of individual distance values matching to every goal. Every purpose characteristic is regularizing ahead of computing the crowding distance. The set of rules underneath portrays the crowding distance calculation method of the entire answers in a nondominated set G.

Algorithm 2: Crowding distance assignment

```
$l = |G|$                                  digit of answer in G
for each $i$, set $F[i]_{distance} = 0$          expressed distance  in favour of every intention $n$
$G =$ Sort$(G, n)$   Arrange by means of every objective assessment
$G[1]_{distance} = F[l]_{distance} = \propto$
```

in favour of $j=2$ to $(k-1)\ G[j]_{distance} = G[j]_{distance} + (G[j+1].n - G[j-1].n)/(f_m^{\max} - f_m^{\min})$ Here, $G[i].n$ refers to the mth objective function value of the i^{th} entity in the position G. $f_m^{\max}$ and $f_m^{\min}$ are the greatest and least standards of the mth objective purpose.

iii) Crowded-comparison manipulator

The crowded- comparison manipulator conducts the collection technique at a selection of tiers of the set of rules closer to a uniformly spread-out pareto-optimal front. All individual within the populace has two aspects:

a) nondomination rank (i_{rank})

b) crowding distance $(i_{distance})$

$i \prec j$ if $i_{rank} < j_{rank}$ or $((i_{rank} = j_{rank})$ and $(i_{distance} > j_{distance}))$

Between populaces with varying nondomination positions, the individuals with the lower (better) position are wanted. On the off chance that the two populaces have a place with the equivalent front, at that point the masses with bigger swarming separation is supported.

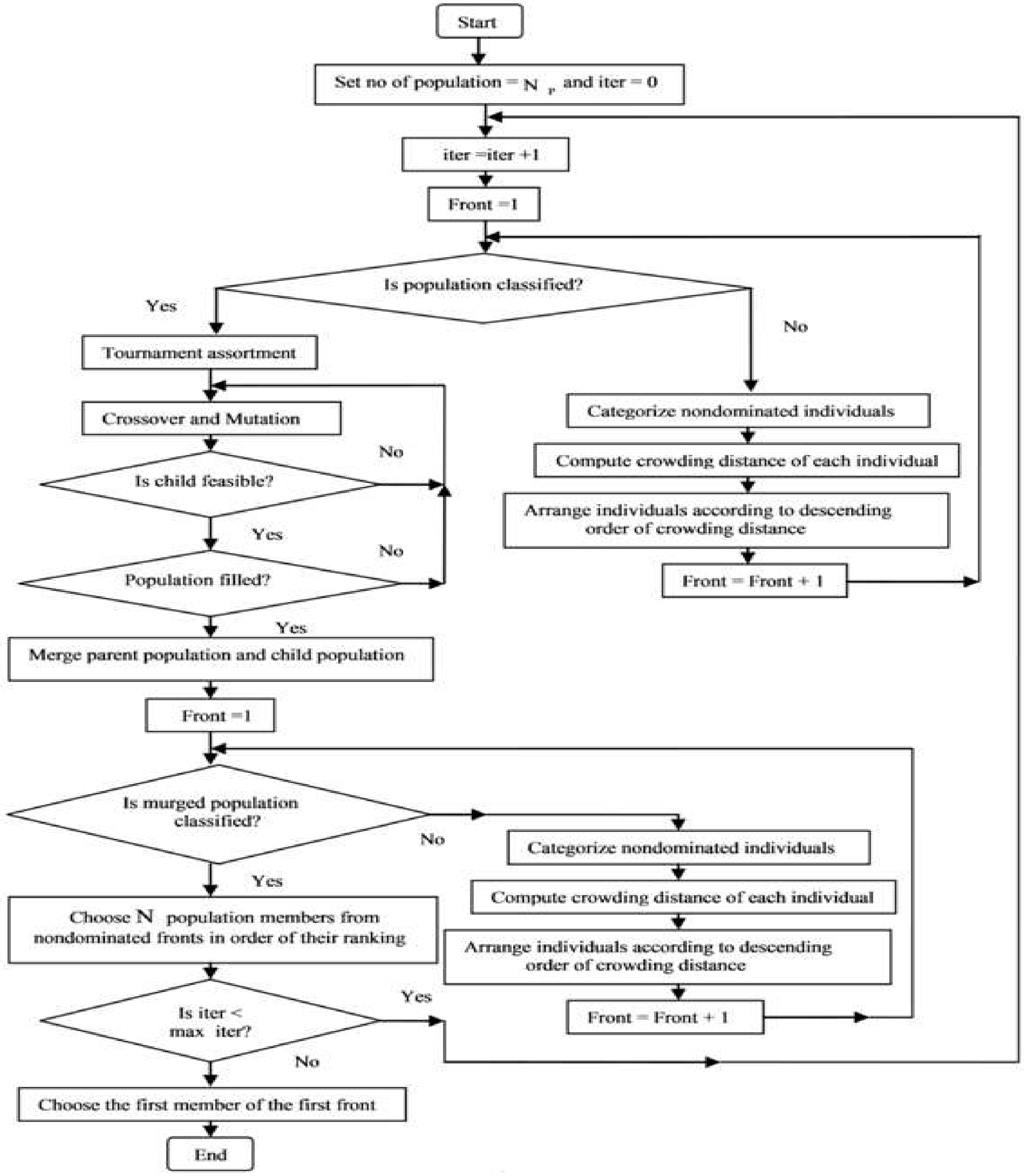

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Figure 1: Flowchart of NSGA II

2.5 Case Study of Multi-objective Economic Environmental Dispatch of Variable Hydro-Wind-thermal Power System:

The suggested method has been used to resolve Test Systems 1 and 2. SPEA 2 has been used to solve the problem in order to assess the effectiveness of the suggested NSGA-II technique. On a PC, MATLAB 7.0 has been used to run the planned NSGA-II, SPEA 2, and RCGA (Pentium-IV, 80 GB, 3.0 GHz).

The current study uses Real-Coded Genetic Algorithm to individually minimize Cost, NOx Emission, and SO2 Emission as the three goal functions (RCGA). For the sake of this study, the population size, crossover probability, and mutation probability values for these two test systems have been set at 100, 0.9, and 0.2, respectively. For Test System1 and Test System2, the maximum iterations have been set at 200 and 300, respectively. The population size, maximum number of iterations, crossover, and mutation probabilities for NSGA-II and SPEA 2 has been chosen as 20, 30, 0.9, and 0.2 for both test systems.

2.5.1 Test System 1

This system takes into account a cascade of three thermal power plants, two wind power generating units, and four reservoir hydroelectric plants. One day, divided into 24 intervals, makes up the entire schedule period. It considers the impact of transmission loss and valve point loading. The parameters for Test System 1 were derived from [49]. Cost coefficients, NOx and SO2 coefficients were obtained from [34].The Weibull shape and scale factor for the two wind power generators have been taken as: $k_{s1} = 1.5$, $k_{s2} = 1.5$ and $c_1 = 15$, $c_2 = 15$. The direct, reserve and penalty cost coefficients for the two wind power generating units are taken as $d_1 = 1, d_2 = 1$, $\mathrm{K}_{r1} = 5, \mathrm{K}_{r2} = 5$, $\mathrm{K}_{\mathrm{P}1} = 5$ and $\mathrm{K}_{\mathrm{P}2} = 5$ respectively. The specification of wind power generators are $P_{wr1} = 175$ MW and $P_{wr2} = 175$ MW respectively. The cut in, cut out and rated wind speeds are $v_{in} = 5$, $v_o = 45$ and $v_r = 15$ respectively.

Cost, NO_x emission and SO_2 emission objectives are minimized individually by using RCGA. In this approach power generations and power loss acquired from cost minimization, NO_x emission minimization and SO_2 emission minimization have been shown in Table 1, Table 2 and Table 3 respectively. Table 4 summarizes the power loss acquired from cost, NOx emission, and SO2 emission objectives that were simultaneously optimized using NSGA-II for hydro-wind-thermal power generation.. It is seen from Table 1 that under economic dispatch, cost, NOx emission and SO_2 emission are 131136.6 \$, 14.7240 t and 51.9371 t respectively. Table 2 shows that under NOx emission dispatch, cost, NOx emission and SO_2 emission are 137042.8 \$, 14.1433 t and 53.0266 t respectively. Table 3 shows that under SO_2 emission dispatch, cost, NOx emission and SO_2 emission are 134140.7 \$, 14.6116 t and 51.4082 t respectively. Table 4 indicates that cost, NOx emission and SO_2 emission are 135476.2\$, 14.4511 t and 52.2727 t respectively, which are the optimized values obtained from NSGA-II.

Figures 2(a), 2(b), 2(c), and 2(d) show the hourly discharges of four hydroelectric plants as determined by cost minimization, NOx emission minimization, SO2 emission minimization, and NSGA-II, respectively. The reservoir storage volumes of four hydroelectric plants are shown in Figures 3(a), 3(b), 3(c), and 3(d), respectively, based on cost minimization, NOx emission minimizing, SO2 emission minimization, and NSGA-II. Figure 4 illustrates the characteristics of cost convergence, NOx emission convergence, and SO2 emission convergence. In the last iteration of suggested techniques, where cost, NOx emission, and SO2 emission targets are all maximized simultaneously, the distribution of 20 nondominated alternatives is also shown.

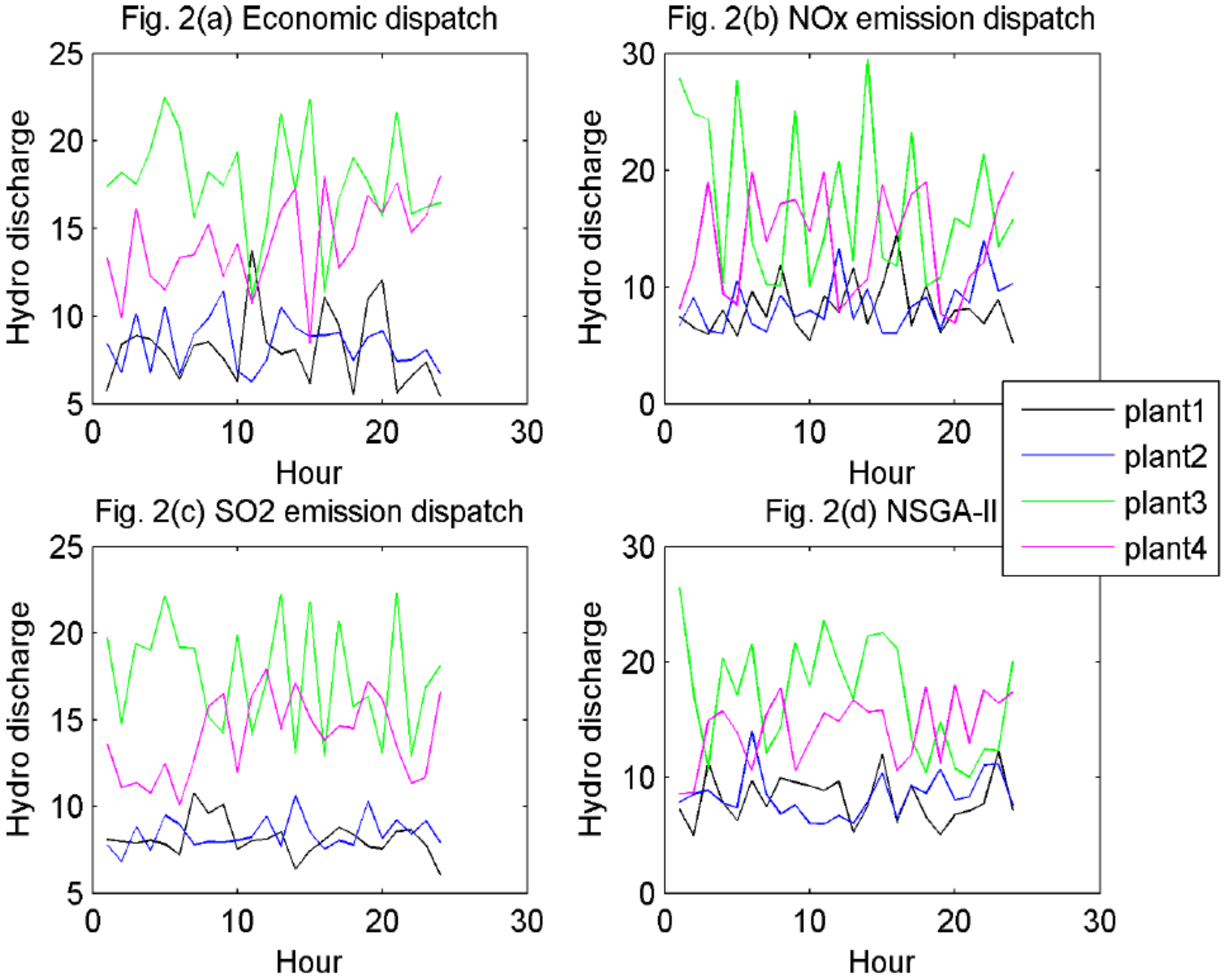

Figure 2. Discharges from hydro plants ($\times 10^4 m^3$) of Test System 1 obtained from NSGA-II, NOx emission dispatch, SO2 emission dispatch, and economic dispatch.

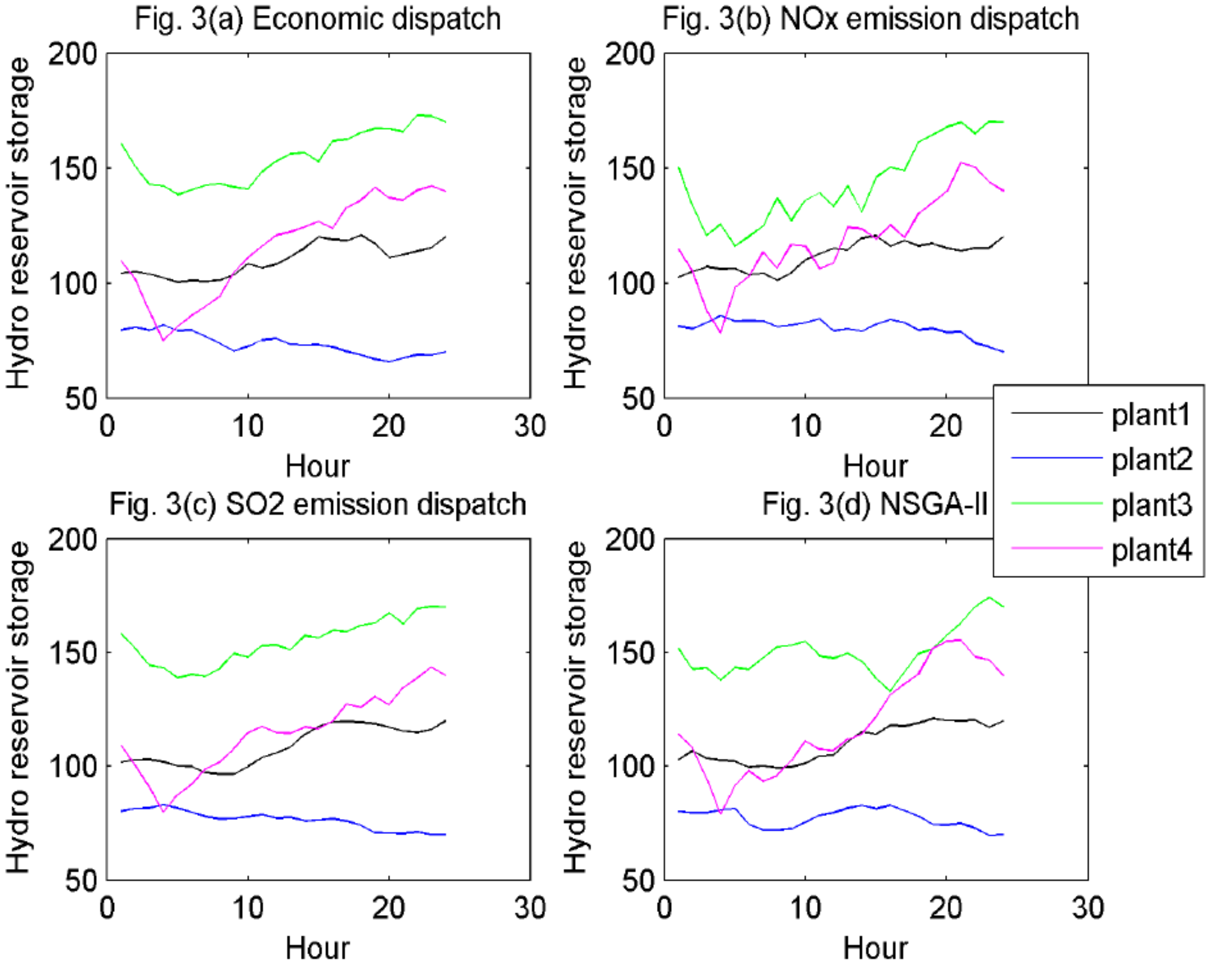

Figure 3. Hydro reservoir storage volumes $(\times 10^4 m^3)$ for Test System 1 collected from NSGA-II, economic dispatch, Nox emission dispatch and SO2 emission dispatch.

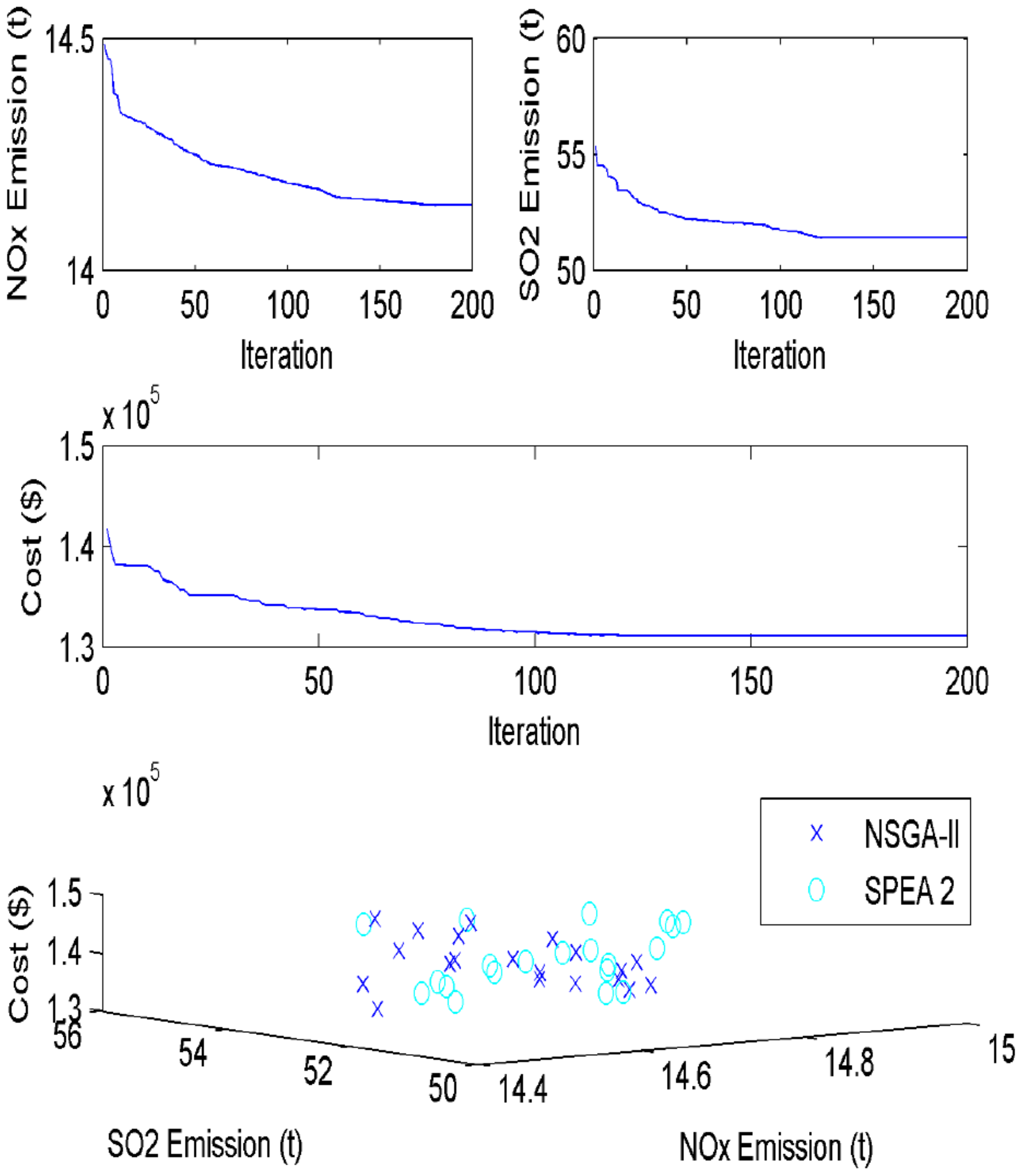

Figure 4 shows the convergence of NOx emission, SO2 emission, cost convergence, and the pareto-optimal front for test system 1.

Table 1: Hydro-wind-thermal power generation (MW) and power loss (MW) for economic dispatch of test system.

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{w1}	P_{w2}	P_{loss}	Cost ($)	NO_x Emission (t)	SO_2 Emission (t)
1	58.6670	64.4252	53.5261	214.5944	31.4136	79.7999	96.2354	82.4915	71.9621	3.1152	131136.6	14.7240	51.9371
2	78.8174	54.1759	48.7241	169.1242	69.9557	79.5411	162.6131	43.0297	79.6574	5.6385			
3	81.8590	73.7617	47.7658	215.0032	66.6061	111.5108	52.7675	39.0292	15.0754	3.3789			
4	80.3897	54.0310	38.0945	167.1017	53.6166	42.1251	51.7547	87.2665	77.8836	2.2634			
5	74.6719	76.2189	22.6866	144.3796	79.3127	45.1722	96.6843	66.6551	67.7312	3.5224			
6	64.1841	53.4148	30.8960	168.0002	76.0752	190.7405	95.3453	35.8661	90.2586	4.7808			
7	77.5250	67.1284	49.1015	175.3937	116.5783	185.4166	143.6534	73.1026	69.9635	7.8629			
8	78.5759	69.7897	42.7681	193.7605	74.3587	235.4526	188.5435	100.5031	35.08847	8.8368			
9	72.8276	74.3503	45.5819	175.3031	111.9991	170.5344	234.8136	93.9160	122.4107	11.7368			
10	63.9555	48.7099	38.2114	203.4738	68.2881	161.6936	282.0584	121.3983	105.3237	13.1128			
11	100.9770	46.1358	51.5407	179.2435	114.5632	151.2234	237.0384	125.1303	105.9186	11.7710			
12	79.9906	46.1358	52.3823	209.8763	114.3658	183.0854	191.1519	129.8883	143.1642	9.7710			
13	76.1483	72.0709	32.2193	237.0924	113.9466	108.0959	280.5692	104.8789	99.2591	14.2806			
14	78.5584	64.9511	50.2617	247.6656	129.0499	132.8524	102.7892	137.2664	93.5324	6.9270			
15	64.6907	62.2431	28.7471	167.4421	70.9756	237.9013	181.7342	102.0617	102.5145	8.3101			
16	96.6770	62.5460	54.6848	257.5210	106.8541	222.2970	52.5442	108.5192	104.9003	6.5436			
17	88.4038	62.7299	53.1803	212.9159	117.3670	74.5038	146.8396	155.7116	145.2385	6.8904			
18	59.9219	52.5667	46.3241	232.8608	65.8151	252.8712	235.4944	59.2136	126.3026	11.3704			
19	96.2021	58.8642	51.8160	260.3356	68.6218	168.1914	178.3802	96.6069	98.6759	7.6941			
20	99.7088	59.4606	56.3667	258.9437	98.7705	136.8491	140.3301	92.6694	113.7932	6.8921			
21	59.7924	48.9957	36.4170	266.3451	116.6123	67.5906	96.9494	112.4650	110.4447	5.6121			
22	67.6460	50.6037	55.8473	243.9298	81.1450	125.5576	69.4260	106.9726	63.0578	4.1858			
23	73.9776	55.0365	56.8221	255.6265	68.3440	46.5475	118.3550	33.3099	146.4871	4.5061			
24	58.4930	46.6518	56.2441	274.7020	116.4122	40.7737	51.5321	34.6606	125.3615	4.8309			

Table 2: Hydro-wind-thermal generation (MW) and power loss (MW) for NOx emission dispatch of test system 1.

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{w1}	P_{w2}	P_{loss}	Cost ($)	NO_x Emission (t)	SO_2 Emission (t)
1	71.4793	53.5779	10.0000	159.9269	136.6307	64.6679	79.7147	16.6073	162.9612	535659	137042.8	14.1433	53.026
2	65.6506	68.9010	10.2544	193.6053	55.5402	104.7393	191.2541	81.1847	15.7186	6.8482			
3	61.7210	50.8154	6.1863	236.3718	44.7646	97.1640	51.2729	20.5305	133.9313	2.7577			
4	77.0915	51.0313	45.2646	140.1162	34.3975	67.3664	96.6601	118.8558	21.9026	2.6860			
5	60.7180	78.5236	10.0000	118.8526	87.5987	49.3977	161.3592	17.0012	92.2868	5.7378			
6	860376	56.8747	43.1900	230.3967	54.3364	45.2139	257.9151	35.3230	1.2625	10.5499			
7	72.2965	52.4473	45.0268	199.3249	93.3178	63.0797	159.6895	159.8799	111.1267	6.1891			
8	94.7638	71.1532	46.3521	236.0543	53.9173	120.3118	346.7685	46.3390	12.2811	17.9710			
9	68.0480	59.4505	2.6923	229.4335	84.1812	57.6923	354.7748	102.3571	150.2269	18.8566			
10	56.6718	63.0650	46.8574	222.5389	67.6067	277.6026	128.8764	145.6033	78.2167	7.0388			
11	85.2493	58.9143	49.9332	254.6423	41.0069	117.9022	247.1741	136.3928	118.4260	10.1871			
12	76.8952	87.8571	30.8655	142.5906	29.5066	163.9563	355.2231	158.8547	122.7038	18.4529			
13	975345	56.5829	50.0620	163.2980	106.0733	88.1138	263.7045	123.1087	173.9211	12.3989			
14	70.0639	71.8768	10.0000	192.2768	173.9277	57.9578	183.7456	167.7372	113.5362	11.1220			
15	92.0152	49.0123	49.2882	258.1480	163.2639	70.7875	177.1387	40.4235	120.5127	10.5899			
16	106.5547	50.6036	53.4685	222.7132	40.8811	49.7910	375.0555	89.1325	91.7630	19.9630			
17	69.4356	66.2231	21.0472	255.1529	78.9552	40.3319	287.1652	133.4175	111.4443	13.1730			
18	91.7229	69.9676	52.3755	254.7661	62.8626	105.8782	181.3548	139.0116	169.1503	7.0932			
19	64.2734	50.9431	55.9345	163.3034	119.6758	77.5846	246.8345	135.7810	167.2638	11.5943			
20	79.0746	71.8853	55.3931	156.4002	103.7163	40.0815	293.3790	90.2797	1173.8198	14.0269			
21	79.3624	64.6697	57.3522	209.1756	93.9506	41.1125	218.8325	122.3488	32.1977	9.0020			
22	70.1650	85.7441	38.4950	233.6094	89.4164	65.6622	180.0411	100.6355	3.4740	7.2396			
23	84.7623	66.8976	57.9286	276.3305	38.2660	41.1614	248.8832	42.8118	3.1312	10.1791			
24	56.7749	68.6244	56.9935	2883441	72.1462	56.6330	88.1669	91.5921	24.9633	4.2384			

Table 3: Hydro-wind-thermal generation (MW) and power loss (MW) for SO_2 emission dispatch of test system.

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{w1}	P_{w2}	P_{loss}	Cost ($)	NO_x Emission (t)	SO_2 Emission (t)
1	75.6565	60.5969	45.8941	216.9332	59.5078	116.6570	75.3116	25.7792	77.1299	3.4662	134140.7	14.6116	51.4082
2	75.5258	54.7273	55.4728	181.3766	50.6198	121.7569	88.5475	69.7781	85.5173	3.3223			
3	75.1562	67.5086	41.6085	174.3589	42.8820	72.37512	127.5438	38.1439	64.2835	3.8604			
4	76.2271	59.6625	40.6552	157.0418	38.6582	63.2490	58.9519	121.5958	36.1026	2.1441			
5	74.5371	72.0995	25.2040	159.0797	65.9294	107.6330	63.6926	27.2297	77.6234	3.0284			
6	69.9864	68.3670	37.9138	146.0815	61.0009	74.7541	151.2516	121.8014	73.7054	4.8620			
7	89.2597	60.6294	38.6074	175.9152	100.5326	123.6553	107.5238	144.8219	114.3505	5.2957			
8	83.0825	60.3511	49.6728	208.6145	95.3126	125.0788	146.3978	148.3556	99.5523	6.4180			
9	85.1973	59.7205	51.9490	217.6424	66.2824	179.3663	230.2673	96.5423	113.0948	10.0622			
10	71.1576	60.4276	38.8308	188.1625	102.7414	230.8210	121.0708	142.4686	131.5824	7.2625			
11	75.3071	61.9988	53.4691	232.6765	54.3089	158.7983	298.2596	116.6549	62.6481	14.1212			
12	76.9855	69.1397	49.1914	246.1153	109.9291	202.3275	201.5248	116.7666	88.5918	10.5715			
13	80.0289	58.5903	28.5972	218.2686	99.1760	128.5238	272.3107	125.9800	111.7548	13.2302			
14	65.5060	73.8754	54.8542	237.4534	76.7608	146.1569	208.0560	84.0798	92.0879	8.8301			
15	74.5796	62.2871	32.3233	226.0168	78.5568	159.3403	211.5420	124.8549	49.6645	9.1651			
16	79.5280	57.0709	56.1857	214.5959	87.8302	183.9545	123.3602	164.9662	98.6253	6.1170			
17	84.6513	60.2833	38.7690	225.2987	115.6069	132.9144	219.8010	75.7146	107.6919	10.7311			
18	81.8985	57.9697	54.3112	232.5514	79.9419	221.4399	230.3204	94.7477	77.9396	11.1203			
19	77.1205	69.9101	53.9336	251.3686	141.9437	144.3804	124.1467	128.3823	87.1451	8.3312			
20	76.0371	56.8133	57.5975	249.5226	92.4469	151.2201	143.5973	93.9999	135.4825	6.7173			
21	82.7663	62.3183	33.0058	222.3363	58.0402	98.4064	173.9359	96.3254	89.1460	6.2806			
22	82.8097	57.9712	57.4937	209.5639	100.0068	73.9123	133.9837	112.9206	37.0603	5.7224			
23	77.0149	62.3482	54.7404	217.3289	87.6239	84.2634	65.7317	121.6490	83.17426	3.8731			
24	64.2916	54.9317	51.6764	266.1435	51.6664	105.8023	65.3240	70.2788	73.3327	3.4473			

Table 4 shows the power loss (MW) and hydro-wind-thermal generation (MW) for affordable NOx emission. SO2 emission dispatch from Test System 1's NSGA-II.

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{w1}	P_{w2}	P_{loss}	Cost ($)	NO_x Emission (t)	SO_2 Emission (t)
1	70.1122	61.3839	5.8746	164.99666	102.3068	45.6839	174.9972	36.8805	94.6771	6.9117	135476.2	14.4511	52.2727
2	53.0474	65.3109	49.1163	160.0694	92.0739	114.7821	79.8285	126.2754	43.5599	4.0739			
3	93.5802	66.7582	51.8798	213.6953	54.4065	43.2808	93.8290	56.0533	29.9693	3.4526			
4	75.2750	60.7295	34.4325	203.2963	27.0764	51.2570	65.0095	105.1461	30.1447	2.3668			
5	63.6585	58.7220	44.4984	168.9269	137.7776	77.1495	73.9618	0	50.9491	5.6438			
6	85.4239	87.6115	28.5042	256.4116	95.5524	89.8315	87.4755	60.5782	112.9221	4.3110			
7	71.6722	61.5195	52.6840	205.3969	22.8309	198.2610	162.2360	106.0462	75.3039	5.9507			
8	85.9001	49.5599	53.2051	213.7117	106.4731	151.6077	120.1377	116.8360	118.9064	6.3377			
9	83.7824	54.5363	31.0564	161.7476	119.1625	115.3537	281.2741	116.7155	140.7826	14.4113			
10	82.2805	44.5936	47.3005	192.8194	85.9305	152.4863	297.2390	108.9581	83.0875	14.6955			
11	80.6865	46.2032	20.7134	222.5163	57.2409	122.5699	249.1257	149.5988	161.7314	10.3863			
12	85.8154	53.1364	38.2966	212.5437	99.8138	60.5615	364.9595	108.2438	146.8335	20.2042			
13	55.5839	48.9059	48.7916	225.2389	64.5971	199.7909	279.1255	126.8532	74.4236	13.3106			
14	74.3834	62.2354	26.9480	224.4220	86.7535	133.8194	280.9090	65.8632	88.1335	13.4674			
15	99.0970	76.2847	24.0189	227.6522	70.8472	124.4858	136.2093	114.2392	142.7255	5.5598			
16	64.2147	52.8011	28.4392	188.9293	105.7035	111.1296	257.0272	93.8841	169.9674	12.0961			
17	87.6103	71.0022	49.5886	212.8881	43.6039	144.6329	202.9257	130.6253	114.8636	7.7407			
18	68.5675	65.8905	51.1624	266.9955	40.7414	186.9343	169.7488	152.5915	124.1978	6.8298			
19	55.2013	74.5861	53.0457	214.1838	59.6713	161.6012	291.6398	66.9209	106.7981	13.6481			
20	70.4048	58.7163	53.9054	284.9324	99.1897	155.9465	134.2504	68.2649	131.3767	6.9870			
21	73.2511	60.1221	53.9762	245.1787	118.4735	103.7160	175.4283	23.6926	64.5891	8.4275			
22	77.3807	73.8774	57.5350	285.3385	86.1205	54.1233	92.0701	30.9579	107.3503	4.7537			
23	101.1250	72.7540	58.8431	269.4852	96.6483	56.3484	116.3108	11.4098	72.7012	5.6258			
24	72.8923	52.8014	45.6964	275.1584	109.2668	52.8621	51.5329	89.4146	55.0659	4.6907			

2.5.2 Test System 2

This system considers a multi-chain cascade of four reservoir hydro plants, two wind power generating units and eight thermal power plants. The entire scheduling period is 1 day and divided into 24 intervals. The effect of valve point loading is taken into consideration. The detailed parameters for this case are taken from [51] except the last two thermal power generating units are replaced by wind power generators. Two wind power generators data is same as Test System1. The cost coefficients, NO_x coefficients and SO_2 coefficients are taken from [66].

Cost, NO_x emission and SO_2 emission objectives are minimized individually by utilizing RCGA. In this strategy, table 5, table 6, and table 7 provide summaries of the power generation results achieved from cost minimization, NOx emission minimization, and SO2 emission minimizing, respectively. Table 8 provides a summary of the hydro-wind-thermal power generation results obtained from cost, NOx emission, and SO2 emission objectives optimised simultaneously using NSGA-II.Table 5 shows that under economic dispatch, cost, NOx emission and SO_2 emission are 533923.3 $, 34.8325 t and 179.2198 t respectively. Table 6 shows that under NOx emission dispatch, cost, NOx emission and SO_2 emission are 543721.5 $, 33.7843 t and 181.4056 t respectively. Table 7 shows that the SO_2 emission dispatch and the values of cost, NOx emission and SO_2 emission are 538797.0 $, 34.9024 t and 178.4407 t respectively. It is seen from Table 8 that under cost, NO_x emission and SO_2 emission objectives optimized simultaneously by using NSGA-II, cost, NOx emission and SO_2 emission are 539775.2 $, 34.5880t and 179.8939 t respectively.

Figures 5(a), 5(b), 5(c), and 5(d) show, respectively, the hourly discharges of four hydro plants obtained from cost minimization, NOx emission minimizing, SO2 emission minimization, and from NSGA-II. The reservoir storage volumes of four hydroelectric plants are shown in Figs. 6(a), 6(b), 6(c), and 6(d), respectively, based on cost minimization, NOx emission minimizing, SO2 emission minimization, and NSGA-II. Figure 7 illustrates the characteristics of cost convergence, NOx emission convergence, and SO2 emission convergence. In the last iteration of the recommended strategy, where cost, NOx emission, and SO2 emission targets are all optimized simultaneously, the distribution of 20 nondominated solutions is found.

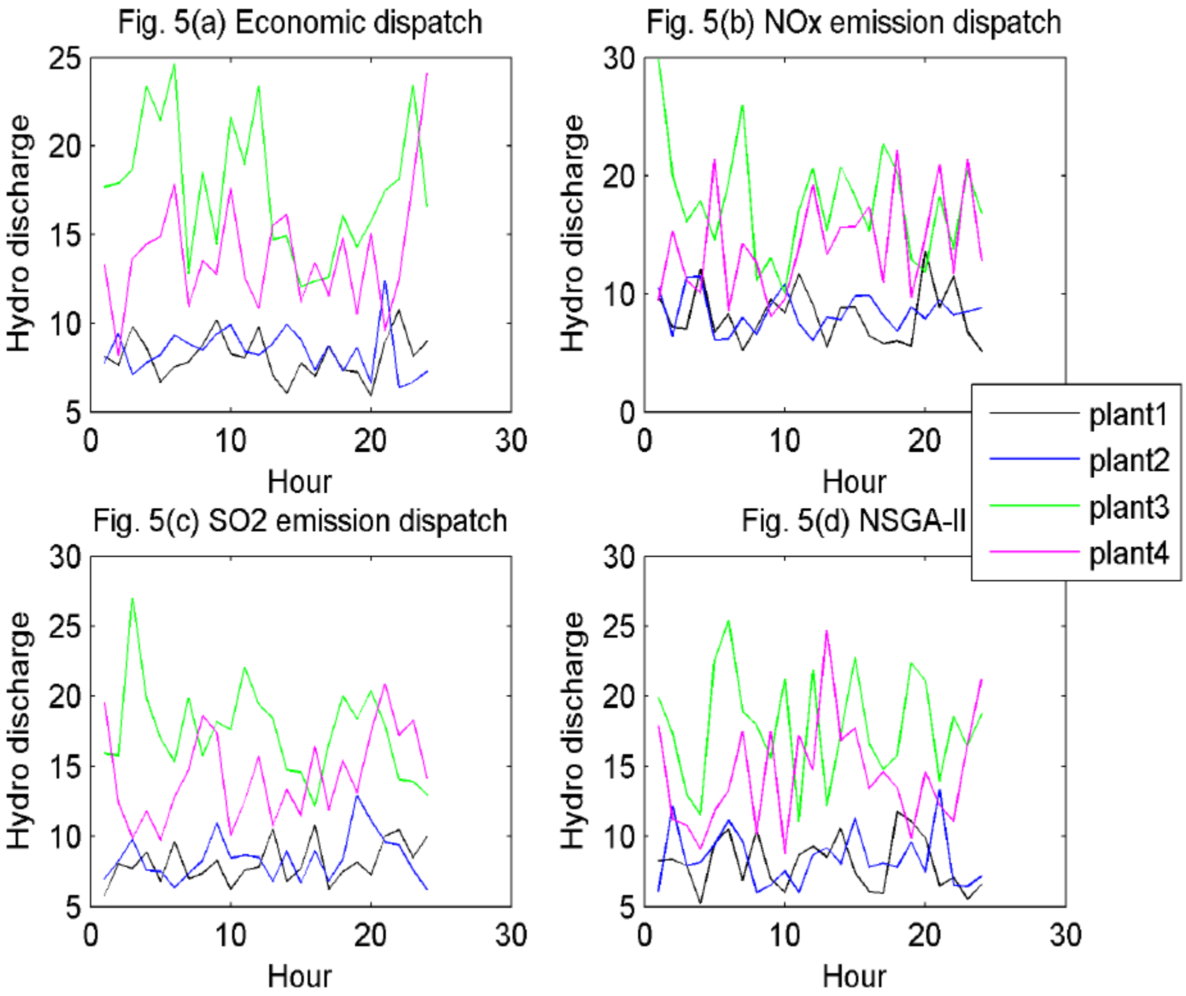

Figure 5. Hydro plant discharges ($\times 10^4 m^3$) of Test System 2 obtained from Economic Dispatching, NOx Dispatching, SO2 Dispatching, and NSGA-II

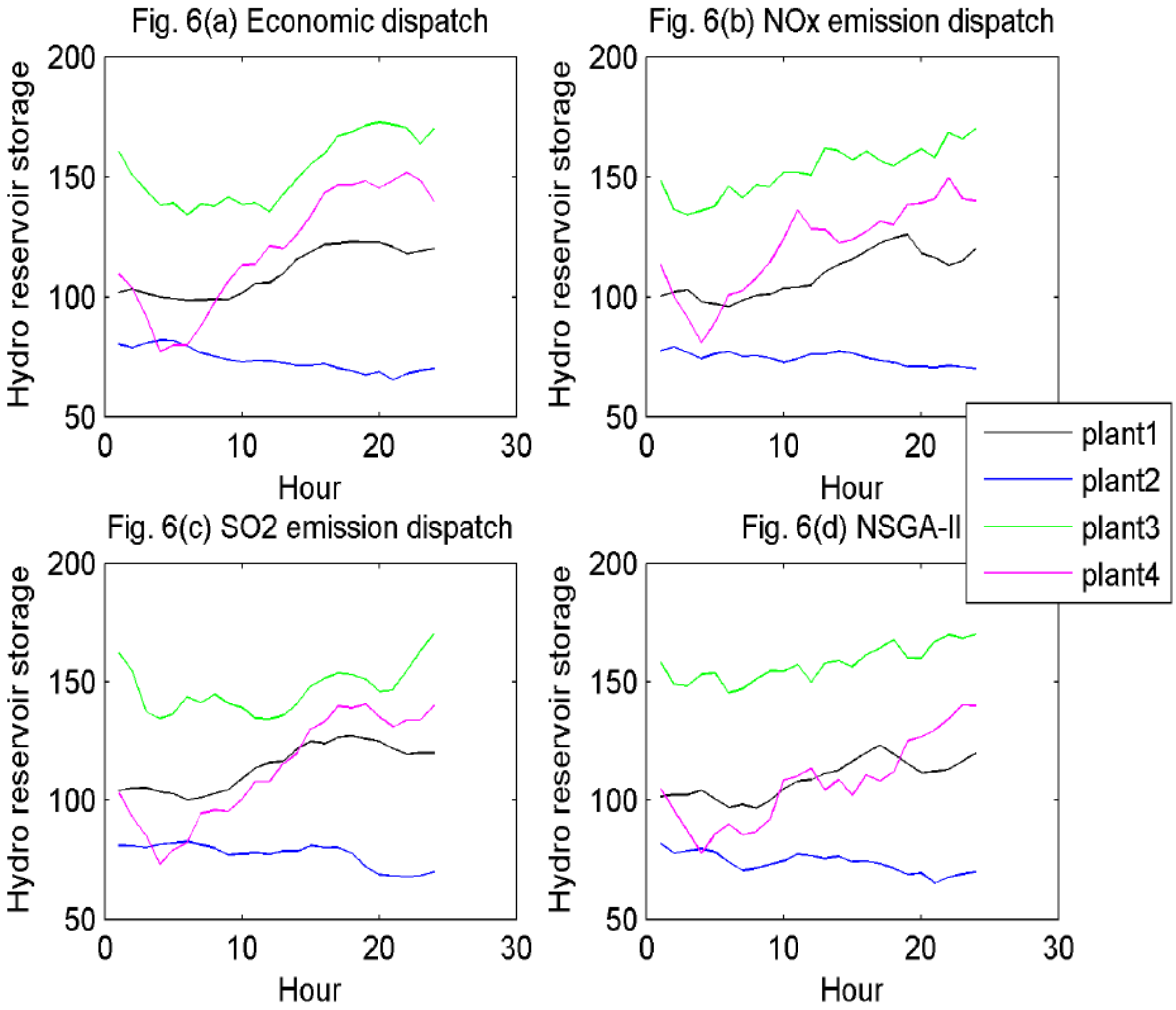

Figure 6 shows the hydro reservoir storage volumes ($\times 10^4 m^3$) of Test System 2 as determined by Economic Dispatching, NOx Emission Dispatching, SO2 Emission Dispatching, and NSGA-II

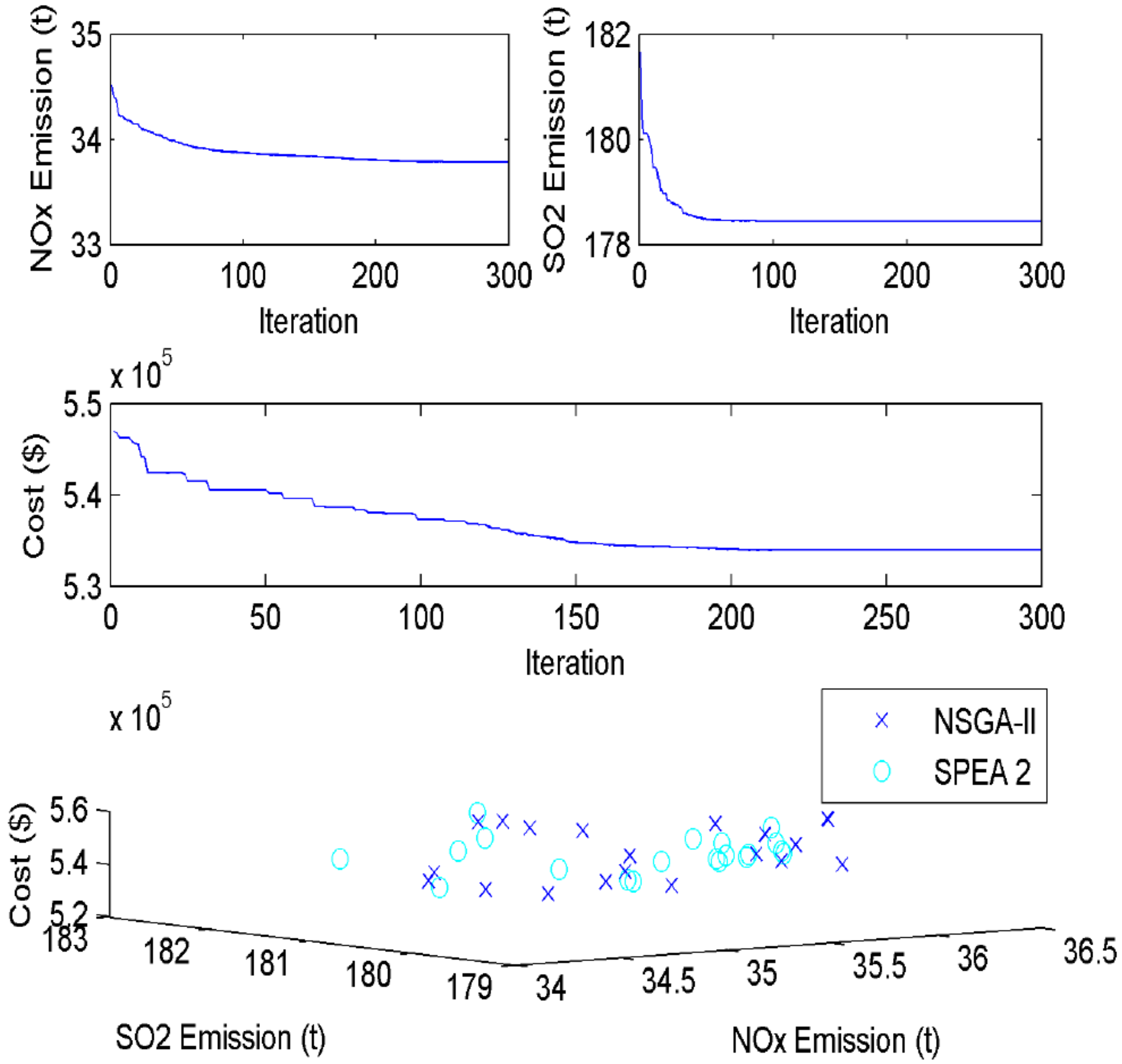

Figure 7 shows the convergence of NOx emission, SO2 emission, cost convergence, and the pareto-optimal front for test system 2.

Table 5: Hydro-wind-thermal generation (MW) for economic dispatch of Test System 2.

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{s5}	P_{s6}	P_{s7}	P_{s8}	P_{w1}	P_{w2}	Cost ($)	NO_x Emission (t)	SO_2 Emission(t)
1	75.8560	60.6292	52.8338	213.9390	2409237	152.0032	23.0127	44.5501	2272549	309.7903	123.7987	91.7342	61.9109	71.7634	533923.3	34.8325	79.2198
2	73.3370	69.8629	49.6200	149.7748	185.9742	131.2324	47.6416	71.8529	256.8512	315.6901	134.6561	130.2361	66.0724	97.1983			
3	86.1392	55.6119	44.0553	198.6084	173.3140	63.9257	93.1986	82.9985	269.7080	101.4905	218.8484	103.1430	77.7643	131.1938			
4	79.2733	61.1275	18.0505	1904623	78.4008	192.8798	60.6670	116.7547	167.9168	241.6624	170.6909	38.5460	94.2370	139.3310			
5	65.8763	64.4579	27.0103	173.9683	248.8988	178.7487	42.1807	64.6210	222.2316	42.4957	231.5674	127.5248	98.1049	82.3137			
6	71.9790	70.3883	6.7032	195.7188	105.9487	234.7689	64.8362	107.5148	174.3629	205.1629	209.7189	180.0231	114.6803	58.1941			
7	73.5166	66.3346	50.2473	145.7239	97.5278	388.4164	51.1773	71.1895	369.3288	128.8375	181.0899	83.2816	95.1770	148.1520			
8	79.3609	62.5623	40.3607	178.0703	103.5320	188.5999	85.6965	121.1968	162.9279	319.2538	278.1182	131.6645	87.1904	171.4657			
9	86.3848	66.3932	50.1269	183.6085	284.0720	278.0620	76.3824	57.2095	321.0192	182.3248	179.6981	117.6277	137.8977	69.1932			
10	76.4279	67.9725	26.9677	230.2120	299.1549	147.0499	68.2957	51.0341	270.4675	317.0972	90.9747	180.0187	149.1291	105.1983			
11	75.7585	59.6170	38.8005	199.9972	302.0547	277.0083	48.9242	55.4811	172.2614	354.1913	167.8209	182.3792	71.3031	94.4024			
12	86.9099	58.9218	15.8300	183.1101	413.4306	183.8262	82.3290	71.6484	452.0875	102.2011	139.8623	180.3331	162.0744	17.4357			
13	70.1525	62.2114	49.0352	233.6386	248.5563	283.5335	68.9366	76.6187	268.8336	211.3474	240.9221	61.5423	124.7268	109.9450			
14	63.1829	67.0917	51.0115	237.3266	242.5838	181.6826	69.4731	65.2169	222.7189	253.8207	234.6259	117.1435	89.6565	134.4654			
15	77.0543	62.2919	54.2902	199.4164	257.8131	288.7750	63.2979	73.9090	86.9186	321.8770	224.5198	86.9513	123.3741	89.5115			
16	72.0917	52.5911	558309	229.2898	175.6648	337.2574	69.4132	82.4559	116.0706	226.8754	244.7039	188.0084	126.8360	82.9113			
17	84.0822	60.7899	56.8721	220.0837	99.1057	219.9031	87.1347	107.6052	2703796	190.7174	312.0769	79.4699	133.0440	128.7356			
18	75.0318	51.4321	55.6275	254.8133	200.9548	318.8598	82.5821	86.7023	235.8797	169.4452	269.4009	108.2949	71.5671	139.4086			
19	74.2396	57.9401	58.3724	211.1655	204.3447	211.1333	97.5114	118.1480	306.2881	96.5761	179.6849	228.3288	129.0292	97.2253			
20	63.2396	45.1257	57.3030	258.3480	295.4370	195.6666	107.5669	66.3936	289.3774	144.4510	133.0144	155.6133	150.4125	87.9785			
21	85.7317	73.9976	54.0727	199.5745	150.0338	230.9265	53.2398	54.9694	301.7711	122.3378	231.6312	112.7886	120.3005	118.6249			
22	95.4391	42.0031	52.0147	234.3547	19873113	96.9740	74.5242	60.2323	231.2962	309.8698	94.6289	175.2364	133.9171	72.1981			
23	80.1092	45.8520	27.3421	284.2950	157.5764	98.6115	122.9629	127.6617	323.6570	174.3583	169.7909	109.9340	29.7386	98.1103			
24	85.5545	50.5269	53.7271	311.6680	110.8552	165.7197	59.2682	68.3317	205.4517	188.1693	135.8793	128.9549	111.4716	124.4274			

Table 6: Test System 2 hydro-wind-thermal generation (MW) for NOx emission dispatch

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{s5}	P_{s6}	P_{s7}	P_{s8}	P_{w1}	P_{w2}	**Cost ($)**	**NO_x Emission (t)**	**SO_2 Emission(t)**
1	85.1077	74.8384	10.0000	174.8074	123.3876	82.8759	51.5256	29.7573	346.9029	167.1358	139.6441	209.0721	103.5840	151.3611	543721.5	33.7843	181.4056
2	69.6848	50.1938	37.9359	222.7590	84.3573	351.8174	31.0241	56.3218	95.5149	238.3838	87.7852	187.4173	128.6139	138.1907			
3	69.2136	77.9822	46.9235	1722350	91.1414	89.5659	109.4088	51.1744	282.5102	219.8434	94.4885	159.1101	122.4463	113.9565			
4	95.0177	76.4562	41.1024	1501256	106.3593	214.4485	61.4505	44.5258	27.9709	231.6230	135.8997	191.5725	103.0884	170.3594			
5	65.9819	46.1794	49.4304	211.2467	232.0001	130.7758	120.9347	99.7454	121.8075	153.1995	88.1273	189.9682	146.0909	14.5121			
6	76.1150	47.8576	36.7684	132.7607	200.6444	57.9801	129.2668	118.1978	125.4763	330.7296	138.9627	247.2972	157.0358	0.9075			
7	53.1957	59.9503	10.0000	200.0379	172.6881	288.1670	46.5028	92.2560	239.3523	197.7106	224.0589	111.8480	174.5577	79.6746			
8	68.8592	49.9060	51.7761	188.2604	90.5908	358.9191	66.3445	65.8324	175.5597	276.6379	274.5975	162.3211	88.1726	92.2227			
9	83.8075	65.2269	53.7114	146.5120	294.6621	384.1714	24.0456	52.0364	237.1722	204.5106	107.3997	244.8195	100.5435	91.3813			
10	77.5911	72.3695	51.7761	169.8963	279.8423	4073073	34.9082	54.7399	417.2827	68.3580	110.6726	136.4133	59.9410	139.0076			
11	94.0058	53.8581	49.4307	222.2839	54.9336	217.2731	102.4257	93.0637	321.4088	201.0867	245.1011	299.6345	84.7625	60.7317			
12	83.0607	45.4856	36.4336	275.9503	114.6462	157.5589	40.8492	102.5536	201.2596	369.7161	237.9699	164.6600	148.3389	171.5174			
13	57.6129	59.7486	52.6929	222.7779	194.2715	175.3238	46.6017	103.9337	141.3997	453.8891	278.8839	68.1169	82.4217	172.3256			
14	82.8955	58.3674	39.3340	242.2436	399.7501	407.3916	71.6680	24.3897	69.0864	170.2329	223.0164	115.6864	93.6959	32.2422			
15	84.0097	69.9750	48.6408	236.2072	421.1752	130.9251	64.1344	68.9794	358.9102	141.2839	54.4043	210.8967	54.9374	65.5208			
16	67.2283	69.4822	54.5463	249.6829	159.4624	405.9240	34.1670	23.7985	202.1188	282.8812	251.6265	83.0368	35.0568	140.9882			
17	61.8028	59.4640	28.3519	198.2679	154.2334	224.9443	129.9554	73.1474	128.6599	147.3001	433.9556	233.3772	85.5497	90.9903			
18	64.1687	50.4407	39.7360	284.0869	452.7086	240.5118	96.8948	68.3205	185.0793	113.2698	237.0869	174.3479	66.5825	46.7658			
19	60.4306	61.8408	55.7629	187.1851	248.5428	437.0218	26.7932	92.1704	273.5470	161.3599	160.2067	154.3439	104.8474	45.9474			
20	106.4250	55.2445	56.3214	246.3223	253.6419	437.0257	31.0245	37.8876	163.8107	129.4105	67.8481	299.8095	156.3933	8.8341			
21	84.6688	63.8536	49.0618	287.7528	186.5157	205.3920	95.8893	46.1425	134.5848	83.2509	164.3044	234.9963	165.9570	107.6307			
22	97.5205	56.8674	56.2420	219.2403	129.0273	445.8007	98.6421	69.2875	187.1726	145.0987	101.1466	125.2404	103.0402	25.6727			
23	69.3947	59.1374	42.4827	301.9769	340.9260	192.6582	63.4396	65.2305	334.1876	112.4471	64.7091	109.2456	43.3742	50.7904			
24	56.1742	60.1731	53.9358	230.1732	90.2093	246.9323	86.2375	32.1424	189.0564	92.8448	213.3656	215.7925	81.6638	151.2992			

Table 7 shows the hydro-wind-thermal generation (MW) for Test System 2's SO2 emission dispatch.

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{s5}	P_{s6}	P_{s7}	P_{s8}	P_{w1}	P_{w2}	**Cost ($)**	**NO_x Emission (t)**	**SO_2**
1	58.8914	55.4699	56.6609	258.1955	205.8955	194.6258	58.5943	63.1529	165.5641	179.1467	233.1098	53.3980	72.7912	94.5040	538797.0	34.9024	178.4407
2	76.8243	63.9707	55.0769	187.4557	347.2163	210.3030	58.8051	60.2417	124.9690	105.8136	138.6515	143.1194	92.1433	115.4395			
3	74.5317	71.9957	10.0000	150.8550	187.7691	179.6836	70.5921	102.5228	211.4190	100.0274	129.9572	206.1179	158.9492	45.5796			
4	81.9220	59.5357	34.4503	159.8627	244.1694	182.0840	85.2222	78.99710	243.9391	101.8333	60.4059	95.6109	97.5499	124.4174			
5	67.8059	59.8986	44.0181	125.4472	151.7630	331.7276	73..3602	104.5942	197.5736	56.9653	105.9571	127.6158	111.6871	111.5863			
6	85.2476	52.5497	48.3819	161.3766	264.5891	168.9188	59.1406	44.0610	243.0072	148.1030	226.1337	84.4684	87.0083	127.0141			
7	68.2105	59.8107	36.9687	179.4492	231.4970	245.6220	110.7256	36.6408	252.8606	206.4422	113.4204	139.7952	168.2799	100.2772			
8	71.2821	64.5095	49.1674	220.1394	327.3507	109.4120	75.2169	99.2399	309.2987	111.4603	224.5417	153.8038	59.2549	135.3226			
9	77.6830	76.6765	43.8574	215.2820	352.2636	71.2083	23.0857	97.6427	352.5335	170.2260	238.3920	94.1434	149.0606	127.9454			
10	63.6572	62.7541	44.2265	155.6400	386.0818	160.1792	53.0500	69.9071	108.5515	382.5673	137.0421	242.7317	78.1713	135.4403			
11	74.6795	64.1512	23.8381	185.3801	378.4088	213.7792	105.4330	41.1432	248.2160	295.5018	245.0367	75.5289	40.6021	108.3014			
12	77.2566	63.7191	35.2432	219.6576	271.1972	105.8745	50.0622	101.6855	305.2038	158.9677	418.5798	127.1376	106.0584	109.3569			
13	93.2704	52.6672	39.2449	176.4433	276.4131	192.0271	80.1967	106.8423	200.6081	286.6747	239.2824	221.9101	26.4886	117.9311			
14	70.3053	66.4546	49.1145	209.4456	125.3296	88.3734	116.4943	72.8562	303.2472	392.0691	89.0289	237.0402	88.1054	122.1355			
15	77.5986	52.6426	50.8476	196.5011	82.3274	215.7846	79.4486	73.5225	206.2642	406.7785	138.0233	193.8494	130.3397	106.0689			
16	96.5679	68.0961	54.1033	250.7438	285.8748	241.5057	52.5971	64.3518	247.9691	102.6232	122.8016	181.2614	160.7114	130.7928			
17	66.0124	54.6548	50.6297	213.8229	327.3329	289.8336	60.0564	84.6560	213.3165	147.6728	125.8442	215.8471	102.9837	97.3379			
18	76.4544	64.2768	39.6826	252.8624	360.7501	222.3047	66.2855	39.7278	272.3187	109.4507	278.7137	154.1022	119.7463	63.3242			
19	81.3447	82.1747	45.8915	231.6338	239.0833	179.8815	117.0247	74.4237	203.8910	319.7992	159.3331	201.2839	56.1449	78.0899			
20	74.3900	72.0419	37.0472	268.9248	264.0781	200.7166	77.0904	66.0489	235.3483	157.7293	205.4954	174.1797	108.6349	108.2744			
21	92.6047	62.8884	45.2095	283.1229	201.9594	105.9112	72.0031	34.0437	361.2550	191.6769	94.2159	197.0508	133.2690	34.7896			
22	94.2377	61.5315	53.1216	257.0695	130.0427	227.0938	49.9049	64.4413	226.4832	69.5751	192.1262	185.2340	162.7610	86.3774			
23	82.4127	51.4914	55.3550	267.3517	70.7529	297.3571	68.8265	44.9501	195.6688	278.8782	117.8259	134.8062	113.1866	71.1370			
24	91.4282	43.0322	57.5887	236.6817	429.7196	253.7878	101.8032	69.9383	56.1552	75.1846	92.5513	67.1315	105.8452	119.1526			

Table 8: Acquired from NSGA-II of Test System, hydro-wind-thermal generation (MW) for economical NOx and SO2 emission dispatch

Hour	P_{h1}	P_{h2}	P_{h3}	P_{h4}	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{s5}	P_{s6}	P_{s7}	P_{s8}	P_{w1}	P_{w2}	**Cost ($)**	**NO_x Emission (t)**	SO_2 Emission(t)
1	76.7664	49.6310	45.3672	248.9566	105.8014	50.0000	109.0789	75.1276	244.8386	179.5371	218.4060	74.7687	1108.526	163.1939	539775.2	34.5880	179.8939
2	77.8236	82.6442	50.4672	177.6876	130.6860	124.6168	65.6437	88.6088	233.7409	326.0260	148.9332	114.6946	123.4403	34.9869			
3	75.6151	60.1693	54.3535	163.8760	146.3927	165.7843	90.0583	85.5168	162.6502	184.1375	140.4961	136.3640	147.4504	87.1358			
4	54.6519	62.1167	53.8590	135.3837	59.9986	92.7338	49.3116	63.4795	414.7421	168.0999	124.3568	73.0032	145.1274	53.1358			
5	85.1973	69.4201	26.1883	15.09543	104.1227	316.4530	112.1190	68.7934	119.8758	69.0081	189.5343	90.8377	157.0734	110.4227			
6	88.5665	76.4297	7.4615	173.4867	66.5782	340.9986	94.8524	68.8704	377.6052	173.4297	45.0000	114.1045	35.7509	136.8658			
7	67.0124	66.8373	41.3446	207.5144	151.4673	278.3156	115.5812	62.9293	234.5609	121.0207	248.0648	120.3037	105.1103	129.9374			
8	87.1718	43.0487	45.3917	145.3089	69.0067	144.6186	96.1763	122.9841	258.0510	407.8807	167.3834	193.2473	78.2764	151.4545			
9	67.1370	47.2006	52.4115	203.4369	347.0648	218.4830	93.9471	87.3068	205.3320	377.1531	185.4157	123.2194	21.0204	60.8718			
10	60.8960	54.7401	34.1477	137.4016	247.2207	237.6530	121.8458	112.4915	387.7867	162.3785	111.0855	223.5759	72.1938	116.5832			
11	80.6536	45.6154	54.8406	230.5971	288.1483	104.2259	60.3240	20.0000	343.7191	378.6246	185.3489	68.7072	73.1057	166.0896			
12	85.1410	64.2836	31.8310	215.5743	309.1195	303.0534	102.2815	83.0742	132.3290	253.5745	223.3045	65.2036	153.6801	127.5498			
13	80.7654	66.6140	54.5596	267.1917	453..285	73.7072	66.3790	72.9168	151.9563	249.5662	94.7142	243.6149	146.3421	88.3875			
14	92.2374	59.4406	50.5285	222.9888	101.5023	310.8607	69.1081	109.0507	367.6889	325.7574	61.8261	117.4536	73.2267	68.3301			
15	74.2310	75.9441	24.4031	233.9380	220.0218	260.3097	49.4817	114.8575	252.4293	109.8189	186.0042	124.2457	113.0740	168.2411			
16	64.1996	57.1440	51.8756	194.8937	159.4351	241.3256	105.7178	71.6369	276.1241	265.9795	271.5212	94.7315	115.4114	90.0040			
17	63.4720	59.0281	56.2642	214.6135	110.1124	199.0774	53.3513	54.9097	288.1522	342.9395	209.5736	169.9647	131.3716	97.1695			
18	100.2357	56.5856	55.5226	202.1177	198.3104	162.0730	92.5747	75.6774	392.1409	231.9970	202.5839	106.9598	162.8931	80.3282			
19	96.5228	64.8130	32.7299	171.6594	154.6488	333.3694	60.0701	45.8289	201.5371	331.3388	115.3517	241.2010	110.5231	110.4062			
20	89.9698	51.3228	37.0081	230.6824	253.7229	178.1468	29.5353	121.5283	325.7178	242.0180	58.1369	127.6755	161.7139	142.8215			
21	66.9571	77.1063	56.6392	211.4636	175.4577	183.8555	35.1015	80.5357	210.8812	239.0052	127.3899	248.2843	100.8250	96.4979			
22	71.5816	42.6791	49.3481	202.2612	322.2724	210.1328	37.0842	62.2920	308.8215	40.0000	215.5574	141.1487	107.6948	49.1262			
23	59.1928	43.9927	55.6893	255.6436	202.7221	125.6693	20.9733	90.3647	90.3485	121.5472	450.8685	190.3126	99.7135	42.9621			
24	68.2833	49.8181	49.0770	290.5519	289.6403	138.5927	48.9333	33.5360	25.0000	253.2381	251.1592	79.1714	152.0833	70.9153			

2.6 Conclusion:

In this article, NSGA-II has been applied for solving complex physical world economic environmental dispatch of wind integrated hydro thermal power system where three objectives i.e. cost, NO_x emission and SO_2 emission are optimized at the same time while taking into consideration the wind power uncertainty, cascaded hydro plant with water transport delay, valve point effect of thermal generators and other constraints. The experimental outcomes from the proposed approach have been compared with those obtained from SPEA 2. The comparative analysis clearly establishes that the current proposition gives better result than SPEA 2.

CHAPTER-3

Economic Environmental Dispatch of Wind Integrated Thermal Power System

3.1. Introduction:

Most electrical energy is produced by burning fossil fuels nowadays which releases various pollutants like oxides of sulfur (SO2), Nitrogen oxides (NOx), oxides of carbon (CO,CO2) etc into the air. One of the principles defies for electric utilities is to decrease air contamination. The act proposed in the year 1990 related to Clean Air is planned to diminish global warming. It necessitates that the conventional generation units ought to the above mentioned pollutants spread dimension [31].

More than one method has been projected in the writing to cut down the pollution of natural. This considers the installation of switching device that maintains the discharge level, utilization of low emanation raw materials, and replacement of the old combustion chamber through new models and get away with outflow thought [33]. These preliminary methods either call for the setting up of latest equipments or alteration of the existing equipment that involves significant funds disbursement. Therefore, the last method is more recommended. Diverse techniques [34]-[34] have been discussed related to the Economic Emission Dispatch (EED) problem. However, these techniques cannot handle the non-linear fuel charge and discharge level functions.

The three aims- price, NO_x extraction and SO_2 extraction are contradictory in nature and for discovering overall optimal dispatch they have to be considered concurrently[67]-[69]. For arranging the on line generator productivity having the expected load requirement for getting most effective result in terms of price, NO_x extraction and SO_2 extraction at the same time while satisfying each and every operational constraint the Economic environmental dispatch (EED) has been used.

Several methods related to EED problem are discussed in the text. Nanda et al. took up EED as a multiple, contradictory intentional issue & used goal-programming methods to resolve that [70].Optimization procedure based upon linear programming are discussed in [71] where the objectives are regarded one by one. In the previous ten years, the EED issue was changed into an issue with single target through linear combining of differing points as a weighted entirety [72]-[73]. It necessitates through changing weights to acquire a bunch of non-subservient answer. Regrettably, in case of problems with non-convex Pareto-optimal front it is of no use. For circumventing such problem, the ε-constraint technique is discussed in [74].It makes the most use of the most favorable aim and regards the other aims as constraints leaped through a number of acceptable levels. However, the stochastic search algorithms are very faster; accurate for example probabilistic technique for approximating the global optimum of a given.

Numerous investigations were done to assess the development of multi-objective evolutionary search strategies throughout the previous couple of years [75]-[77]. It is found that in all these approaches, the extraction function is formulated as a mixture of either sulphur dioxide (SO_2) and oxides of nitrogen (NOx) or only nitrogen oxides (NO_x). However, in this paper sulphur dioxide (SO_2) and nitrogen oxides (NO_x) extraction objectives are regarded as separate functions.

In reduction of the effect of Global Warming, wind power and solar PV plants are becoming popular along with fulfilling power stipulate at reasonable price having no dangerous extractions. But intermittent wind and solar power require schemes and dispatch strategies for upholding economy with dependability and safety measures.

A non-dominated sorting genetic algorithm-II is recommended in this paper for economic environmental dispatch of thermal wind sun oriented power framework with battery vitality stockpile framework where price, sulphur dioxide (SO_2) extraction and oxides of nitrogen (NO_x) extraction are contending ideas. Here difficulty arrived as a nonlinear restricted multi-objective optimization [78].

Real-Coded Genetic Algorithm (RCGA) has been utilized in order to get rid of the cumbersome binary notation of dealing with continuous search space with large dimensions. Moreover, the Simulated Binary Crossover (SBX) and polynomial mutation is employed in the current proposition.

Extensive experiments have been carried out for validating the proposed scheme by pertaining it on two separate modules as considered. The results reported from the investigation on NSGA-II is compared and analyzed to that obtained from SPEA2.

3.2. Problem Formulation

Here Thermal-Wind-Solar integrated scheme is proposed to standardize respective target capacities - rate, arrival of SO2 and NOx in chorus while gratifying the operational restriction. The resulting goal and variables that are utilized in current work are as talked about individually.

3.2.1. Objectives

(i)Fuel charge

The prepared expense of a thermal-wind-solar system involves the raw material rate for coal-based units alongside the expense of wind energy creating entity. The complete expense can be expressed as:

$$F_C = \sum_{i=1}^{N_s} f_{si}(P_{si}) + \sum_{k=1}^{N_w} f_{wk}(P_{wk}) \tag{3.1}$$

The raw material charge capacity of every coal based unit, thinking about the valve point impact, is articulated like.

$$f_{si}\left(\mathrm{P}_{si}\right) = a_{si} + b_{si}\mathrm{P}_{si} + c_{si}\mathrm{P}_{si}^{2} + \left| d_{si} \times \sin\left\{ e_{si} \times \left(\mathrm{P}_{si}^{\min} - \mathrm{P}_{si}\right)\right\}\right| \tag{3.2}$$

The expense of wind power incorporates three segments - an immediate fuel charge, an under estimation penalty fuel charge and a spare fuel charge due to over estimation of wind control. Henceforth, the charge related to wind energy conversion of ith generated entity at mth time is figured as [77]

$$f_{wk} = \left\{\left(d_k \times \mathrm{P}_{wk}\right) + C_{pk}\left(W_{k,av} - \mathrm{P}_{wk}\right) + C_{rk}\left(\mathrm{P}_{wk} - W_{k,av}\right)\right\} \tag{3.3}$$

$$C_{pk}\left(W_{k,av} - \mathrm{P}_{wk}\right) = \mathrm{K}_{\mathrm{P}k}\left(W_{k,av} - \mathrm{P}_{wk}\right) = \mathrm{K}_{\mathrm{P}k} \times \int_{\mathrm{P}_{wk}}^{\mathrm{P}_{wrk}} \left(w - \mathrm{P}_{wk}\right) f_w(w)\,dw \tag{3.4}$$

$$C_{rk}\left(\mathrm{P}_{wk} - W_{k,av}\right) = \mathrm{K}_{rk}\left(\mathrm{P}_{wk} - W_{k,av}\right) = \mathrm{K}_{rk} \times \int_{0}^{\mathrm{P}_{wk}} \left(\mathrm{P}_{wk} - w\right) f_w(w)\,dw \tag{3.5}$$

$$f_w(w) = \frac{k_s h v_{in}}{\mathrm{P}_{wr} c}\left[\frac{\left(1 + \frac{hw}{\mathrm{P}_{wr}}\right) v_{in}}{c}\right]^{k_s - 1} \times \exp\left\{-\left[\frac{\left(1 + \frac{hw}{\mathrm{P}_{wk}}\right) v_{in}^{k_s}}{c}\right]\right\} \tag{3.6}$$

The wind power categorization is ended via employing Weibulpdf, $f_w(w)$. At this point $h = \frac{v_r}{v_{in}} - 1$.

(ii) NO$_x$ Discharge

NOx outflows of coal-fired unit are increasingly hard to imitation in view of the fact that has originated from various causes and their creation is connected in the company of a few aspects, for example, hotness of boiler and atmospheric contamination. Simple way to deal with describes NOx outflow is a blend of polynomial and exponential expressions and be able to be expressed in the following way.

$$D_{NO_x} = \sum_{i=1}^{N_s} \left[\alpha_{ni} + \beta_{ni} P_{si} + \gamma_{ni} P_{si}^2 + \eta_{ni} \exp\left(\delta_{ni} P_{si} \right) \right] \tag{3.7}$$

(iii) SO_2 Discharge

SO_2 emanation of coal-fired plant relies upon the measure of coal consumed and be able to be reproduced as quadratic polynomial capacity expressed in the following way.

$$D_{SO_2} = \sum_{i=1}^{N_s} \left[\alpha_{si} + \beta_{si} P_{si} + \gamma_{si} P_{si}^2 \right] \tag{3.8}$$

3.2.2. Constraints

(i) Real power balance constraint:

The complete active power production must adjust the anticipated power request in addition to active power losses in the transmission lines.

$$\sum_{i=1}^{N_s} P_{si} + \sum_{k=1}^{N_w} P_{wk} - P_D - P_L = 0 \tag{3.9}$$

Where P_L is computed via the B coefficients which can be articulated in the quadratic form stated as:

$$P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} P_i B_{ij} P_j \tag{3.10}$$

At this juncture, entire quantity of plants $N = N_s + N_w$ and P_i is the relevant coal-fired and wind power production.

(ii) Real power operating limits

$$P_{si}^{\min} \le P_{si} \le P_{si}^{\max} \quad i \in N_s \tag{3.11}$$

and

$$P_{wk}^{\min} \le P_{wk} \le P_{wk}^{\max} \quad k \in N_w \tag{3.12}$$

3.3 Finding Generation Point of Relaxed Generator

N dedicated coal-fired stations along with the output involve allocation of their based on the power balance restraints (3.9) and the relevant capacity restraints (3.11) and (3.12). By knowing the respective burden of $(N-1)$ generators, the power altitude of the N^{th} unit (i.e. the relaxed generator) is acknowledged as

$$P_N = P_D + P_L - \sum_{i=1}^{N-1} P_i \tag{3.13}$$

The transmission loss P_L is a function of all generator outputs together with the relaxed generator and it is stated by

$$P_L = \sum_{i=1}^{N-1}\sum_{j=1}^{N-1} P_i B_{ij} P_j + 2P_N\left(\sum_{i=1}^{N-1} B_{Ni} P_i\right) + B_{NN} P_N^2 + \sum_{i=1}^{N-1} B_{0i} P_i + B_{0N} P_N + B_{00} \tag{3.14}$$

Escalating and rearranging, equation (13) becomes

$$B_{NN} P_N^2 + \left(2\sum_{i=1}^{N-1} B_{Ni} P_i + B_{0N} - 1\right) P_N + \left(P_D + \sum_{i=1}^{N-1}\sum_{j=1}^{N-1} P_i B_{ij} P_j + \sum_{i=1}^{N-1} B_{0i} P_i - \sum_{i=1}^{N-1} P_i + B_{00}\right) = 0 \tag{3.15}$$

The loading of the relaxed generator (i.e. N th) can then be acquired by resolving equation (3.15) utilizing standard algebraic technique.

3.4 Principle of Multi-Objective Optimization:

Multi-target optimization issue involving various destinations and constraints like primary and secondary may be expressed like:

Minimize $f_i(x)$, $i = 1, \ldots.., N_{obj}$ (3.16) area under discussion $\begin{cases} g_k(x) = 0 & k = 1,\ldots,\mathrm{K} \\ h_l(x) \le 0 & l = 1,\ldots,L \end{cases}$ (3.17)

Where f_i is the i^{th} intent function, x is a assessment vector.

3.5. Nondominated Sorting Genetic Algorithm-II:

To deal with multi-target optimization issues, NSGA has been proposed in the year of 1995. Non-domination is utilized to offer position to arrangements, and strength contribution is profited in support of expansion command over in the investigation area. Because of not highly susceptible to fitness sharing parameters of NSGA, [19] have instigated NSGA-II as it produce more authentic and dependable solution speedy than its precursor. Because of word constraints, the fact depiction of NSGA-II isn't given in the paper. The progression of occasions in ‘NSGA-II’ is introduced in Figure.I after given all the section one by one.

i) Fast nondominated sorting procedure

To accumulate way out of the initial nondominated the face in a inhabitants of dimension, each answer be able to be matched up to all extra answer inside the inhabitants to unearth if it's far conquered. By the side of the particular step, all community inside the first nondominated the front are created. In order to unearth the individuals inside the next nondominated front, the solutions of the first front are marked down for the time being and every answer of the residual populace can be matched as much as each different answer of the residual inhabitants to unearth if it is to governed. Accordingly the entire particular inside the next nondominated face are created. This is right for creating third and higher tiers of nondomination.

In support of every way out two components are computed: a) dominion count n_q, the quantity of arrangements which overwhelm the arrangement q, and b) S_q, a lot of arrangements that the arrangement overwhelms. The approach for the rapid nondominated category can be stated as:

So as to uncover the people in the following nondominated front, the arrangements of the principal front are discounted for the present and every arrangement of the lingering populace can be coordinated up to each other arrangement of the remaining populace to uncover on the off chance that it is ruled. In this manner all people in the subsequent nondominated face are made. This is directly for making third and more elevated degrees of non-domination.

The algorithm for the fast nondominated category can be stated as: Algorithm 1: Fast non dominated category.

```
For each $p \in P$
  $S_p = \phi$
$n_p = 0$
for each $q \in P$
if $(p \prec q)$ then              if $p$ dominates $q$
$S_p = S_p \cup \{q\}$             add $q$ to the set $p$
else if $(q \prec p)$ then
$n_p = n_p + 1$                    augmentation of $p$
if $n_p = 0$ then                  $p$ fit in to the initial face
$P_{rank} = 1$
$F_1 = F_1 \cup \{p\}$
```

Every one inhabitants is given a grade identical to its nondomination degree or the face wide variety (1 for the exceptional stage and 2 for the following-great degree and so forth).

ii) Fast crowded distance estimation procedure

To collect an estimation of the concentration of answers contiguous a specific clarification within the populace, the common space of spots on both part of this thing beside all the targets is computed. This number provides as an estimation of the outer limits of the cuboid primarily based by the use of the closest pals because the vertices which may defined as crowding distance. This computation necessitates categorization of the populace in keeping with every goal feature fee in rising array of significance. Subsequently, in favor of every goal characteristic, the boundary populations (populations among nominal and biggest characteristic standards) are provided especially excessive distance fuel rate in order that boundary elements are constantly chosen. All different transitional inhabitants are supplied a distance price identical to the fixed regularized distinction inside the function standards of adjoining inhabitants. This computation is kept on with added goal capabilities. The crowding-distance assessment is computed because the total of individual distance values matching to every goal. Every purpose characteristic is regularizing ahead of computing the crowding distance. The set of rules underneath portrays the crowding distance calculation method of the entire answers in a nondominated set G.

Algorithm 2: Crowding distance assignment

```
$l = |G|$                                  digit of answer in G

for each $i$, set $F[i]_{distance} = 0$         expressed distance

in favour of every intention $n$

$G =$ Sort$(G, n)$   Arrange by means of every objective assessment

$G[1]_{distance} = F[l]_{distance} = \propto$
```

in favour of $j = 2$ to $(k-1)$ $G[j]_{distance} = G[j]_{distance} + (G[j+1].n - G[j-1].n)/(f_m^{\max} - f_m^{\min})$ Here, $G[i].n$ refers to the mth objective function value of the i^{th} entity in the position G. $f_m^{\max}$ and $f_m^{\min}$ are the greatest and least standards of the mth objective purpose.

iii) Crowded-comparison manipulator

The crowded- comparison manipulator conducts the collection technique at a selection of tiers of the set of rules closer to a uniformly spread-out pareto-optimal front. All individual within the populace has two aspects:

a) nondomination rank (i_{rank})

b) crowding distance $(i_{distance})$

$i \prec j$ if $i_{rank} < j_{rank}$ or $((i_{rank} = j_{rank})$ and $(i_{distance} > j_{distance}))$

Between populaces with varying nondomination positions, the individuals with the lower (better) position are wanted. On the off chance that the two populaces have a place with the equivalent front, at that point the masses with bigger swarming separation is supported.

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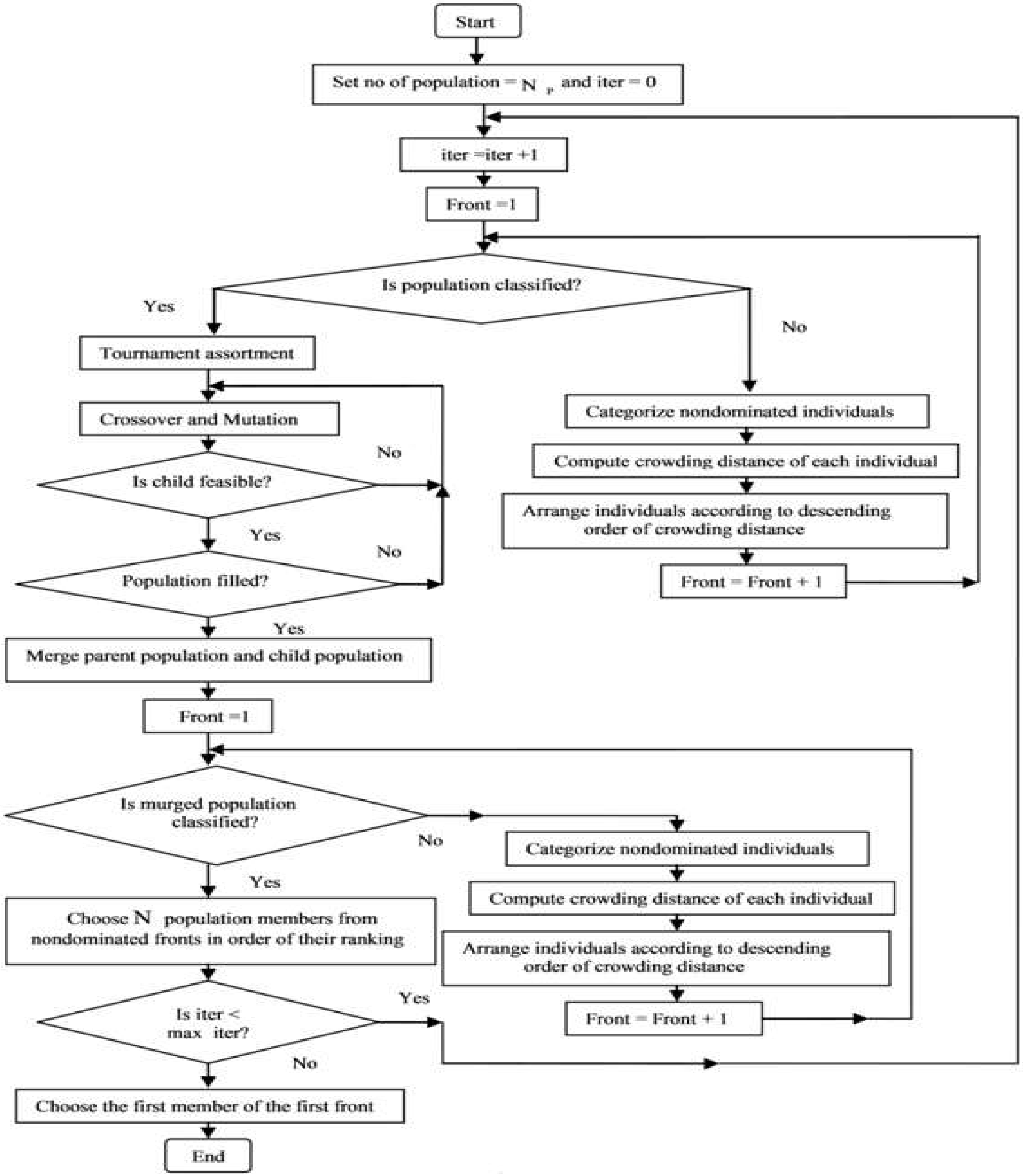

Figure 1: Flowchart of NSGA II

3.6 Case Study of Economic Environmental Dispatch of Wind Integrated Thermal Power System:

The counseled NSGA-II, SPEA 2 and RCGA had been accomplished in MATLAB 7.0 on a PC (Dual-core, 160 GB, 3.3 GHz).

Fuel charge, NOx outflow and SO2 discharge are taken as the three target capacities. So as to clarify clashing relations among the goal capacities, every target work for example fuel charge, NOx discharge and SO2 outflow is limited exclusively by using genuine coded hereditary calculation (RCGA). Here, the populace level, greatest figure of cycles, hybrid and change possibilities have been picked as 100, 200, 0.9 and 0.2, separately for these two test frameworks.

First, NSGA-II has been pertained to optimize separately both fuel charge and NO_x discharge objectives all together and both fuel charge and SO_2 discharge objectives all together.

At that point, NSGA-II has been related to streamline specified targets i.e. Fuel charge, NOx discharge and SO2 discharge targets concurrently. For evaluation, SPEA 2 has been prevailed for fixing this trouble.

Here, the inhabitants' magnitude, most quantity of iterations, hybrid and transformation probabilities were preferred as 10, 30, 0.9 and 0.2.

3.6.1 Test framework 1

This test system comprises nine thermal generating units and two wind power generators. Thermal unit data has been adopted from [51]. The wind power accessibility is formed as probabilistic restriction in power stability representation. The Weibull shape factor and scale factor for the two wind power generators are $k_{s1} = 1.5$, $k_{s2} = 1.5$ and $c_1 = 15$, $c_2 = 15$ respectively. The reserve and penalty fuel charge coefficients for the two wind power generating units are chosen as $\mathrm{K}_{r1} = 5$, $\mathrm{K}_{r2} = 5$, $\mathrm{K}_{\mathrm{P1}} = 5$, $\mathrm{K}_{\mathrm{P2}} = 5$ correspondingly. The wind power generators having specification is

$P_{wr1} = 175$ MW and $P_{wr2} = 175$ MW respectively. The cut in, cut out and rated wind speeds are $v_{in} = 5$, $v_o = 45$ and $v_r = 15$ respectively. Load demand is 2400 MW.

Fuel Charge, NOx discharge and SO2 discharge goals are minimized separately with the aid of utilizing RCGA. Results received on or after fuel charge reduction, NOx discharge reduction and SO2 discharge reduction, are précised in Table 1.Fig.1 portrays fuel charge, NOx discharge and SO2 discharge meeting characteristics. Results received from each fuel charge and NOx discharge targets optimized at the same time and each Fuel charge and SO2 discharge goals optimized concurrently through the usage of NSGA-II and SPEA 2 are précised in Table 1. Results obtained from Fuel charge, NOx discharge and SO2 discharge targets optimized simultaneously by way of the usage of NSGA-II and SPEA 2 also are summarized in Table 1. Fig. 2 portrays the allocation of 10 nondominated clarifications received in the final new release of recommended NSGA-II and SPEA2 obtained from both Fuel charge and NOx discharge targets optimized concurrently and both price and SO2 discharge targets optimized concurrently and from Fuel charge, NOx discharge and SO2 discharge targets optimized concurrently.

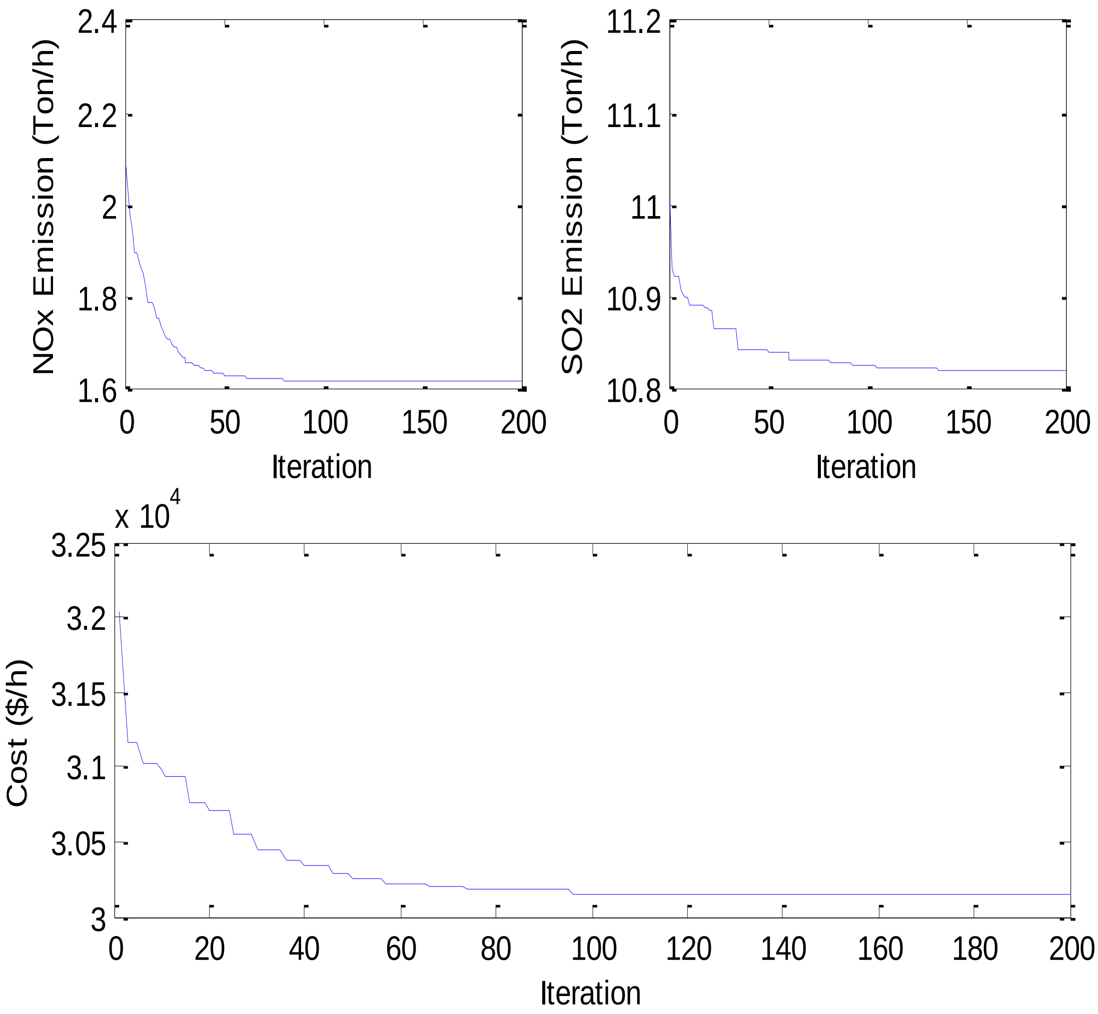

Fig. 1. NO_x discharge, SO_2 discharge and fuel charge convergence for test framework 1.

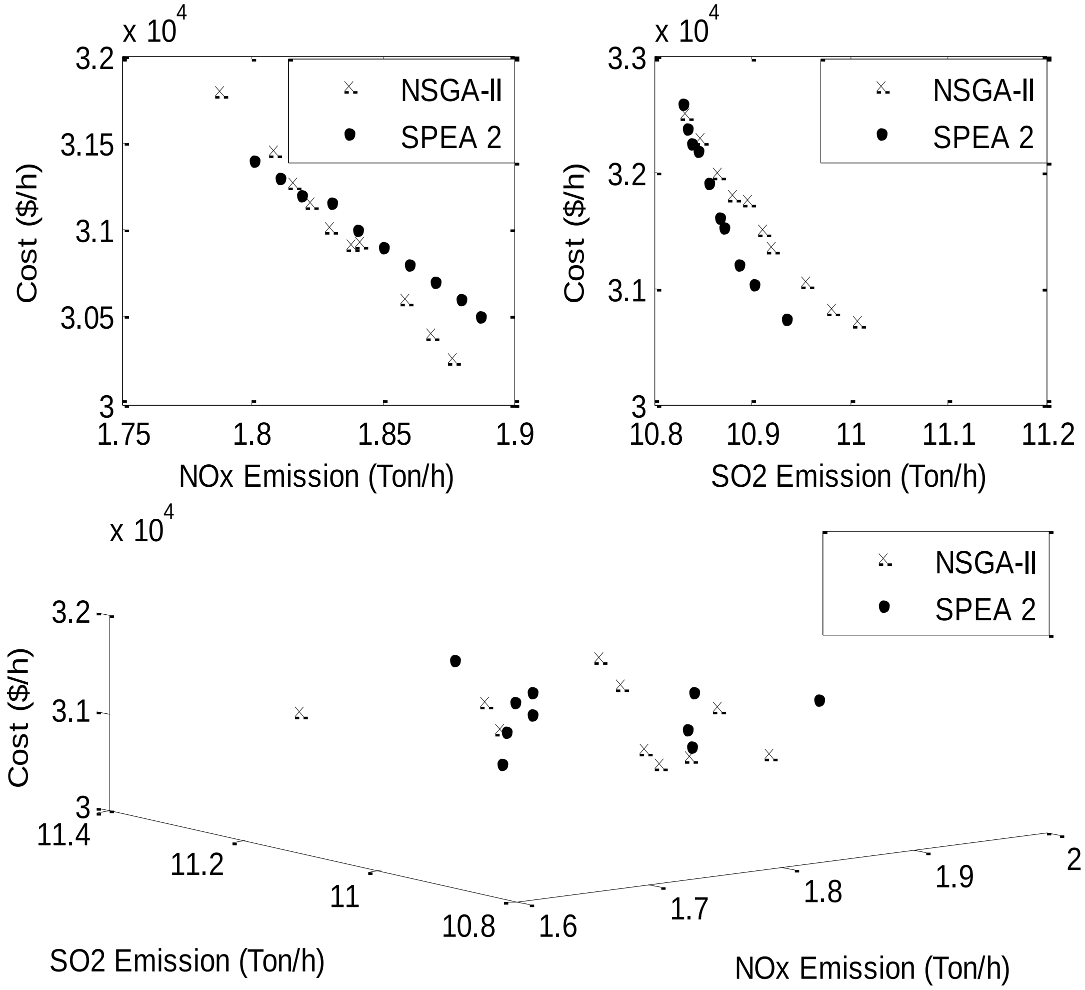

Fig. 2. Pareto-optimal front gained from the final iteration for test framework 1

Table 1: Test results of test system 1 for P_D = 2400 MW

PARAMETERS	**RCGA**			**NSGA-II**	**SPEA 2**	**NSGA-II**	**SPEA 2**	**NSGA-II**	**SPEA 2**
	Economic dispatch	**NO_x Emission Dispatch**	**SO_2 Emission Dispatch**	**Economic NO_x Emission Dispatch**		**Economic SO_2 Emission Dispatch**		**Economic NO_x emission SO_2 Emission Dispatch**	
P_{s1} (MW)	238.29	117.26	46.403	240.000	194.168	46.509	45.000	240.000	187.457
P_{s2} (MW)	238.29	127.59	45.557	240.000	186.082	92.622	161.381	186.284	240.000
P_{s3} (MW)	367.39	449.83	277.512	450.000	450.000	357.011	325.057	418.291	450.000
P_{s4} (MW)	346.34	150.14	349.923	201.201	150.000	3500.000	350.000	289.347	244.381
P_{s5} (MW)	346.34	150.00	349.982	331.431	350.000	350.000	350.000	240.241	350.000
P_{s6} (MW)	350.00	749.17	390.789	350.000	558.404	351.232	363.876	408.286	350.000
P_{s7} (MW)	35.000	35.301	175.000	35.000	35.000	98.487	53.530	35.000	37.100
P_{s8} (MW)	35.000	35.000	175.000	35.000	35.000	175.000	175.000	35.000	35.000
P_{s9} (MW)	93.327	235.725	239.967	176.288	97.382	232.605	227.153	197.549	70.140
P_{sp} (MW)	174.99	175.00	174.995	170.001	170.149	171.551	175.000	175.000	163.343
P_{PV} (MW)	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000
P_b (MW)	100.00	100.00	99.869	96.077	98.813	100.000	100.000	100.000	97.576
cost ($/h)	30302.	32113	32634.6	30944.6	35411.0	32199.00	32212.9	31105.3	31025.2
NO_x emission (Ton/h)	1.825	1.620	2.098	1.737	1.709	2.005	1.976	1.738	1.764
SO_2 emission (Ton/h)	11.062	11.281	10.820	11.192	11.235	10.882	10.885	11.136	11.170
CPU time (sec)	5.106	5.265	4.951	2.857	3.254	2.873	3.289	2.947	3.427

3.6.2 Test framework 2

Twelve Thermal divisions have been comprised. Thermal unit data has been adopted from [51]. Two wind power generators data is same as test system 1. Load demand is 3600 MW.

Fuel rate, NOx discharge and SO2 discharge goals are reduced personally through employing RCGA. Results received from Fuel rate reduction, NOx discharge reduction and SO2 discharge reduction, are précised in Table 2. Fig. 3 portrays Fuel rate, NOx discharge and SO2 discharge convergence. Results obtained from each price and NOx discharge objectives optimized concurrently and both Fuel rate and SO2 discharge goals optimized in chorus via means of the usage of NSGA-II and SPEA 2 are précised inside Table 2.Results obtained from different criteria i.e. fuel rate, NOx discharge and SO2 discharge goals optimized concurrently through the usage of NSGA-II and SPEA 2 are also précised in Table 2. Fig. 4 portrays the circulation of 10 nondominated answers gained inside the remaining generation of recommended NSGA-II and SPEA2 received from each price and NOx discharge targets optimized concurrently and both fuel rate and SO2 discharge optimized all together and from fuel rate, NOx discharge and SO2 discharge objectives optimized concurrently.

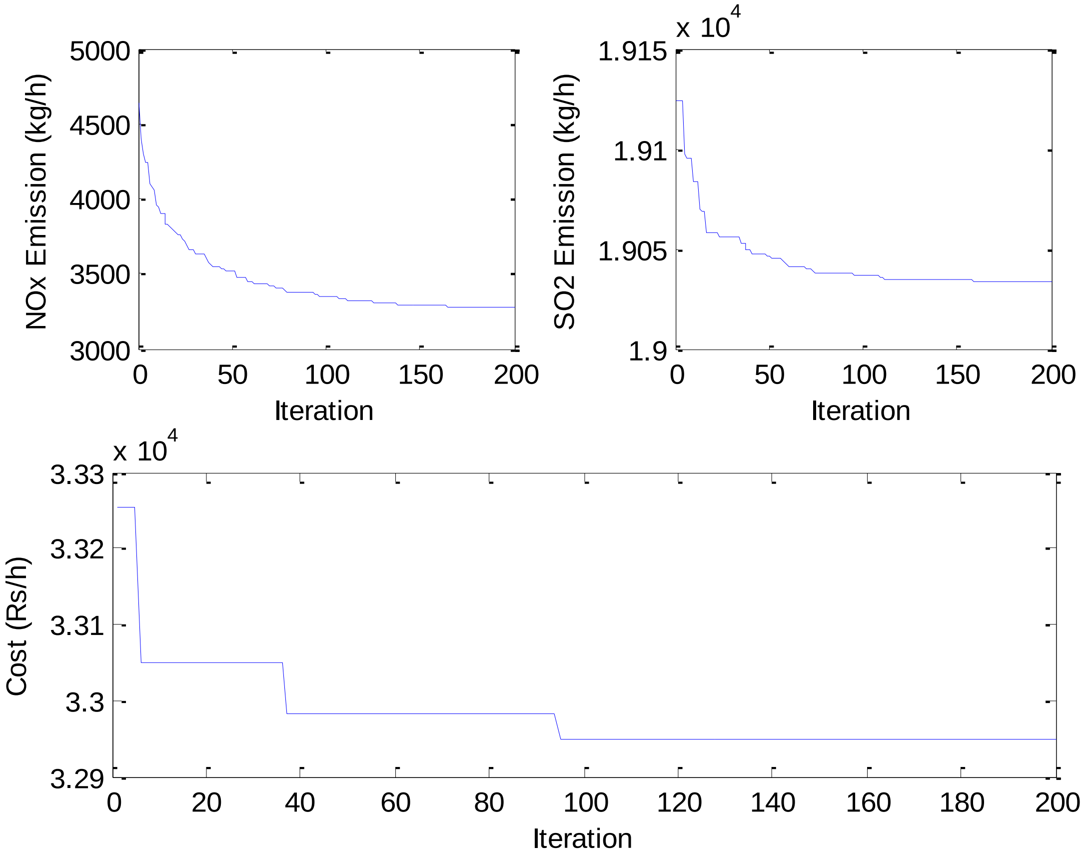

Fig. 3. NO_x discharge, SO_2 discharge and fuel charge convergence for test framework 2.

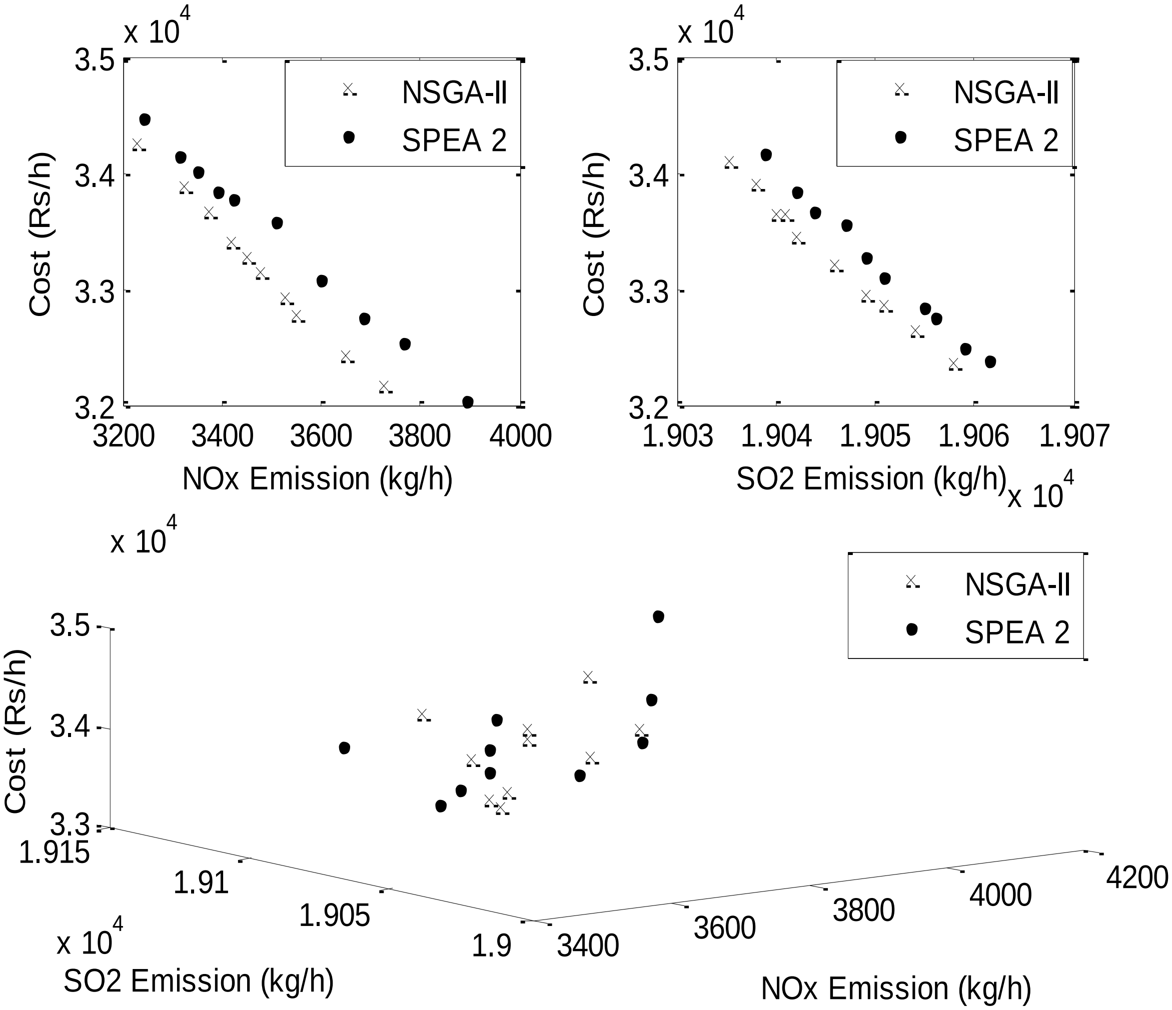

Fig. 4. Pareto-optimal front acquired from the last iteration for test framework 2.

Table 2: Test results of test system 1 for P_D = 3600 MW

PARAMETERS	**RCGA**			**NSGA-II**	**SPEA 2**	**NSGA-II**	**SPEA 2**	**NSGA-II**	**SPEA 2**
	Economic dispatch	**NO_x Emission Dispatch**	**SO_2 Emission Dispatch**	**Economic NO_x Emission Dispatch**		**Economic SO_2 Emission Dispatch**		**Economic NO_x emission SO_2 Emission Dispatch**	
P_{s1} (MW)	195.545	169.794	174.072	196.133	147.122	170.373	146.797	154.832	132.602
P_{s2} (MW)	207.263	163.347	138.358	175.955	164.876	138.469	120.589	208.708	169.608
P_{s3} (MW)	303.170	202.574	333.360	199.555	189.367	315.244	299.461	308.181	305.293
P_{s4} (MW)	417.665	409.932	364.360	401.501	412.877	375.676	395.627	432.207	300.640
P_{s5} (MW)	276.115	296.088	248.484	273.383	318.981	283.039	245.927	181.507	200.936
P_{s6} (MW)	468.187	394.020	365.629	389.301	385.856	328.700	368.734	382.450	414.266
P_{s7} (MW)	137.249	163.762	174.026	177.150	178.179	199.177	161.950	110.0738	193.098
P_{s8} (MW)	259.277	172.155	126.482	131.339	134.030	191.665	161.263	138.019	127.971
P_{s9} (MW)	298.717	187.048	330.045	203.869	219.933	321.417	329.731	277.317	332.468
P_{s10} (MW)	306.886	406.464	364.022	437.259	410.420	362.885	433.869	442.206	329.715
P_{s11} (MW)	100.000	290.743	257.948	307.990	287.464	197.438	241.190	249.726	308.709
P_{s12} (MW)	279.921	394.067	373.301	353.689	401.102	365.911	345.511	364.105	435.021
P_{sp} (MW)	175.000	175.000	174.948	171.871	174.787	175.000	175.000	175.000	175.000
P_{PV} (MW)	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000
P_b (MW)	100.000	100.000	99.999	100.000	100.000	100.000	99.985	100.000	99.665
cost ($/h)	32849.4	33892.7	34089.1	33839.2	33689.1	34024.3	34062.7	33984.0	34063.6
NO_x emission (Ton/h)	3957.02	3274.31	3610.96	3440.07	3485.82	3626.28	3556.28	3572.42	3685.16
SO_2 emission (Ton/h)	19119.7	19135.2	19034.6	19146.6	191285.5	19046.0	19049.0	19082.7	19067.3
CPU time (sec)	5.752	5.809	5.934	2.885	3.605	2.905	3.580	2.975	3.609

3.7 Conclusion:

Here, NSGA-II has been referred as finding solution of economic environmental dispatch of wind integrated coal-fired generating unit. The problem has been devise as multi-objective optimization problem with challenging fuel charge; NO_x discharge and SO_2 discharge targets. Analysis outcome gained from the recommended proposal have been evaluated by means of those obtained from SPEA 2. It is seen from the similarity that the recommended idea tendered a viable presentation in provisions of clarification.

CHAPTER-4

Environmental Economic Dispatch of Thermal-Wind-Solar Power System using NSGA II

4.1. Introduction:

Most electrical energy is produced by burning fossil fuels nowadays which releases various pollutants like oxides of sulfur (SO_2), Nitrogen oxides (NO_x), oxides of carbon (CO,CO_2) etc into the air. One of the principles defies for electric utilities is to decrease air contamination. The act proposed in the year 1990 related to Clean Air is planned to diminish global warming. It necessitates that the conventional generation units ought to the above mentioned pollutants spread dimension [31].

More than one method has been projected in the writing to cut down the pollution of natural contamination [33]. This considers the installation of switching device that maintains the emission level, utilization of low emanation raw materials, and replacement of the old combustion chamber through new models and get away with outflow thought [34]-[37]. These preliminary methods either call for the setting up of latest equipments or alteration of the existing equipments that involves significant funds disbursement. Therefore, the last method is more recommended. Diverse techniques [36]-[38] have been discussed related to the Economic Emission Dispatch (EED) problem. However, these techniques cannot handle the non-linear fuel cost and emission level functions. Therefore, the last method is more recommended.

The three aims - price, NO_x extraction and SO_2 extraction are contradictory in nature and for discovering overall optimal dispatch they have to be considered concurrently. For arranging the on line generator productivity having the expected load requirement for getting most effective result in terms of price, NO_x extraction and SO_2 extraction at the same time while satisfying each and every operational constraint the Economic environmental dispatch (EED) has been used.

Several methods related to EED problem are discussed in the text. The EED as a multiple, contradictory intentional issue & used goal-programming methods to resolve the non linear problem [39]-[40].Optimization procedure based upon linear programming are discussed in [41]-[42] where the objectives are regarded one by one. Numerous investigations were done to assess the development of multi-objective evolutionary search strategies throughout the previous couple of years. Strength Pareto Evolutionary Algorithm (SPEA 2) [43], Non-Dominating Sorting Genetic Algorithm II (NSGA II) [44], Multi-Objective Evolutionary Algorithm (MOEA) [45] etc., comprise evolving multi-purpose techniques which are pertained towards solving the EED issues.

In the previous ten years, the EED issue was changed into an issue with single target through linear combining of differing points as a weighted entirety [46]. It necessitates through changing weights to acquire a bunch of non-subservient answer. Regrettably, in case of problems with non-convex Pareto-optimal front it is of no use. However, the stochastic search algorithms are very faster and accurate [47]-[48].

It is found that in all these approaches, the extraction function is formulated as a mixture of either sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) or only nitrogen oxides (NO_x) [49]. However, in this paper sulphur dioxide (SO_2) and nitrogen oxides (NO_x) extraction objectives are regarded as separate functions.

In reduction of the effect of Global Warming, wind power and solar PV plants are becoming popular along with fulfilling power stipulate at reasonable price having no dangerous extractions [50]. But intermittent wind and solar power require schemes and dispatch strategies for upholding economy with dependability and safety measures.

Real-Coded Genetic Algorithm (RCGA) [49], [51]-[52] has been utilized in order to get rid of the cumbersome binary notation of dealing with continuous search space with large dimensions. Moreover, the Simulated Binary Crossover (SBX) and polynomial mutation is employed in the current proposition.

A non-dominated sorting genetic algorithm-II is recommended in this paper for economic environmental dispatch of thermal wind sun oriented power framework with battery vitality stockpiling framework where price, sulphur dioxide (SO_2) extraction and oxides of nitrogen (NO_x) extraction are competing objectives. This problem is produced as a nonlinear restricted multi-objective optimization difficulty.

Extensive experiments have been carried out for validating the proposed scheme by pertaining it on Test System 1 and Test System 2. The results reported from the investigation on NSGA-II is compared and analyzed to that obtained from SPEA 2.

4.2. Problem Formulation

The Economic Emission Dispatch (EED) of Thermal-Wind-Solar Power System is proposed to normalize the three objective functions - cost, release of SO_2 and NO_x in chorus while fulfilling the operational limitation. The subsequent objective and factors that are used in current work are as discussed one by one:

4.2.1. Objective function

4.2.1.1 Cost

The operational expense of a thermal-wind-solar system involves the raw material rate for coal-based units alongside the expense of wind speed creating entity and sun oriented PV plants. The complete expense can be expressed as:

$$F_C = \sum_{i=1}^{N_s} f_{si}\left(P_{si}\right) + \sum_{i=1}^{N_w} f_{ti}\left(P_{ti}\right) + \sum_{i=1}^{N_{PV}} \left[K_{si} \times P_{PVi}\right] \tag{4.1}$$

The raw material charge capacity of every coal based unit, thinking about the valve point impact, is articulated like:

$$f_{si}\left(P_{si}\right) = a_{si} + b_{si}P_{si} + c_{si}P_{si}^2 + \left|d_{si} \times \sin\left\{e_{si} \times \left(P_{si}^{\min} - P_{si}\right)\right\}\right| \tag{4.2}$$

The expense of wind power incorporates three segments - an immediate cost, an under estimation penalty cost and a spare cost due to over estimation of wind control. Henceforth, the charge related to wind energy conversion of ith generated entity at mth time is figured as [49]

$$f_{wi} = \left\{\left(d_{wi} \times P_{ti}\right) + C_{pi}\left(W_{avg,i} - P_{ti}\right) + C_{ri}\left(P_{ti} - W_{avg,i}\right)\right\} \tag{4.3}$$

$$C_{pi}\left(W_{avg,i} - P_{ti}\right) = J_{ci}\left(W_{avg,i} - P_{ti}\right) = J_{ci} \times \int_{P_{wi}}^{P_{wri}} \left(w - P_{ti}\right) f_w(w)\,dw \tag{4.4}$$

$$C_{ri}\left(P_{ti} - W_{avg,i}\right) = K_{ri}\left(P_{ti} - W_{avg,i}\right) = K_{ri} \times \int_{0}^{P_{wi}} \left(P_{ti} - w\right) f_w(w)\,dw \tag{4.5}$$

$$f_w(w) = \frac{k_s h v_{in}}{P_{wr} c} \left[\frac{\left(1 + \frac{hw}{P_{wr}}\right) v_{in}}{c}\right]^{k_s - 1} \times \exp\left\{-\left[\frac{\left(1 + \frac{hw}{P_{ti}}\right) v_{in}^{k_s}}{c}\right]\right\} \tag{4.6}$$

The characterization of wind power is carried out by utilizing Weibull Probability Density Function. $f_w(w)$ is Weibull Probability Density Function of wind power. Here $h = \frac{v_r}{v_{in}} - 1$. The detailed description can be found in [49].

4.2.1.2 NO$_x$ Emission:

NO$_x$ emissions of thermal power plant are hard to replicate as they are generated from various sources. NO$_x$ emission is not simple to represent since they are highly nonlinear. The proposed NO$_x$ emission [53] is considered to be a combinational relation between quadratic and exponential expressions and be able to be expressed in the following way.

$$E_{\mathrm{NO}_x} = \sum_{i=1}^{\mathrm{N}_s} \left[\alpha_{ni} + \beta_{ni} \mathrm{P}_{si} + \gamma_{ni} \mathrm{P}_{si}^2 + \eta_{ni} \exp\left(\delta_{ni} \mathrm{P}_{si} \right) \right] \tag{4.7}$$

4.2.1.3 *SO$_2$ Emission*:

SO$_2$ emission of thermal power plant depends on the amount of fuel burned and can be replica as quadratic polynomial function stated as:

$$E_{\mathrm{SO}_2} = \sum_{i=1}^{\mathrm{N}_s} \left[\alpha_{si} + \beta_{si} \mathrm{P}_{si} + \gamma_{si} \mathrm{P}_{si}^2 \right] \tag{4.8}$$

4.2.2 Constraints:

4.2.2.1 Real power balance constraint:

The total real power generation must balance the predicted power demand plus the real power losses in the transmission lines.

$$\sum_{i=1}^{\mathrm{N}_s} \mathrm{P}_{si} + \sum_{i=1}^{\mathrm{N}_w} \mathrm{P}_{wi} + \sum_{i=1}^{\mathrm{N}_{PV}} \mathrm{P}_{PVi} + \mathrm{P}_b - \mathrm{P}_D - \mathrm{P}_L = 0 \tag{4.9}$$

The power from PV cell is communicated by the accompanying articulation:

$$\left.\begin{aligned} \mathrm{P}_{PVi} &= \mathrm{P}_{PVr}\left(\frac{G^2}{G_{std}R_c}\right), \quad \text{for } 0 < G < R_c \\ \mathrm{P}_{PVi} &= \mathrm{P}_{PVr}\left(\frac{G}{G_{std}}\right), \quad \text{for } G > R_c \end{aligned}\right\} \tag{4.10}$$

The most extreme charge and release limit of the battery which relies upon battery-capacities is spoken to by Eq. (4.11).

$$-\mathbf{P}_b^{\max} \le \mathbf{P}_b \le \mathbf{P}_b^{\max} \tag{4.11}$$

Where, P_b is certain for releasing and negative for charging.

Transmission loss P_L is a function of power of all generating units and can be expressed as:

$$\mathrm{P}_L = \sum_{i=1}^{\mathrm{N}}\sum_{j=1}^{\mathrm{N}} \mathrm{P}_i \mathrm{B}_{ij} \mathrm{P}_j + \sum_{i=1}^{\mathrm{N}} \mathrm{B}_{0i} \mathrm{P}_i + \mathrm{B}_{00} \tag{4.12}$$

Here, total number of plants $\mathrm{N} = \mathrm{N}_s + \mathrm{N}_w + \mathrm{N}_{PV}$ and P_i is the power generation of thermal, wind and solar units respectively.

4.2.2.2 Real power operating limits:

$$\mathrm{P}_{si}^{\min} \le \mathrm{P}_{si} \le \mathrm{P}_{si}^{\max} \quad i \in \mathrm{N}_s \tag{4.13}$$

$$\mathrm{P}_{wi}^{\min} \le \mathrm{P}_{wi} \le \mathrm{P}_{wi}^{\max} \quad i \in \mathrm{N}_w \tag{4.14}$$

4.3. Determination of Generation Level of Slack Generator

M faithful generating units include portion of their capacity yield exposed towards balancing supply requirement as specified in Eq. (4.9) and the individual capability limitations are expressed in Eq. (4.13) and Eq. (4.14) respectively. Supply aspect of the M^{th} generator (for example - relaxed one) can express through given relation by considering power stacking of former (*M*-1) generating units which is expressed as follows:

$$\mathbf{P}_{\mathrm{N}} = \mathbf{P}_{D} + \mathbf{P}_{L} - \sum_{i=1}^{M-1} \mathbf{P}_{i} \tag{4.15}$$

The transmission loss is a component of all generator yields together with the casual generator and it is expressed as:

$$\mathrm{P}_{L} = \sum_{i=1}^{\mathrm{N}-1}\sum_{j=1}^{\mathrm{N}-1} \mathrm{P}_{i}\mathrm{B}_{ij}\mathrm{P}_{j} + 2\mathrm{P}_{\mathrm{N}}\left(\sum_{i=1}^{\mathrm{N}-1}\mathrm{B}_{\mathrm{N}i}\mathrm{P}_{i}\right) + \mathrm{B}_{\mathrm{NN}}\mathrm{P}_{\mathrm{N}}^{2} + \sum_{i=1}^{\mathrm{N}-1}\mathrm{B}_{0i}\mathrm{P}_{i} + \mathrm{B}_{0\mathrm{N}}\mathrm{P}_{\mathrm{N}} + \mathrm{B}_{00} \tag{4.16}$$

Escalating along with rescheduling Eq. (15), it turns into the following:

$$\mathrm{B}_{\mathrm{NN}}\mathrm{P}_{\mathrm{N}}^{2} + \left(2\sum_{i=1}^{\mathrm{N}-1}\mathrm{B}_{\mathrm{N}i}\mathrm{P}_{i} + \mathrm{B}_{0\mathrm{N}} - 1\right)\mathrm{P}_{\mathrm{N}} + \left(\mathrm{P}_{D} + \sum_{i=1}^{\mathrm{N}-1}\sum_{j=1}^{\mathrm{N}-1}\mathrm{P}_{i}\mathrm{B}_{ij}\mathrm{P}_{j} + \sum_{i=1}^{\mathrm{N}-1}\mathrm{B}_{0i}\mathrm{P}_{i} - \sum_{i=1}^{\mathrm{N}-1}\mathrm{P}_{i} + \mathrm{B}_{00}\right) = 0 \tag{4.17}$$

4.4. Principle of Multi-objective Optimization:

Multi-target optimization issue involving various destinations and constraints like primary and secondary may be expressed like:

Minimize $f_i(x)$, i =1,…..,$\mathrm{N}_{\mathrm{obj}}$ (4.18)

area under discussion $\begin{cases} g_k(x) = 0 & k = 1,\ldots,\mathrm{K} \\ h_l(x) \le 0 & l = 1,\ldots,L \end{cases}$ (4.19)

where f_i is the i th intent function, x is a assessment vector.

4.5. Non-dominated Sorting Genetic Algorithm-II

To deal with multi-target optimization issues, NSGA has been proposed in the year of 1995. Non-domination is utilized to offer position to arrangements, and strength contribution is profited in support of expansion command over in the investigation area. Because of not highly susceptible to fitness sharing parameters of NSGA, [19] have instigated NSGA-II as it produce more authentic and dependable solution speedy than its precursor. Because of word constraints, the fact depiction of NSGA-II isn't given in the paper. The progression of occasions in 'NSGA-II' is introduced in Figure.I after given all the section one by one.

i) Fast nondominated sorting procedure

To accumulate way out of the initial nondominated the face in a inhabitants of dimension, each answer be able to be matched up to all extra answer inside the inhabitants to unearth if it's far conquered. By the side of the particular step, all community inside the first nondominated the front are created. In order to unearth the individuals inside the next nondominated front, the solutions of the first front are marked down for the time being and every answer of the residual populace can be matched as much as each different answer of the residual inhabitants to unearth if it is to governed. Accordingly the entire particular inside the next nondominated face are created. This is right for creating third and higher tiers of nondomination.

In support of every way out two components are computed: a) dominion count n_q, the quantity of arrangements which overwhelm the arrangement q, and b) S_q, a lot of arrangements that the arrangement overwhelms. The approach for the rapid nondominated category can be stated as:

So as to uncover the people in the following nondominated front, the arrangements of the principal front are discounted for the present and every arrangement of the lingering populace can be coordinated up to each other arrangement of the remaining populace to uncover on the off chance that it is ruled. In this manner all people in the subsequent nondominated face are made. This is directly for making third and more elevated degrees of non-domination.

The algorithm for the fast nondominated category can be stated as: Algorithm 1: Fast non dominated category.

```
For each $p \in P$
  $S_p = \phi$
$n_p = 0$
for each $q \in P$
if $(p \prec q)$ then              if $p$ dominates $q$
$S_p = S_p \cup \{q\}$             add $q$ to the set $p$
else if $(q \prec p)$ then
$n_p = n_p + 1$                    augmentation of $p$
if $n_p = 0$ then                  $p$ fit in to the initial face
$P_{rank} = 1$
$F_1 = F_1 \cup \{p\}$
```

Every one inhabitants is given a grade identical to its nondomination degree or the face wide variety (1 for the exceptional stage and 2 for the following-great degree and so forth).

ii) Fast crowded distance estimation procedure

To collect an estimation of the concentration of answers contiguous a specific clarification within the populace, the common space of spots on both part of this thing beside all the targets is computed. This number provides as an estimation of the outer limits of the cuboid primarily based by the use of the closest pals because the vertices which may defined as crowding distance. This computation necessitates categorization of the populace in keeping with every goal feature fee in rising array of significance. Subsequently, in favor of every goal characteristic, the boundary populations (populations among nominal and biggest characteristic standards) are provided especially excessive distance fuel rate in order that boundary elements are constantly chosen. All different transitional inhabitants are supplied a distance price identical to the fixed regularized distinction inside the function standards of adjoining inhabitants. This computation is kept on with added goal capabilities. The crowding-distance assessment is computed because the total of individual distance values matching to every goal. Every purpose characteristic is regularizing ahead of computing the crowding distance. The set of rules underneath portrays the crowding distance calculation method of the entire answers in a nondominated set G.

```
Algorithm 2: Crowding distance assignment
$l = |G|$                                   digit of answer in G
for each $i$, set $F[i]_{distance} = 0$          expressed distance
in favour of every intention $n$
$G =$ Sort$(G, n)$   Arrange by means of every objective assessment
$G[1]_{distance} = F[l]_{distance} = \propto$
in favour of $j = 2$ to $(k-1)$ $G[j]_{distance} = G[j]_{distance} + (G[j+1].n - G[j-1].n)/(f_m^{\max} - f_m^{\min})$
```

Here, $G[i].n$ refers to the mth objective function value of the i^{th} entity in the position G. $f_m^{\max}$ and $f_m^{\min}$ are the greatest and least standards of the mth objective purpose.

iii) Crowded-comparison manipulator

The crowded- comparison manipulator conducts the collection technique at a selection of tiers of the set of rules closer to a uniformly spread-out pareto-optimal front. All individual within the populace has two aspects:

a) nondomination rank (i_{rank})

b) crowding distance $(i_{dis\tan ce})$

$i \prec j$ if $i_{rank} < j_{rank}$ or $((i_{rank} = j_{rank})$ and $(i_{dis\tan ce} > j_{dis\tan ce}))$

Between populaces with varying nondomination positions, the individuals with the lower (better) position are wanted. On the off chance that the two populaces have a place with the equivalent front, at that point the masses with bigger swarming separation is supported.

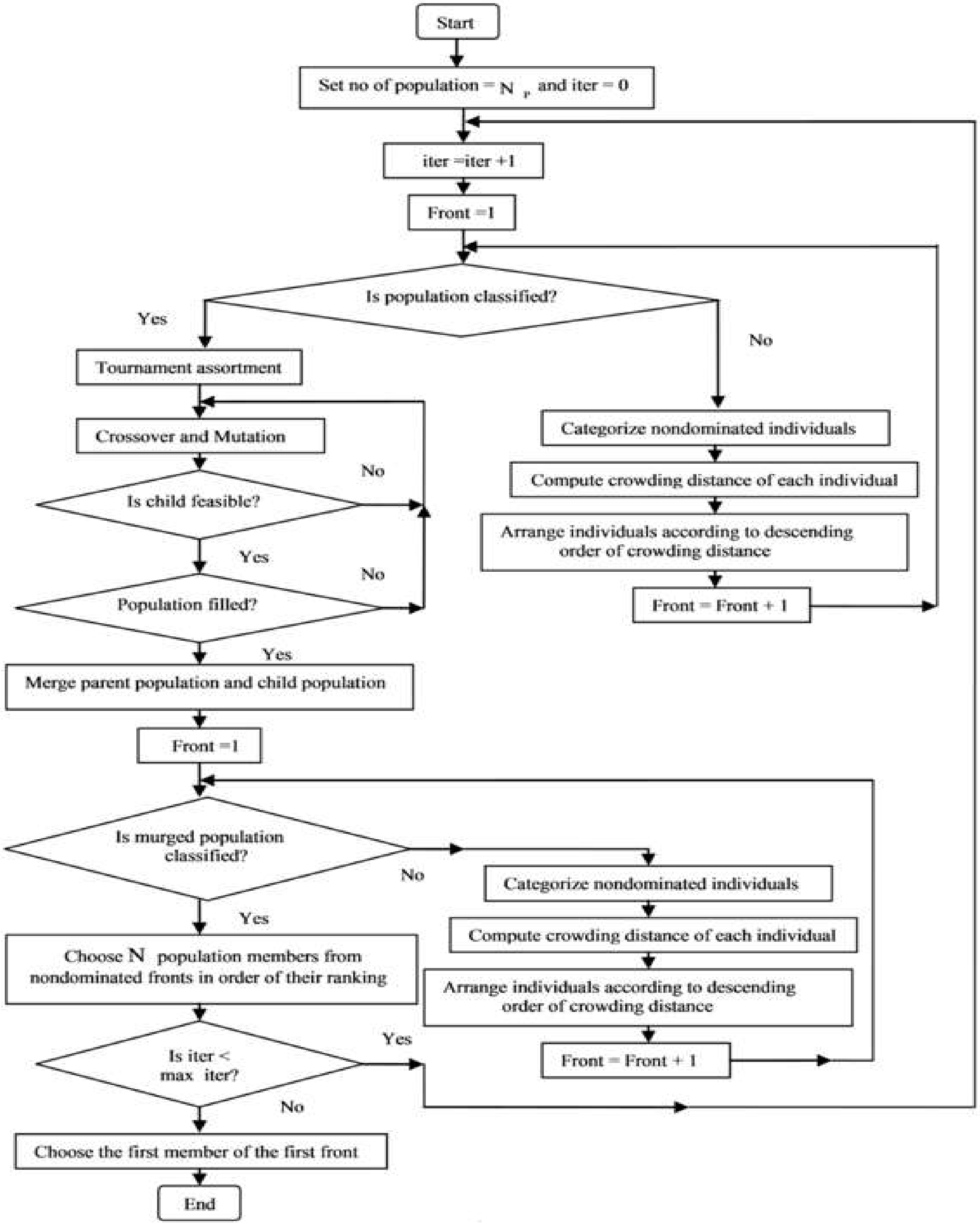

Figure 1: Flowchart of NSGA II

4.6 Case Study of Environmental Constraint Economic Dispatch of Thermal-Wind-Solar Power System:

A projected approach has been functional for solving framework 1 and framework 2. So as to check the exhibition of given recommended “NSGA-II” comes close to, “SPEA 2’ has been related for taking care of the issue. The proposed NSGA-II, SPEA 2 and RCGA are executed in MATLAB 7.0 taking place a computer (Dual-Core, 80 GB, 3.3 GHz).

The current work considers Cost, NO_x emission and SO_2 emission as the three objective functions are limited exclusively via employing “Real Coded Genetic Algorithm”. In this examination, the populace dimension, hybrid and transformation likelihood esteems have been taken as 100, 0.9 and 0.2, individually for these two test frameworks. The most extreme number of iterations has been picked as 200 and 300 for test framework 1 and test framework 2 separately. On the off chance that there ought to be an event of NSGA-II notwithstanding SPEA 2, the populace estimate, most extreme number of iterations, hybrid and transmutation probabilities have been chosen as 20, 30, 0.9 and 0.2 in favour of both assessment frameworks.

4.6.1 Test framework 1

Our assessment test framework 1 contains nine thermal generating units, one identical wind generator, one comparable sunlight based PV plant and one proportional battery storage system. Thermal unit data has been adopted from [51]. The openness of wind power is shown as probabilistic necessity in power equalization condition. The factor related to Weibull shape for given area and the factor related to scale for given area in wind energy converter are $k_{s1} = 1.7$ and $c_1 = 17$ separately. Spare and penalty charge coefficients in favour of turbine units preferred like $\mathrm{K}_{r1} = 5$ and $\mathrm{K}_{\mathrm{P1}} = 5$ respectively. The power limiting capacity of wind turbine is $\mathrm{P}_{wr1} = 175$ MW. Given cut-in, cut-off and apprised wind velocities are $v_{in} = 5$, $v_o = 45$ and $v_r = 15$ individually.

The power of PV based generation is $\mathrm{P}_{PVr} = 150$ MW. 3.5 is the given parameter related to direct cost (K_s) of solar based generation. The daylight based rays during the benchmark condition (G_{std}) furthermore a specific light point (R_c) be engaged as 1100 W/m^2 as well as 175 W/m^2. It is assumed that the forecasted solar radiation is 500w/m^2. The introduced limit ($\mathrm{P}_b^{\max}$) of storage system of battery is 100MW. Power requirement is 2400 MW.

Price, NO_x discharge and SO_2 emanation destinations are limited independently by using RCGA. Outcomes gained from cost minimization, NO_x emanation minimization and SO_2 discharge minimization, are condensed in Table 1. Figure 2 depicts cost, NO_x discharge and SO_2 emanation intermingling qualities. Results got from both price and NO_x discharge targets streamlined all the while and both price and SO_2 emanation goals upgraded at the same time via employing NSGA-II along with SPEA 2 be condensed into Table 1. Allocation of 10 non-dominating arrangements procured in the end iteration of projected NSGA-II in addition to SPEA 2 obtained from both price and NO_x discharge goals upgraded at the same time and both price and SO_2 emanation targets improved all the while and from price, NO_x outflow and SO_2 emanation destinations enhanced all the while and are shown in Figure 3.

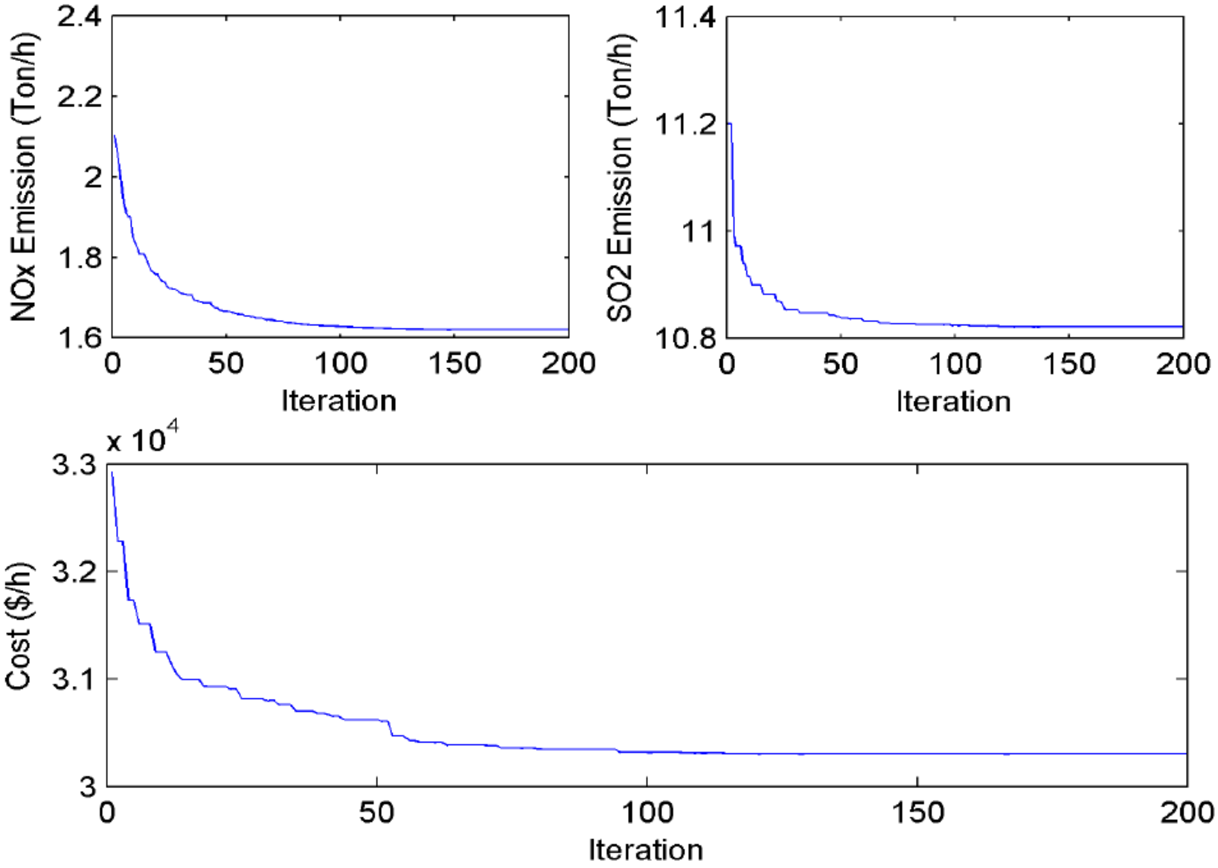

Figure 2: NO_x emission, SO_2 emission and cost convergence for Test framework 1.

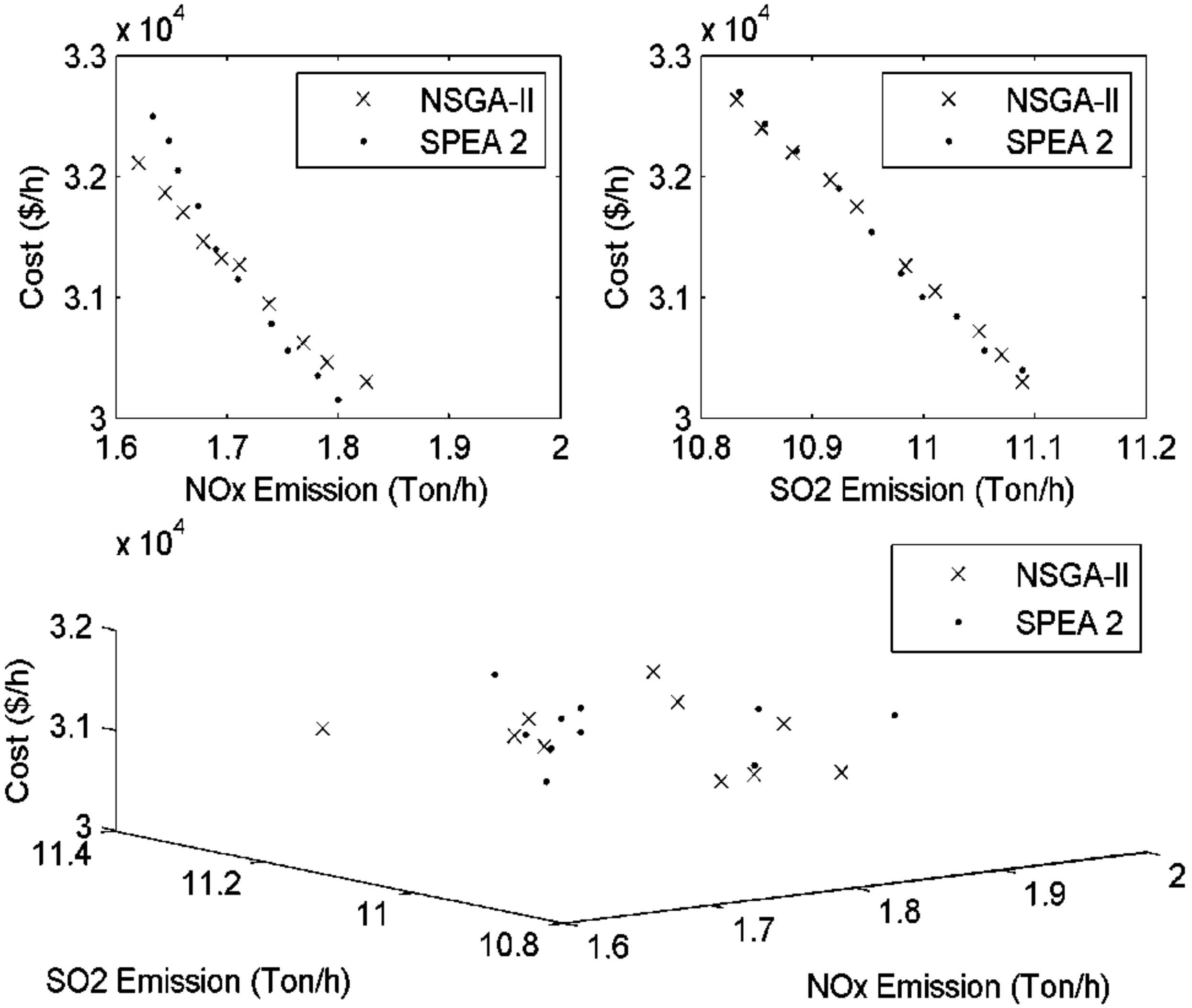

Figure 3: Pareto-optimal face locates from end iteration in support of test framework 1.

Table 1: Test results of test system 1 for P_D = 2400 MW

PARAMETERS	**RCGA**			**NSGA-II**	**SPEA 2**	**NSGA-II**	**SPEA 2**	**NSGA-II**	**SPEA 2**
	Economic dispatch	**NO_x Emission Dispatch**	**SO_2 Emission Dispatch**	**Economic NO_x Emission Dispatch**		**Economic SO_2 Emission Dispatch**		**Economic NO_x emission SO_2 Emission Dispatch**	
P_{s1} (MW)	238.29	117.26	46.403	240.000	194.168	46.509	45.000	240.000	187.457
P_{s2} (MW)	238.29	127.59	45.557	240.000	186.082	92.622	161.381	186.284	240.000
P_{s3} (MW)	367.39	449.83	277.512	450.000	450.000	357.011	325.057	418.291	450.000
P_{s4} (MW)	346.34	150.14	349.923	201.201	150.000	3500.000	350.000	289.347	244.381
P_{s5} (MW)	346.34	150.00	349.982	331.431	350.000	350.000	350.000	240.241	350.000
P_{s6} (MW)	350.00	749.17	390.789	350.000	558.404	351.232	363.876	408.286	350.000
P_{s7} (MW)	35.000	35.301	175.000	35.000	35.000	98.487	53.530	35.000	37.100
P_{s8} (MW)	35.000	35.000	175.000	35.000	35.000	175.000	175.000	35.000	35.000
P_{s9} (MW)	93.327	235.725	239.967	176.288	97.382	232.605	227.153	197.549	70.140
P_{sp} (MW)	174.99	175.00	174.995	170.001	170.149	171.551	175.000	175.000	163.343
P_{PV} (MW)	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000
P_b (MW)	100.00	100.00	99.869	96.077	98.813	100.000	100.000	100.000	97.576
cost ($/h)	30302.	32113	32634.6	30944.6	35411.0	32199.00	32212.9	31105.3	31025.2
NO_x emission (Ton/h)	1.825	1.620	2.098	1.737	1.709	2.005	1.976	1.738	1.764
SO_2 emission (Ton/h)	11.062	11.281	10.820	11.192	11.235	10.882	10.885	11.136	11.170
CPU time (sec)	5.106	5.265	4.951	2.857	3.254	2.873	3.289	2.947	3.427

4.6.2 Test framework 2

This test system comprises twelve generators, single equivalent wind turbine, single equivalent solar PV plant and single equivalent battery energy storage system. Thermal unit data has been adopted from [51] and other ratings are like test framework 1 except the power requirement which has been considered as 3600 MW.

Price, NO_x discharge and SO_2 emanation destinations are limited independently by using RCGA. Outcomes gained from cost minimization, NO_x emanation minimization and SO_2 discharge minimization, are condensed in Table 2. Figure 4 depicts cost, NO_x discharge and SO_2 emanation intermingling qualities. Results got from both price and NO_x discharge targets streamlined all the while and both price and SO_2 emanation goals upgraded at the same time through employ NSGA-II in addition to SPEA 2 are condensed in Table 2.

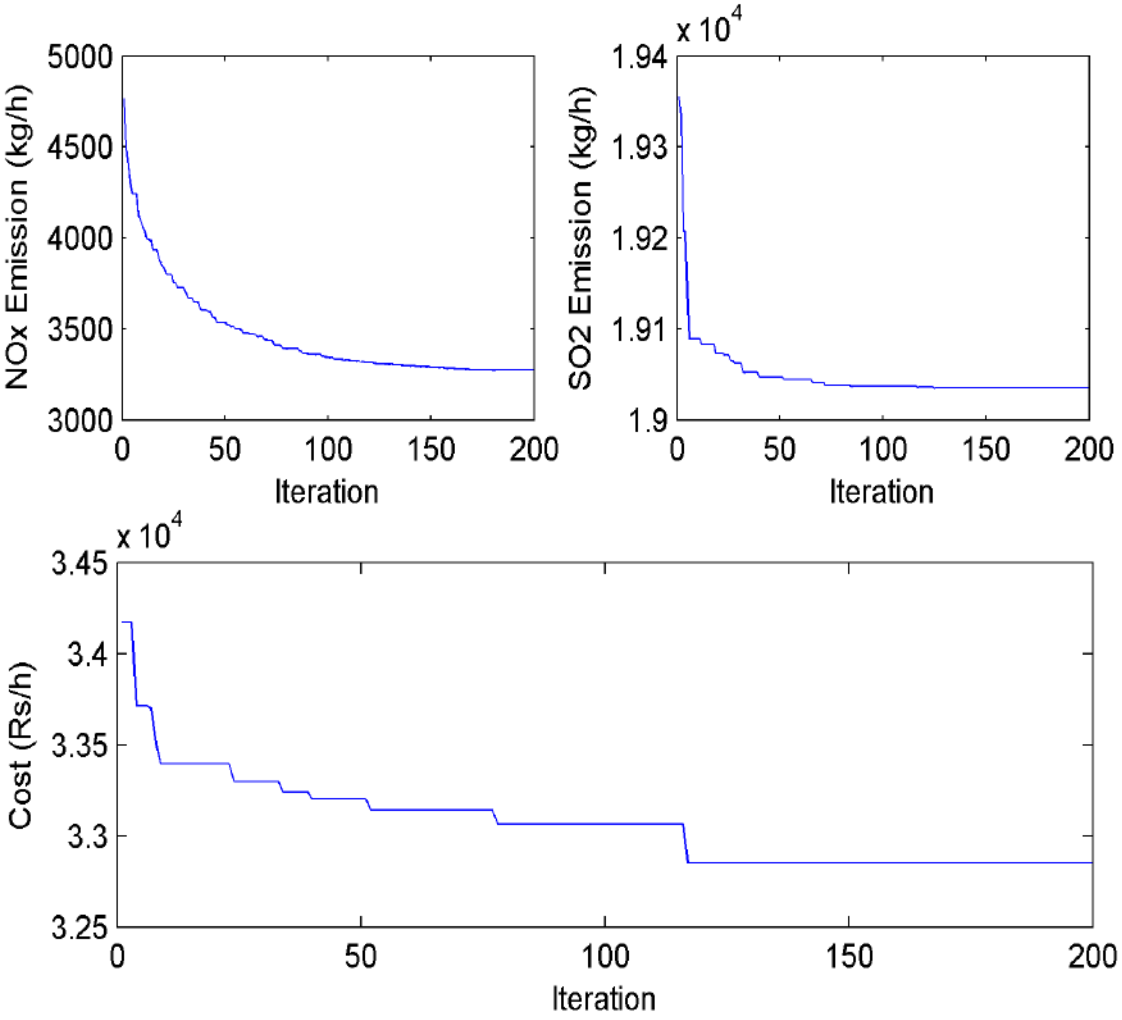

Figure 4: NO_x emission, SO_2 emission and cost convergence for test framework 2.

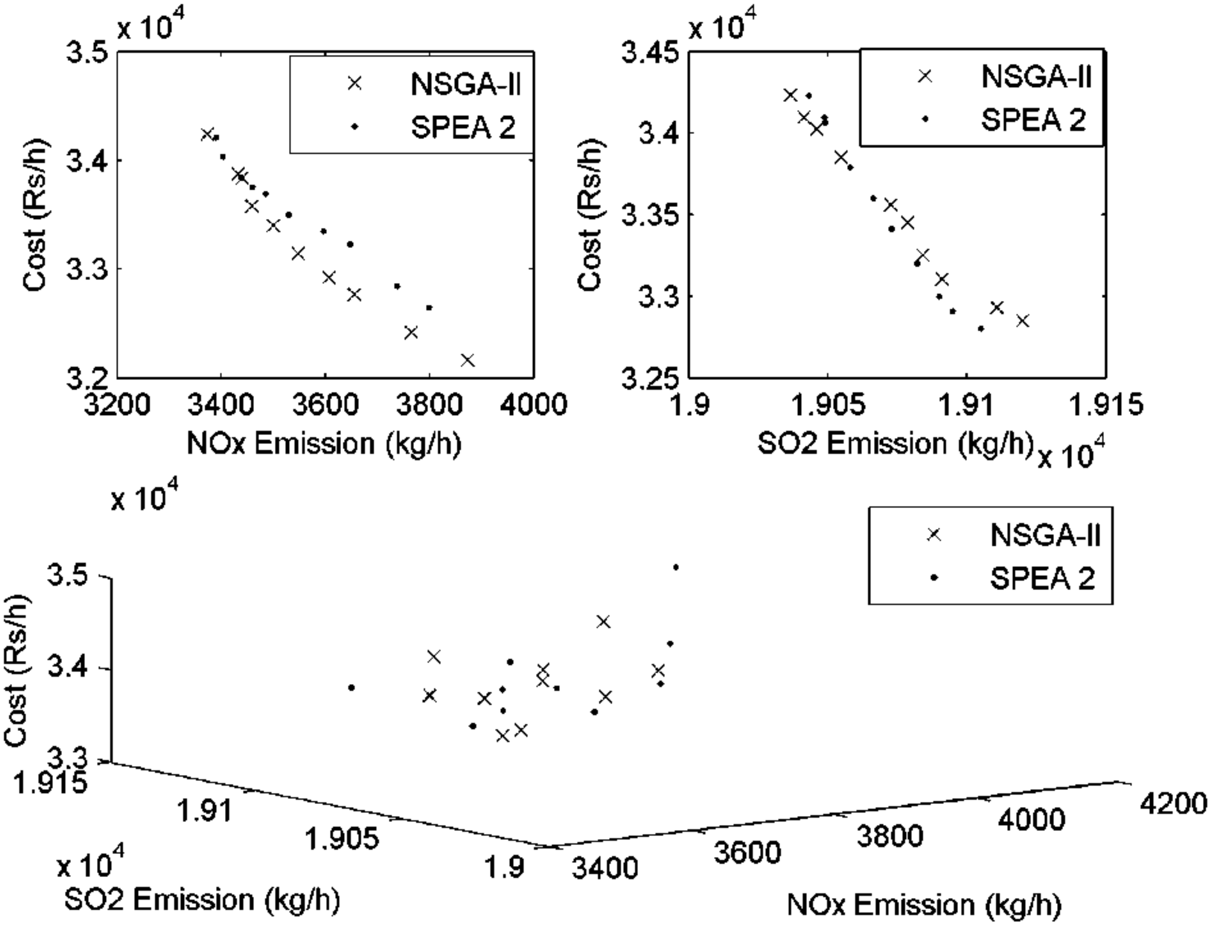

Figure 5: Pareto-optimal face locate from end iteration in support of test framework 2

Table 2: Test results of test system 1 for P_D = 3600 MW

PARAMETERS	RCGA			NSGA-II	SPEA 2	NSGA-II	SPEA 2	NSGA-II	SPEA 2
	Economic dispatch	NO_x Emission Dispatch	SO_2 Emission Dispatch	Economic NO_x Emission Dispatch		Economic SO_2 Emission Dispatch		Economic NO_x emission SO_2 Emission Dispatch	
P_{s1} (MW)	195.545	169.794	174.072	196.133	147.122	170.373	146.797	154.832	132.602
P_{s2} (MW)	207.263	163.347	138.358	175.955	164.876	138.469	120.589	208.708	169.608
P_{s3} (MW)	303.170	202.574	333.360	199.555	189.367	315.244	299.461	308.181	305.293
P_{s4} (MW)	417.665	409.932	364.360	401.501	412.877	375.676	395.627	432.207	300.640
P_{s5} (MW)	276.115	296.088	248.484	273.383	318.981	283.039	245.927	181.507	200.936
P_{s6} (MW)	468.187	394.020	365.629	389.301	385.856	328.700	368.734	382.450	414.266
P_{s7} (MW)	137.249	163.762	174.026	177.150	178.179	199.177	161.950	110.0738	193.098
P_{s8} (MW)	259.277	172.155	126.482	131.339	134.030	191.665	161.263	138.019	127.971
P_{s9} (MW)	298.717	187.048	330.045	203.869	219.933	321.417	329.731	277.317	332.468
P_{s10} (MW)	306.886	406.464	364.022	437.259	410.420	362.885	433.869	442.206	329.715
P_{s11} (MW)	100.000	290.743	257.948	307.990	287.464	197.438	241.190	249.726	308.709
P_{s12} (MW)	279.921	394.067	373.301	353.689	401.102	365.911	345.511	364.105	435.021
P_{sp} (MW)	175.000	175.000	174.948	171.871	174.787	175.000	175.000	175.000	175.000
P_{PV} (MW)	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000	75.000
P_b (MW)	100.000	100.000	99.999	100.000	100.000	100.000	99.985	100.000	99.665
cost ($/h)	32849.4	33892.7	34089.1	33839.2	33689.1	34024.3	34062.7	33984.0	34063.6
NO_x emission (Ton/h)	3957.02	3274.31	3610.96	3440.07	3485.82	3626.28	3556.28	3572.42	3685.16
SO_2 emission (Ton/h)	19119.7	19135.2	19034.6	19146.6	191285.5	19046.0	19049.0	19082.7	19067.3
CPU time (sec)	5.752	5.809	5.934	2.885	3.605	2.905	3.580	2.975	3.609

4.7 Conclusion:

In this paper, a Non-Dominating Sorting Genetic Algorithm II (NSGA II) is suggested with the aim of resolving economic environmental dispatch of coal- wind-sun based power framework with battery vitality stockpiling framework. The problem is devised as a multi-objective optimization problem with challenging price, NO_x extraction and SO_2 extraction objectives. Extensive experimental evaluation and comparative analysis has been carried out using experimental methodologies for verifying the effectiveness of the propounded system. The test upshots procured on the suggested system are collated with the results procured through Strength Pareto Evolutionary Algorithm 2 (SPEA 2). The results obtained from the experiments clearly demonstrate that the suggested approach offers more combative recital with respect to the solution as compared to the existing algorithm used for comparison.

CHAPTER-5

Multi-region Combined Heat and Power Economic Emission Dispatch

5.1. Introduction:

Economic dispatch (ED) allocates the generation level of all devoted turbines in a most price-effective way whilst gratifying numerous constraints in a solo structure.

In preferred, generating units are separated among several power production areas connected by using interconnections. Multi-region economic dispatch (MRED) is a growth of lone place economic dispatch. MRED reveals the electricity creation stage along with communication of energy among areas for reducing cost of all sections while satisfying miscellaneous constraint. Different strategies [103]-[111] are converse to explain MRED issue.

Vestige fuel is transformed into electricity in unproductive style. The best part of electricity production desecrated during the technique of change is high temperature. Creating power from a particular fuel source, for example, flammable gas, biomass, coal progress the use of flow due to the difference in temperature along with usefulness of the renovation method is accelerated. In contrast with different variety of energy transmitter, the usefulness of energy of cogeneration is extra which creates less significant pollution. The combined heat and power economic dispatch (CHPED) method implies power and heat creation accordingly that production billing is minimized along with satisfying miscellaneous constraint. Different proposal have already been proposed to solve CHPED issues and those are mentioned in reference section.

Huge incorporated power system is generally comprised of divergent locales dependent on an assortment of model for instance topographical, functional, forecast and administration. Every one of these areas has been correlated to its connecting section along with interconnections. Each locale has its capacity and heat creation and energy and heat requirement.

Limiting the complete cost for every spot through stacking of every dedicated generating units along with co-generation and heat-only units in this way that true power equilibrium limit, heat stability imperatives, production boundary requirements, heat production limit requirements with interconnection limit requirements have been fulfilled while from a particular fuel source, for example, flammable gas, biomass, coal are going in the course of limited heat vs. true power plane is the main point of multi-region combined heat and power economic dispatch (MRCHPED) .

Electric power plants based on fossil-fuel release a variety of pollutants which creates air pollution in the ambiance. Declining ambiance greenhouse gasses is another challenge for different power producers. The 1990 Clean Air Act is proposed for reducing atmospheric pollution. So today's civilization wants adequate and safe electricity at the cost-effective as well as minimum echelon of greenhouse gasses.

Various methods are proposed to decrease ambience greenhouse gasses [51]. Among these tactics, dispatching taking into emission consideration is preferable.

The proposed approach is an expansion of multi-region combined heat and power economic dispatch (MRCHPED) trouble. It plans a wide range of committed coal-fired generating units outputs, co-generation unit outputs, heat-only unit outputs and interchange power amongst regions with forecasted active power demand and heat request with the end goal that all out cost and outflow echelon in all sections are streamlined simultaneously satisfying an assortment of requirements.

This paper suggests NSGA-II to solve complicated multi-region combined heat and power economic emission dispatch (MRCHPEED) issues. For the given system, each region comprises coal-fired generating parts, co-generation parts and heat only parts. Every locale of the framework includes generation entity, co-generation entity and heat only entity. To triumph over intricacy of binary version for trading with unremitting explore break with big proportions, real-coded genetic algorithm (RCGA) [53] is exploited. The Simulated Binary Crossover (SBX) and polynomial mutation are used here.

The recommended method is confirmed by relating it with two-region analysis scheme.
Analysis outcome attained in the course of NSGA-II procedure are matched up through the result which are attained from strength -pareto evolutionary algorithm 2 (SPEA2).

5.2. Problem Formulation

Here framework consisting of generation segment, segment related to power from a particular fuel source, for example, flammable gas, biomass, coal and heat-only segment has been taken into consideration. Figure 1 uncovers heat-power reasonable serviceable zone of a joined cycle co-age unit. The warmth and force preparations are inseparable. The heat-power practical functional zone has been encompassed by the wilderness curve ABCDEF.

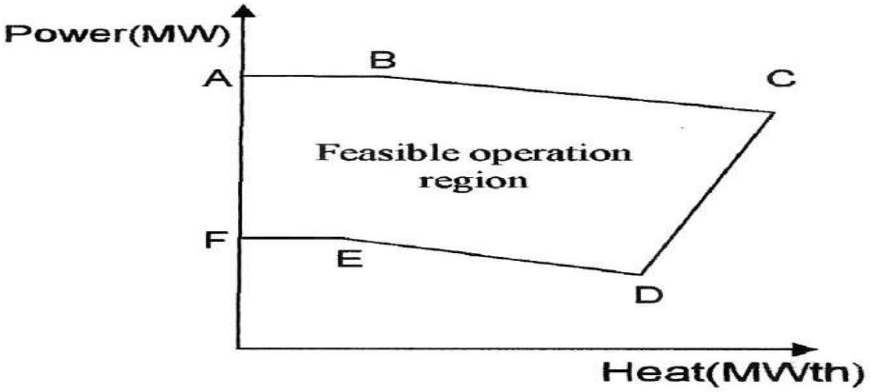

Fig. 1. Heat-Active power viable workable area for a cogeneration

The power output of the thermal generators and the heat output of heat-only units are bounded by their individual maximum and minimum frontiers. The power is produced by thermal generators and co-generation units and the heat is produced by co-generation units and heat-only units.

The MRCHPEED issue chooses the active power and heat creation with the goal that the complete cost and outflow of all locales is upgraded through running every dedicated generating units, units produced power from a particular fuel source, for example, flammable gas, biomass, coal and heat only units in this way where different limitation are fulfilled but units produced power from a particular fuel source, for example, flammable gas, biomass, coal are attempted in an encompassed heat in opposition to power plane. Here MRCHPEED issue is communicated as:

5.2.1. Objectives

(i)Cost

The total price is stated as

$$C_{\mathrm{T}} = \sum_{i=1}^{\mathrm{N_A}} \sum_{j=1}^{\mathrm{N}_{ti}} \left[a_{ij} + b_{ij}\mathrm{P}_{tij} + c_{ij}\mathrm{P}_{tij}^{2} + \left| d_{ij} \times \sin\left\{ e_{ij} \times \left(\mathrm{P}_{tij}^{\min} - \mathrm{P}_{tij} \right) \right\} \right| \right] + \sum_{i=1}^{\mathrm{N_A}} \sum_{j=1}^{\mathrm{N}_{ci}} \Big[\alpha_{ij} + \beta_{ij}\mathrm{P}_{cij} + \gamma_{ij}\mathrm{P}_{cij}^{2} +$$

$$\delta_{ij}\mathrm{H}_{cij} + \varepsilon_{ij}\mathrm{H}_{cij}^{2} + \xi_{ij}\mathrm{P}_{cij}\mathrm{H}_{cij} \Big] + \sum_{i=1}^{\mathrm{N_A}} \sum_{j=1}^{\mathrm{N}_{hi}} \left[\phi_{ij} + \eta_{ij}\mathrm{H}_{hij} + \lambda_{ij}\mathrm{H}_{hij}^{2} \right] \tag{5.1}$$

(ii) Emission

The ambience green house gases consisting of different air pollutants produced as a result of coal-fired generating unit is represented one by one. On the other hand, for assessment cause, the whole secretion of these green house gases is affirmed as the summation of a quadratic and an exponential characteristic [53]. The general discharge from thermal segments, cogeneration segments and heat-only segments in the system may be stated as

$$E_{\mathrm{T}} = \sum_{i=1}^{\mathrm{N_A}} \sum_{j=1}^{\mathrm{N}_{ti}} \left[\mu_{ij} + \kappa_{ij} \mathrm{P}_{tij} + \pi_{ij} \mathrm{P}_{tij}^{2} + \sigma_{ij} e^{\left(\theta_{ij} \mathrm{P}_{tij}\right)} \right] + \sum_{i=1}^{\mathrm{N_A}} \sum_{j=1}^{\mathrm{N}_{ci}} \left[\tau_{ij} \mathrm{P}_{cij} \right] + \sum_{i=1}^{\mathrm{N_A}} \sum_{j=1}^{\mathrm{N}_{hi}} \left[\rho_{ij} \mathrm{H}_{hij} \right] \tag{5.2}$$

5.2.2. Constraints

(i) Power equilibrium constraints:

The general real power production for every generating section and co-generation section need to be same to the region where real power utility in the company of the reflection of incoming and outgoing real power and is acknowledged in the following way:

$$\sum_{j=1}^{\mathrm{N}_{tii}} \mathrm{P}_{tij} + \sum_{j=1}^{\mathrm{N}_{ci}} \mathrm{P}_{cij} = \mathrm{P}_{Di} + \sum_{k,k \neq i} \mathrm{T}_{ik} \;, \; i \in \mathrm{N_A} \tag{5.3}$$

Where T_{ik} is the interconnection real power transmission in between section i to section k. T_{ik} is positive at the same time as energy transfer from section i to section k and T_{ik} is negative while energy transfer from section k to section i.

(ii) Interconnection power capacity constraints:

Power transmission through interconnection T_{xy} from section x to section y should lie within the interconnection real power transfer capacity boundary.

$$-\mathrm{T}_{xy}^{\max} \leq \mathrm{T}_{xy} \leq \mathrm{T}_{xy}^{\max} \tag{5.4}$$

Where $\mathrm{T}_{ik}^{\max}$ the active power flow is limit from region i to region k and $-\mathrm{T}_{ik}^{\max}$ is the active power flow limit from region k to region i.

(iii) Capability frontiers of thermal generators:

$$\mathrm{P}_{tij}^{\min} \leq \mathrm{P}_{tij} \leq \mathrm{P}_{tij}^{\max} \;, \; i \in \mathrm{N_A} \; and \;\; j \in \mathrm{N}_{ti} \tag{5.5}$$

(iv) Restricted effective region of coal-fired generating units:

The physically possible functional section of the j^{th} generation unit in the section i with restricted achievable vicinity is affirmed as:

$$\begin{aligned}
&\mathrm{P}_{tij}^{\min} \le \mathrm{P}_{tij} \le \mathrm{P}_{tij,1}^{l} \\
&\mathrm{P}_{tij,m-1}^{u} \le \mathrm{P}_{tij} \le \mathrm{P}_{tij,m}^{l}\,; \quad m = 2,3,\ldots,n_{ij} \qquad (5.6)\\
&\mathrm{P}_{tij,n_{ij}}^{u} \le \mathrm{P}_{tij} \le \mathrm{P}_{tij}^{\max}
\end{aligned}$$

Where m signifies the quantity of restricted achievable vicinity. $\mathrm{P}_{tij,m-1}^{u}$ is the maximum limit of $(m-1)$th proscribed workable area of jth thermal generator in region i. $\mathrm{P}_{tij,m}^{l}$ is the minimum limit of mth proscribed workable area of jth thermal generator in region i. Total number of proscribed workable areas of j^{th} thermal generator in region i is n_{ij}.

(v) Heat equilibrium constraints:

$$\sum_{j=1}^{\mathrm{N}_{ci}} \mathrm{H}_{cij} + \sum_{j=1}^{\mathrm{N}_{hi}} \mathrm{H}_{hij} = \mathrm{H}_{Di} + \sum_{k,k\neq i} \mathrm{H}_{ik}\,, \quad i \in \mathrm{N}_{\mathrm{A}} \qquad (5.7)$$

Where H_{ik} is the temperature transfer through interconnection from section i to section k. H_{ik} is positive when temperature depart from section i to section k and H_{ik} is negative while temperature depart from section k to section i.

(vi) Tie-line heat capacity constraints:

Temperature transfer through interconnection H_{ik} from region i to region k should be within the tie line heat transfer capacity limits.

$$-\mathrm{H}_{ik}^{\max} \le \mathrm{H}_{ik} \le \mathrm{H}_{ik}^{\max} \qquad (5.8)$$

Where $H_{ik}^{\max}$ is the heat transfer capability in between section i to section k and $-H_{ik}^{\max}$ is the heat transfer capability in between section k to region i.

(vii) Capability frontiers of cogeneration units:

Heat and power outputs of the units produced power from a particular fuel source, for example, flammable gas, biomass and coal are undividable and one output interrupt with other $P_c^{\min}(H_c)$. $P_c^{\max}(H_c)$, $H_c^{\min}(P_c)$ *and* $H_c^{\max}(P_c)$ are the linear primary constraints which render the possible effective part of the cogeneration segments.

$$P_{cij}^{\min}(H_{cij}) \le P_{cij} \le P_{cij}^{\max}(H_{cij}), i \in N_A \text{ and } j \in N_{ci} \tag{5.9}$$

$$H_{cij}^{\min}(P_{cij}) \le H_{cij} \le H_{cij}^{\max}(P_{cij}), i \in N_A \text{ and } j \in N_{ci} \tag{5.10}$$

(vii) Fabrication frontiers of heat-only units

$$H_{hij}^{\min} \le H_{hij} \le H_{hij}^{\max}, i \in N_A \text{ and } j \in N_{hi} \tag{5.11}$$

5.3. Nondominated Sorting Genetic Algorithm-II:

To deal with multi-target optimization issues, NSGA has been proposed in the year of 1995. Non-domination is utilized to offer position to arrangements, and strength contribution is profited in support of expansion command over in the investigation area. Because of not highly susceptible to fitness sharing parameters of NSGA, [19] have instigated NSGA-II as it produce more authentic and dependable solution speedy than its precursor. Because of word constraints, the fact depiction of NSGA-II isn't given in the paper. The progression of occasions in 'NSGA-II' is introduced in Figure.I after given all the section one by one.

i) Fast nondominated sorting procedure

To accumulate way out of the initial nondominated the face in a inhabitants of dimension, each answer be able to be matched up to all extra answer inside the inhabitants to unearth if it's far conquered. By the side of the particular step, all community inside the first nondominated the front are created. In order to unearth the individuals inside the next nondominated front, the solutions of the first front are marked down for the time being and every answer of the residual populace can be matched as much as each different answer of the residual inhabitants to unearth if it is to governed. Accordingly the entire particular inside the next nondominated face are created. This is right for creating third and higher tiers of nondomination.

In support of every way out two components are computed: a) dominion count n_q, the quantity of arrangements which overwhelm the arrangement q, and b) S_q, a lot of arrangements that the arrangement overwhelms. The approach for the rapid nondominated category can be stated as:

So as to uncover the people in the following nondominated front, the arrangements of the principal front are discounted for the present and every arrangement of the lingering populace can be coordinated up to each other arrangement of the remaining populace to uncover on the off chance that it is ruled. In this manner all people in the subsequent nondominated face are made. This is directly for making third and more elevated degrees of non-domination.

The algorithm for the fast nondominated category can be stated as: Algorithm 1: Fast non dominated category.

```
For each $p \in P$
  $S_p = \phi$
$n_p = 0$
for each $q \in P$
```

```
if $(p \prec q)$ then              if $p$ dominates $q$
$S_p = S_p \cup \{q\}$             add $q$ to the set $p$
else if $(q \prec p)$ then
$n_p = n_p + 1$                    augmentation of $p$
if $n_p = 0$ then                  $p$ fit in to the initial face
$P_{rank} = 1$
$F_1 = F_1 \cup \{p\}$
```

Every one inhabitants is given a grade identical to its nondomination degree or the face wide variety (1 for the exceptional stage and 2 for the following-great degree and so forth).

ii) Fast crowded distance estimation procedure

To collect an estimation of the concentration of answers contiguous a specific clarification within the populace, the common space of spots on both part of this thing beside all the targets is computed. This number provides as an estimation of the outer limits of the cuboid primarily based by the use of the closest pals because the vertices which may defined as crowding distance. This computation necessitates categorization of the populace in keeping with every goal feature fee in rising array of significance. Subsequently, in favor of every goal characteristic, the boundary populations (populations among nominal and biggest characteristic standards) are provided especially excessive distance fuel rate in order that boundary elements are constantly chosen. All different transitional inhabitants are supplied a distance price identical to the fixed regularized distinction inside the function standards of adjoining inhabitants. This computation is kept on with added goal capabilities. The crowding-distance assessment is computed because the total of individual distance values matching to every goal. Every purpose characteristic is regularizing ahead of computing the crowding distance. The set of rules underneath portrays the crowding distance calculation method of the entire answers in a nondominated set G.

Algorithm 2: Crowding distance assignment

$l = |G|$ digit of answer in G

for each i, set $F[i]_{distance} = 0$ expressed distance

in favour of every intention n

$G =$ Sort(G, n) Arrange by means of every objective assessment

$G[1]_{distance} = F[l]_{distance} = \propto$

in favour of $j = 2$ to $(k-1)$ $G[j]_{distance} = G[j]_{distance} + (G[j+1].n - G[j-1].n)/(f_m^{\max} - f_m^{\min})$ Here, $G[i].n$ refers to the mth objective function value of the i^{th} entity in the position G. $f_m^{\max}$ and $f_m^{\min}$ are the greatest and least standards of the mth objective purpose.

iii) Crowded-comparison manipulator

The crowded- comparison manipulator conducts the collection technique at a selection of tiers of the set of rules closer to a uniformly spread-out pareto-optimal front. All individual within the populace has two aspects:

a) nondomination rank (i_{rank})

b) crowding distance $(i_{distance})$

$i \prec j$ if $i_{rank} < j_{rank}$ or $((i_{rank} = j_{rank})$ and $(i_{distance} > j_{distance}))$

Between populaces with varying nondomination positions, the individuals with the lower (better) position are wanted. On the off chance that the two populaces have a place with the equivalent front, at that point the masses with bigger swarming separation is supported.

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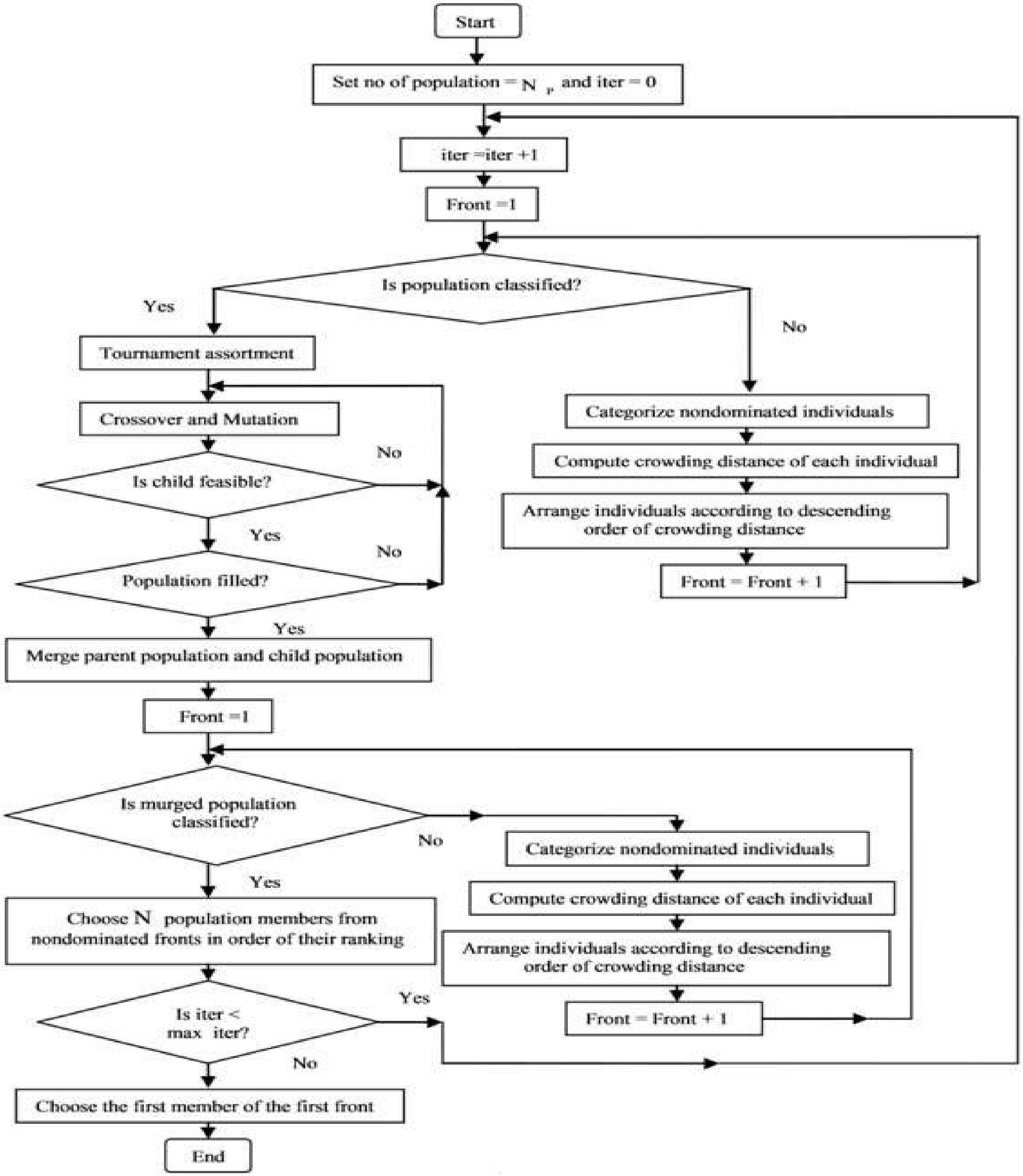

Figure 1: Flowchart of NSGA II

5.4 Case Study Multi-region Combined Heat and Power Economic Emission Dispatch:

The recommended NSGA-II is used to solve a complicated MRCHPEED problem. Here a system has been considered having two separate frameworks. Simulation results have been utilized to coordinate the viability of the suggested NSGA-II along with strength pareto evolutionary algorithm 2 (SPEA 2).Fuel charge and discharge are major conflicting issues. To illuminate opposing connections among the goal capacities, every one for example fuel cost and discharge is limited independently by utilizing genuine coded hereditary calculation (RCGA). The populace size, most extreme number of cycles, hybrid and transformation probabilities are preferred like 100, 300, 0.9 and 0.2 separately.

NSGA-II is confirmed to improve different goals for example fuel cost and discharge at the same time. To analyze the outcomes, SPEA 2 is utilized to take care of this issue.

The population size, upper limit of iterations, crossover and mutation probabilities are preferred 20, 30, 0.9 and 0.2 respectively in NSGA-II and SPEA 2.The NSGA-II, SPEA 2 and RCGA are abused by using MATLAB 7.5 on a PC (Dual core, 1TB, 3.3 GHz).

Section 1 consist of 13 Nos of generation units with restricted effective area and valve point effect, 6 Nos of co-generation units and 5 Nos of heat-only units. Detailed data is summarized in **Table A.1 and Table A.2** in the appendix. The other data of co-generation units is taken from [107].

Section 2 comprises 26 Nos of conventional generation unit restricted effective area and valve point effect, 12 Nos of units which produced power from a particular fuel source, for example, flammable gas, biomass, coal and 10 heat-only units. Records of section 2 are managed by replicating records of section 1.

The active power stream border commencing section 1 to section 2 or commencing section 2 to section 1 is 300MW. The heat stream border commencing section 1 to section 2 or commencing section 2 to section 1 is 300 MWth. Whole active powers and heat requirement separated between section 1 and section 2 are 30% and 70% respectively. Total active power requirement is 7500 MW and entire heat requirement is 5000 MWth.

Multi-region combined heat power economic dispatch problem and multi-region combined heat and power emission dispatch problem are solved by using RCGA. It is examined that under multi-region combined heat and power economic dispatch, total cost is 207472 \$/hr and emission is 287.1266 Kg/hr. But price boosts to 521942 \$/hr and emission reduces to 183.8696 Kg/hr in case of multi-region combined heat and power emission dispatch.

Multi-region combined heat power economic emission dispatch (MRCHPEED) issue is fathomed via using recommended NSGA-II and SPEA 2. Contingent upon MRCHPEED using NSGA-II, fuel cost is 305630 \$/hr and emission is 241.4702 Kg/hr. MRCHPEED using SPEA 2, fuel charge is 317390 \$/hr and discharge is 241.9414 Kg/hr.

The active power and heat production of section 1 and section 2 accomplished from the multi-region combined heat and power economic dispatch along with others by utilizing NSGA-II and SPEA 2 have been pointed out in Table I and Table II correspondingly.

Fuel cost, emission, interconnection active power transmission and interconnection heat transmission acquired commencing multi-region combined heat and power economic dispatch problem along with others are accumulated inside chart 3 as given. The cost convergence and emission convergence characteristics acquired by utilizing RCGA has been revealed in Fig. 2 and Fig. 3 respectively. Figure 4 reveals the distribution of 20 nondominated solutions attained in the final iteration of recommended NSGA-II and SPEA2 attained from MRCHPEED.

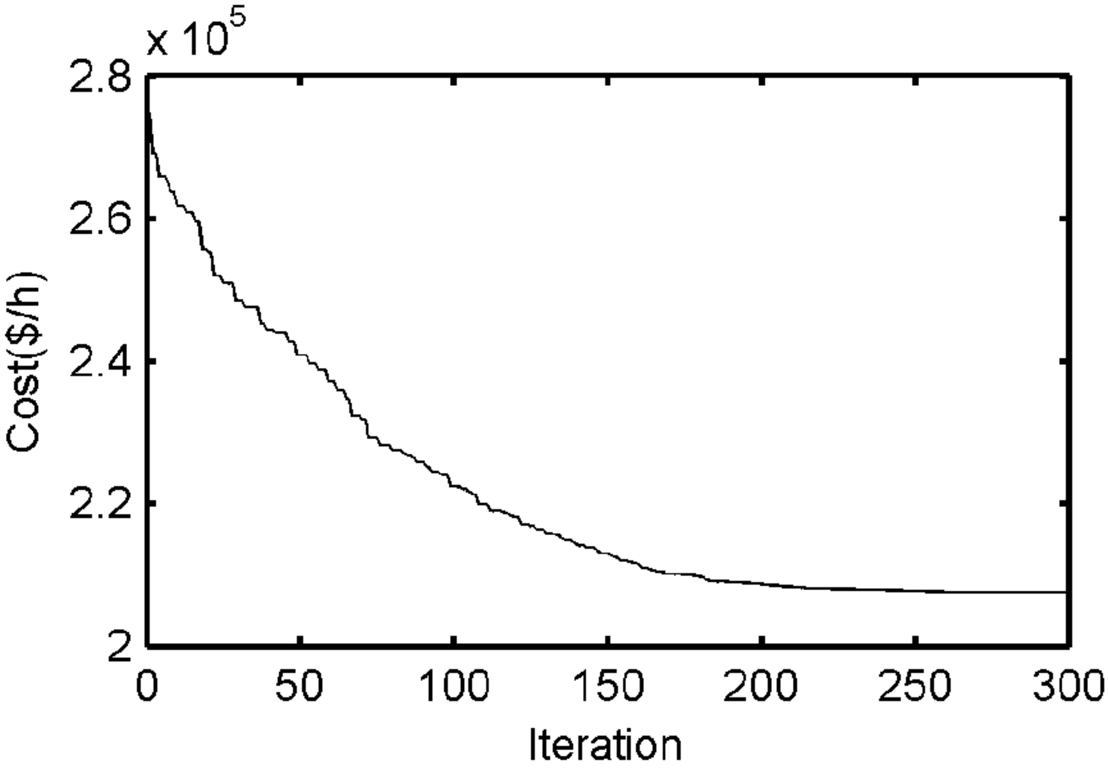

Fig. 2. Cost convergence characteristic.

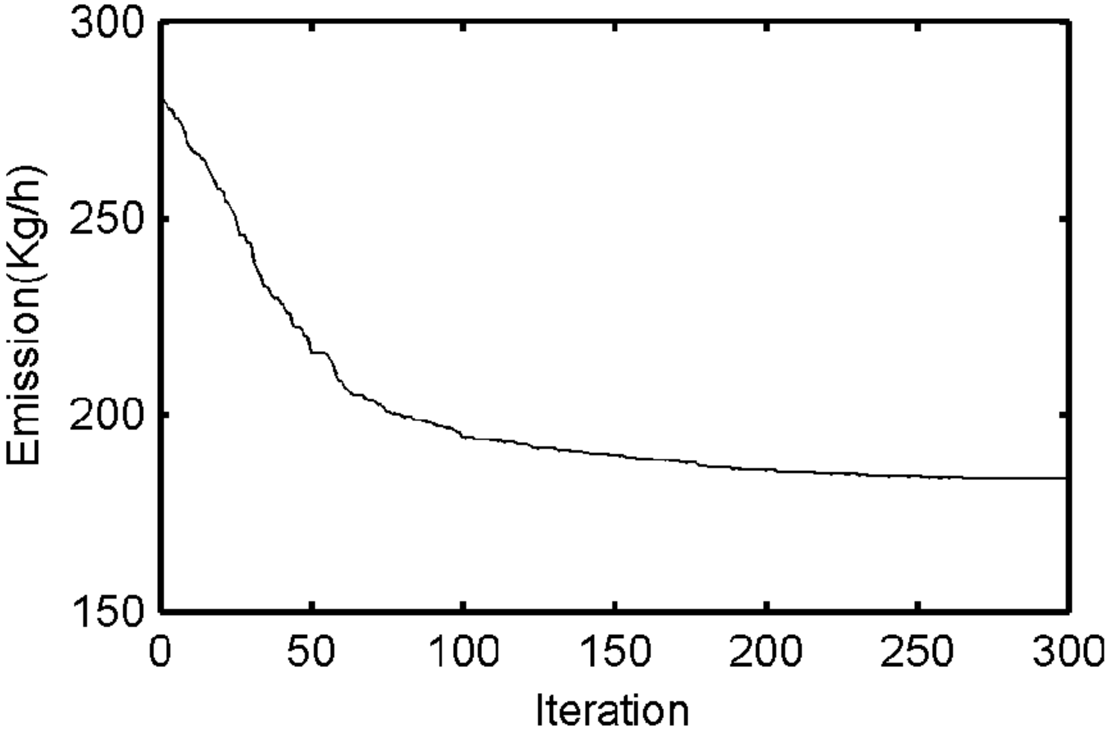

Fig. 3. Emission convergence characteristic

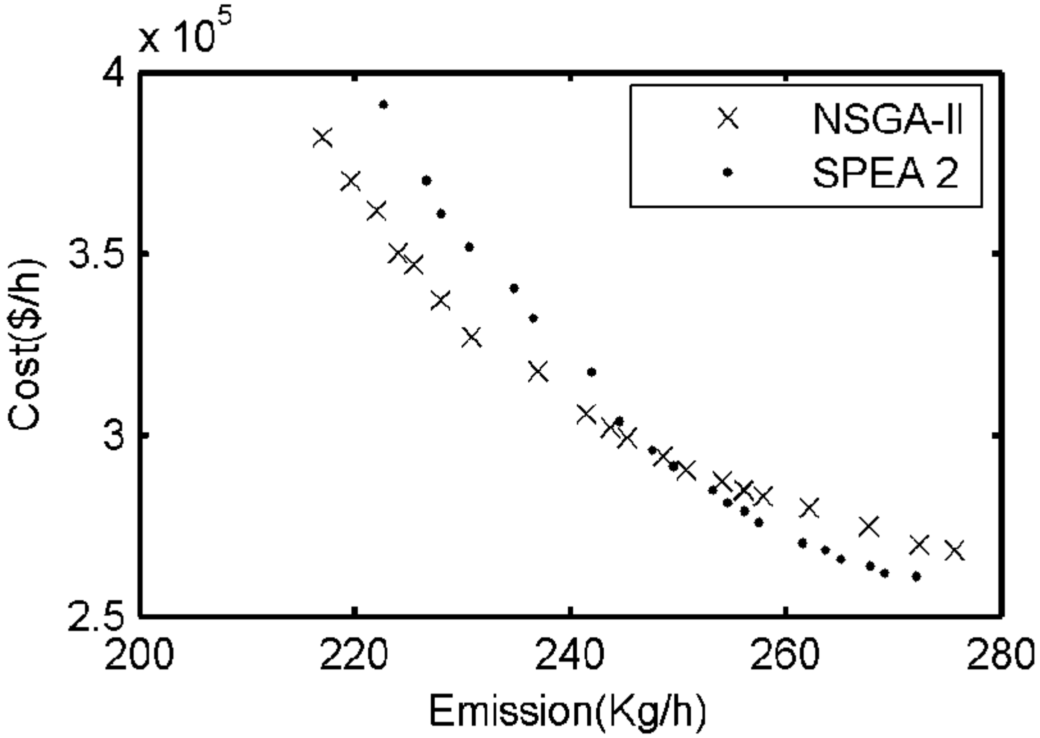

Fig. 4. Pareto-optimal front of the final iteration

Table 3: Assessments of concert:

Parameters	Multi-region combined heat and power economic dispatch	Multi-region combined heat and power emission dispatch	Multi-region combined heat and power economic emission dispatch	
			NSGA-II	SPEA 2
Cost ($/h)	207472	521942	305630	317390
Emission (Kg/h)	287.1266	183.8696	241.4702	241.9414
T_{12} (MW)	42.1859	246.8647	200.0926	100.9626
H_{12} (MWth)	173.3398	116.7972	-271.5332	149.8350

Table I: Active power production (MW) and Heat-production (MWth) of section 1 acquired from multi-region combined heat and power dispatch.

Economic Dispatch	**Emission Dispatch**	**Economic Emission Dispatch**	
		NSGA II	**SPEA 2**
P_{t1} 175.3269	131.3751	238.6961	121.4263
P_{t2} 240.2568	220.0097	169.3303	269.6463
P_{t3} 262.1979	225.0039	252.0785	259.3150
P_{t4} 122.4446	148.1775	137.6074	165.9348
P_{t5} 171.2847	149.4530	180.0000	100.9899
P_{t6} 106.1885	151.0677	107.4919	139.3710
P_{t7} 137.3948	76.0717	86.5014	60.0000
P_{t8} **143.3005**	**76.1873**	**136.9679**	**60.0000**
P_{t9} **131.5079**	**75.4632**	**120.3673**	**71.5266**
P_{t10} 77.5608	96.4404	101.4402	106.8052
P_{t11} 75.2351	97.5335	119.5742	120.0000
P_{t12} 55.0000	77.5996	57.8323	94.8652
P_{t13} **55.9525**	**77.0394**	**57.3955**	**81.6566**
P_{c1} **147.0936**	**246.9580**	**177.5651**	**185.7836**
P_{c2} **87.0206**	**125.7733**	**93.0103**	**82.0021**
P_{c3} 170.5433	247.0000	225.3918	239.8347
P_{c4} 83.6526	125.7509	119.4748	72.5157
P_{c5} 10.7658	60.0000	33.4432	39.6768
P_{c6} 39.4589	89.9604	35.9243	79.6128
H_{c1} 141.7551	0	65.3837	53.9485
H_{c2} 115.5269	32.3889	48.3176	80.0202
H_{c3} 154.8795	0	0	0
H_{c4} 112.6807	32.1705	13.4316	50.2808
H_{c5} 40.3284	0	0.0941	28.3155
H_{c6} 21.9781	24.1873	5.1975	0.0005
H_{h1} 60.0000	1.4000	36.7000	56.7000
H_{h2} 59.9822	0	60.0000	44.7000
H_{h3} 119.9857	0	105.1000	87.2000
H_{h4} 119.9984	1.0000	120.0000	112.2000
H_{h5} 726.2247	1525.60	774.3	1136.4

Table II: Power production (MW) and heat production (MWth) of section 2 acquired from multi-region combined heat and power dispatch.

Economic Dispatch	**Emission Dispatch**	**Economic Emission Dispatch**	
		NSGA II	**SPEA 2**
P_{t1} 175.1141	131.2701	47.8544	125.2241
P_{t2} 242.6539	220.0054	157.7517	270.0507
P_{t3} 304.6120	225.0104	285.2191	243.0064
P_{t4} 147.6799	147.5379	147.5379	176.5720
P_{t5} 166.2134	150.3602	124.0388	163.4945
P_{t6} 136.7123	149.5807	180.0000	133.8819
P_{t7} 173.7326	76.4833	60.0000	117.9709
P_{t8} 154.9804	77.1193	179.4743	60.0577
P_{t9} 121.5496	74.9862	91.3939	125.0197
P_{t10} 40.3942	95.6814	108.0711	80.5614
P_{t11} 40.4158	95.9912	40.2763	119.9426
P_{t12} 56.2225	76.1652	61.9070	55.0000
P_{t13} 55.0172	55.0118	107.3403	55.8733
P_{t14} 421.4253	135.3546	243.2763	257.7605
P_{t15} 234.3023	90.2354	284.8780	266.3629
P_{t16} 252.2307	225.0035	236.0131	227.6083
P_{t17} 146.8343	148.1660	180.0000	63.6185
P_{t18} 147.2141	149.1256	120.8225	152.0744
P_{t19} 174.7218	150.1015	126.8398	153.4561
P_{t20} 161.7564	73.8703	60.0000	79.5739
P_{t21} 148.2109	76.5604	119.8093	135.8604
P_{t22} 180.0000	73.7084	154.0689	76.2866
P_{t23} 55.4384	95.7966	78.8220	120.0000
P_{t24} 41.4238	97.1463	120.0000	120.0000
P_{t25} 57.7860	76.1090	88.2034	98.9655
P_{t26} 55.5977	76.2695	112.2056	74.3555
P_{c1} 117.6495	246.9607	195.6818	215.7340
P_{c2} 70.9362	125.7974	60.4244	74.7606
P_{c3} 148.8926	246.9461	222.8787	130.2030
P_{c4} 103.4972	125.8000	97.6660	118.7039

Economic Dispatch	**Emission Dispatch NSGA II**	**Economic Emission Dispatch**	
		NSGA II	**SPEA 2**
P_{c5} 10.4163	59.9163	47.7762	38.3283
P_{c6} 47.9396	89.8480	82.6971	80.1689
P_{c7} 149.0130	246.8992	156.5276	213.4789
P_{c8} 74.6154	125.6641	121.5002	105.6402
P_{c9} 147.3443	246.9531	135.0682	227.6502
P_{c10} 105.2674	125.7584	82.4985	110.1486
P_{c11} 10.1667	59.9512	36.7629	26.9498
P_{c12} 80.2413	89.9919	84.2810	77.5090
H_{c1} 125.2917	0.0016	60.0660	21.1935
H_{c2} 101.7223	32.1396	63.6122	10.9137
H_{c3} 142.6570	0	89.1739	1.6623
H_{c4} 129.7772	32.3555	5.1826	17.9133
H_{c5} 40.1778	0.0590	9.2503	33.9861
H_{c6} 25.8558	24.5429	21.3635	1.5788
H_{c7} 142.9650	0.1691	65.0978	18.7457
H_{c8} 104.7792	33.1855	0.3305	93.3041
H_{c9} 142.0037	0.1392	94.7179	29.1193
H_{c10} 131.3721	32.2791	104.3493	113.3349
H_{c11} 40.0617	0.1407	4.5180	10.1226
H_{c12} 40.5230	24.4440	7.8781	0
H_{h1} 59.9604	0.6000	57.4000	60.0000
H_{h2} 59.9817	8.8000	51.3000	31.3000
H_{h3} 119.9880	8.6000	113.4000	83.6000
H_{h4} 119.9375	0	106.5000	62.1000
H_{h5} 717.0273	2607.9	1250.8	1146.0
H_{h6} 59.9968	4.3000	33.9000	60.0000
H_{h7} 59.9686	0.8000	27.5000	59.5000
H_{h8} 119.9926	12.6000	120.0000	56.9000
H_{h9} 119.9976	3.2000	113.1000	97.3000
H_{h10} 722.6231	557.000	1372.0	1341.6

5.5 Conclusion:

Here, NSGA-II is recommended to solve complex multi-region combined heat and power economic emission dispatch problem. Simulation results attained from the recommended technique are compared with those attained from SPEA 2. It is seen that the recommended technique proffers a cutthroat performance.

Chapter 6

Whale Optimization Algorithm in Multi-Region Combined Heat and Power Economic Emission Dispatch

6.1. Introduction:

Economic dispatch (ED) allocates the generation level of all devoted turbines in a most price-effective way whilst gratifying numerous constraints in a solo structure.

In preferred, generating units are separated among several power production areas connected by using interconnections. Multi-region economic dispatch (MRED) is a growth of lone place economic dispatch. MRED reveals the electricity creation stage along with communication of energy among areas for reducing cost of all sections while satisfying miscellaneous constraint. Different strategies [103]-[111] are converse to explain MRED issue.

Vestige fuel is transformed into electricity in unproductive style. The best part of electricity production desecrated during the technique of change is high temperature. Creating power from a particular fuel source, for example, flammable gas, biomass, coal progress the use of flow due to the difference in temperature along with usefulness of the renovation method is accelerated. In contrast with different variety of energy transmitter, the usefulness of energy of cogeneration is extra which creates less significant pollution. The combined heat and power economic dispatch (CHPED) method implies power and heat creation accordingly that production billing is minimized along with satisfying miscellaneous constraint. Different proposal have already been proposed to solve CHPED issues and those are mentioned in reference section.

Huge incorporated power system is generally comprised of divergent locales dependent on an assortment of model for instance topographical, functional, and forecast and administration. Every one of these areas has been correlated to its connecting section along with interconnections. Each locale has its capacity and heat creation and energy and heat requirement.

Limiting the complete cost for every spot through stacking of every dedicated generating units along with co-generation and heat-only units in this way that true power equilibrium limit, heat stability imperatives, production boundary requirements, heat production limit requirements with interconnection limit requirements have been fulfilled while from a particular fuel source, for example, flammable gas, biomass, coal are going in the course of limited heat vs. true power plane is the main point of multi-region combined heat and power economic dispatch (MRCHPED) .

Electric power plants based on fossil-fuel release a variety of pollutants which creates air pollution in the ambiance. Declining ambiance greenhouse gasses is another challenge for different power producers. The 1990 Clean Air Act is proposed for reducing atmospheric pollution. So today's civilization wants adequate and safe electricity at the cost-effective as well as minimum echelon of greenhouse gasses.

Various methods are proposed to decrease ambience greenhouse gasses [51]. Among these tactics, dispatching taking into emission consideration is preferable.

The proposed approach is an expansion of multi-region combined heat and power economic dispatch (MRCHPED) trouble. It plans a wide range of committed coal-fired generating units outputs, co-generation unit outputs, heat-only unit outputs and interchange power amongst regions with forecasted active power demand and heat request with the end goal that all out cost and outflow echelon in all sections are streamlined simultaneously satisfying an assortment of requirements.

This chapter suggests NSGA-II to solve complicated multi-region combined heat and power economic emission dispatch (MRCHPEED) issues. For the given system, each region comprises coal-fired generating parts, co-generation parts and heat only parts. Every locale of the framework includes generation entity, co-generation entity and heat only entity. To triumph over intricacy of binary version for trading with unremitting explore break with big proportions, real-coded genetic algorithm (RCGA) [53] is exploited. The Simulated Binary Crossover (SBX) and polynomial mutation are used here.

The recommended method is confirmed by relating it with two-region analysis scheme. Analysis outcome attained in the course of NSGA-II procedure are matched up through the result which are attained from strength -pareto evolutionary algorithm 2 (SPEA2).

6.2. Problem Formulation

Here framework consisting of generation segment, segment related to power from a particular fuel source, for example, flammable gas, biomass, coal and heat-only segment has been taken into consideration. Figure 1 uncovers heat-power reasonable serviceable zone of a joined cycle co-age unit. The warmth and force preparations are inseparable. The heat-power practical functional zone has been encompassed by the wilderness curve ABCDEF.

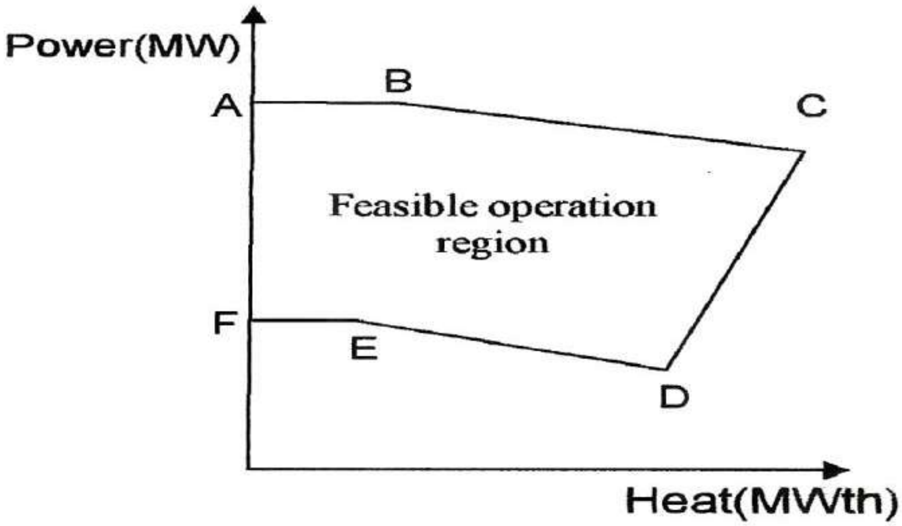

Fig. 1. Heat-Active power viable workable area for a cogeneration

The power output of the thermal generators and the heat output of heat-only units are bounded by their individual maximum and minimum frontiers. The power is produced by thermal generators and co-generation units and the heat is produced by co-generation units and heat-only units.

The MRCHPEED issue chooses the active power and heat creation with the goal that the complete cost and outflow of all locales is upgraded through running every dedicated generating units, units produced power from a particular fuel source, for example, flammable gas, biomass, coal and heat only units in this way where different limitation are fulfilled but units produced power from a particular fuel source, for example, flammable gas, biomass, coal are attempted in an encompassed heat in opposition to power plane. Here MRCHPEED issue is communicated as:

6.2.1. Objectives

(i)Cost

The total price is stated as

$$C_{\mathrm{T}} = \sum_{i=1}^{\mathrm{N_A}}\sum_{j=1}^{\mathrm{N}_{ti}}\left[a_{ij} + b_{ij}\mathrm{P}_{tij} + c_{ij}\mathrm{P}_{tij}^{2} + \left|d_{ij} \times \sin\left\{e_{ij} \times \left(\mathrm{P}_{tij}^{\min} - \mathrm{P}_{tij}\right)\right\}\right|\right] + \sum_{i=1}^{\mathrm{N_A}}\sum_{j=1}^{\mathrm{N}_{ci}}\left[\alpha_{ij} + \beta_{ij}\mathrm{P}_{cij} + \gamma_{ij}\mathrm{P}_{cij}^{2} + \right.$$

$$\left.\delta_{ij}\mathrm{H}_{cij} + \varepsilon_{ij}\mathrm{H}_{cij}^{2} + \xi_{ij}\mathrm{P}_{cij}\mathrm{H}_{cij}\right] + \sum_{i=1}^{\mathrm{N_A}}\sum_{j=1}^{\mathrm{N}_{hi}}\left[\phi_{ij} + \eta_{ij}\mathrm{H}_{hij} + \lambda_{ij}\mathrm{H}_{hij}^{2}\right] \tag{6.1}$$

(ii) Emission

The ambience green house gases consisting of different air pollutants produced as a result of coal-fired generating unit is represented one by one. On the other hand, for assessment cause, the whole secretion of these green house gases is affirmed as the summation of a quadratic and an exponential characteristic [52]. The general discharge from thermal segments, cogeneration segments and heat-only segments in the system may be stated as

$$E_{\mathrm{T}} = \sum_{i=1}^{\mathrm{N_A}}\sum_{j=1}^{\mathrm{N}_{ti}}\left[\mu_{ij} + \kappa_{ij}\mathrm{P}_{tij} + \pi_{ij}\mathrm{P}_{tij}^{2} + \sigma_{ij}e^{\left(\theta_{ij}\mathrm{P}_{tij}\right)}\right] + \sum_{i=1}^{\mathrm{N_A}}\sum_{j=1}^{\mathrm{N}_{ci}}\left[\tau_{ij}\mathrm{P}_{cij}\right] + \sum_{i=1}^{\mathrm{N_A}}\sum_{j=1}^{\mathrm{N}_{hi}}\left[\rho_{ij}\mathrm{H}_{hij}\right] \tag{6.2}$$

6.2.2. Constraints

(i) Power equilibrium constraints:

The general real power production for every generating section and co-generation section need to be same to the region where real power utility in the company of the reflection of incoming and outgoing real power and is acknowledged in the following way:

$$\sum_{j=1}^{\mathrm{N}_{tii}}\mathrm{P}_{tij} + \sum_{j=1}^{\mathrm{N}_{ci}}\mathrm{P}_{cij} = \mathrm{P}_{Di} + \sum_{k,k\neq i}\mathrm{T}_{ik}\;,\quad i \in \mathrm{N_A} \tag{6.3}$$

Where T_{ik} is the interconnection real power transmission in between section i to section k. T_{ik} is positive at the same time as energy transfer from section i to section k and T_{ik} is negative while energy transfer from section k to section i.

(ii) Interconnection power capacity constraints:

Power transmission through interconnection T_{xy} from section x to section y should lie within the interconnection real power transfer capacity boundary.

$$-\mathrm{T}_{xy}^{\max} \leq \mathrm{T}_{xy} \leq \mathrm{T}_{xy}^{\max} \tag{6.4}$$

Where $\mathrm{T}_{ik}^{\max}$ the active power flow is limit from region i to region k and $-\mathrm{T}_{ik}^{\max}$ is the active power flow limit from region k to region i.

(iii) Capability frontiers of thermal generators:

$$\mathrm{P}_{tij}^{\min} \leq \mathrm{P}_{tij} \leq \mathrm{P}_{tij}^{\max}\ ,\ i \in \mathrm{N}_{\mathrm{A}}\, and\ \ j \in \mathrm{N}_{ti} \tag{6.5}$$

(iv) Restricted effective region of coal-fired generating units:

The physically possible functional section of the j^{th} generation unit in the section i with restricted achievable vicinity is affirmed as:

$$\begin{aligned} &\mathrm{P}_{tij}^{\min} \leq \mathrm{P}_{tij} \leq \mathrm{P}_{tij,1}^{l} \\ &\mathrm{P}_{tij,m-1}^{u} \leq \mathrm{P}_{tij} \leq \mathrm{P}_{tij,m}^{l}\ ;\ m = 2,3,\ldots,n_{ij} \\ &\mathrm{P}_{tij,n_{ij}}^{u} \leq \mathrm{P}_{tij} \leq \mathrm{P}_{tij}^{\max} \end{aligned} \tag{6.6}$$

Where m signifies the quantity of restricted achievable vicinity. $\mathrm{P}_{tij,m-1}^{u}$ is the maximum limit of $(m-1)$th proscribed workable area of jth thermal generator in region i. $\mathrm{P}_{tij,m}^{l}$ is the minimum limit of mth proscribed workable area of jth thermal generator in region i. Total number of proscribed workable areas of jth thermal generator in region i is n_{ij}.

(v) Heat equilibrium constraints:

$$\sum_{j=1}^{\mathrm{N}_{ci}} \mathrm{H}_{cij} + \sum_{j=1}^{\mathrm{N}_{hi}} \mathrm{H}_{hij} = \mathrm{H}_{Di} + \sum_{k,k\neq i} \mathrm{H}_{ik}\ ,\ \ i \in \mathrm{N}_{\mathrm{A}} \tag{6.7}$$

Where H_{ik} is the temperature transfer through interconnection from section i to section k. H_{ik} is positive when temperature depart from section i to section k and H_{ik} is negative while temperature depart from section k to section i.

(vi) Tie-line heat capacity constraints:

Temperature transfer through interconnection H_{ik} from region i to region k should be within the tie line heat transfer capacity limits.

$$-\mathrm{H}_{ik}^{\max} \leq \mathrm{H}_{ik} \leq \mathrm{H}_{ik}^{\max} \tag{6.8}$$

Where $\mathrm{H}_{ik}^{\max}$ is the heat transfer capability in between section i to section k and $-\mathrm{H}_{ik}^{\max}$ is the heat transfer capability in between section k to region i.

(vii) Capability frontiers of cogeneration units:

Heat and power outputs of the units produced power from a particular fuel source, for example, flammable gas, biomass and coal are undividable and one output interrupt with other $\mathrm{P}_{c}^{\min}(\mathrm{H}_{c})$. $\mathrm{P}_{c}^{\max}(\mathrm{H}_{c})$, $\mathrm{H}_{c}^{\min}(\mathrm{P}_{c})$ *and* $\mathrm{H}_{c}^{\max}(\mathrm{P}_{c})$ are the linear primary constraints which render the possible effective part of the cogeneration segments.

$$\mathrm{P}_{cij}^{\min}(\mathrm{H}_{cij}) \leq \mathrm{P}_{cij} \leq \mathrm{P}_{cij}^{\max}(\mathrm{H}_{cij}), i \in \mathrm{N}_{\mathrm{A}} \text{ and } j \in \mathrm{N}_{ci} \tag{6.9}$$

$$\mathrm{H}_{cij}^{\min}(\mathrm{P}_{cij}) \leq \mathrm{H}_{cij} \leq \mathrm{H}_{cij}^{\max}(\mathrm{P}_{cij}), i \in \mathrm{N}_{\mathrm{A}} \text{ and } j \in \mathrm{N}_{ci} \tag{6.10}$$

(vii) Fabrication frontiers of heat-only units

$$\mathrm{H}_{hij}^{\min} \leq \mathrm{H}_{hij} \leq \mathrm{H}_{hij}^{\max}, i \in \mathrm{N}_{\mathrm{A}} \text{ and } j \in \mathrm{N}_{hi} \tag{6.11}$$

6.3. Whale Optimization algorithm (WOA):

S. Mirjalili and A. Lewis have created the proposed algorithm, which aims to mimic the behavior of humpback whales. Short statistics about those whales are provided in the subsection below. These are often regarded as the most significant mammals. In rare parts of their brains known as spindle cells, whales do not contain uncommon cells quite similar to those of humans. These cells aid in locating and carrying out actions that are sensitively and publicly appropriate for humans. The public-conducted and excellent hunting strategy is what people will remember most about those whales. This particular feature for foraging is known as the bubble internet feeding mode. They are attempting to capture little fish or schools of krill that are near the water's surface.

6.3.1 Encircling Prey

The location and status of their prey are known to humpback whales. The prey was therefore bound. While manipulative, the key role in the seek gap wasn't known before, so the WOA algorithm infers the best route out at the moment as the prey's willpower or assumes it to be closer to the right value. The competing seek operators must work to align their positions with the location of the excellent seek operator as it becomes more solidified.

The following is an example of this technique:

$$D = |E.X^*(t) - X(t)| \tag{6.12}$$

$$X(t+1) = X^*(t) - B.D \tag{6.13}$$

Where, X* is the position vector of the best solution discovered, X is the position vector, t denotes the most recent iteration, A, and C are coefficient vectors. Each iteration of X* must be reorganized for the desired outcome.

The B and E vectors are calculated as follows:

$$B = 2\,b \cdot s - b \tag{6.14}$$

$$E = 2 \cdot s \tag{6.15}$$

Each s' is an arbitrary vector within the range [0, 1] in which 'b' is smoothly lowered from 2 to 0 for the investigation and operation stages.

6.3.2 Bubble-net attacking method (exploitation phase)

The following procedures are defined in support of initializing the aforementioned version scientifically:

6.3.2.1 Shrinking encircling mechanism:

By decreasing the value of "a," where "A" is an arbitrary assessment in the range [a, a], the variation of "A" is diverse. The recent duty of a seek manipulator is fixed between the specific role of the manipulator and the location of the cutting-edge fine manipulator in [1,1], where the arbitrarily chosen standards for A are used.

6.3.2.2 Spiral updating position:

Here, the spacing between the whale at location (Z) and the victim at position (Z*) is chosen. The positioning of the whale and its victim eventually evolved into a spiral, providing a helix-shaped motion for those whales. The phrase is defined as follows:

$$Z(t+1) = B''. e^{mn}. \cos(2\pi l) + Z^{*}(t)(14)$$
$$\text{Where } B' = |Z^{*}(t) - Z(t)| \quad (6.16)$$

It represented the distance between the ith whale and its victim and is regarded as the best course of action; n is a random number between [1, 1] and m is an invariable with significant character of the logarithmic spiral.

6.3.3 Search for prey (Exploration Phase):

In this section, A is used to create a seek manipulator that moves away from a reference whale using arbitrary standards between 1 and -1. In this stage, the role of a seek manipulator is equivalent to that of a randomly chosen seek representative rather than a developing section.

This approach enables improved research, which enables the WOA algorithm to carry out a global search. The replica in mathematics is as follows:

$$|D = (C.X_{rand} - X)| \tag{6.17}$$

$$X(t+1) = X_{rand} - A.D \tag{6,18}$$

Where, given the existing population, X rand is a random location vector (Random whale).

The starting set of responses for this set of rules may be arbitrary. Search manipulators changed their placements for every iteration in accordance with a search manipulator that was chosen at random or in accordance with the optimal solution so far discovered. For searching, the parameter 'a' has a value of 2, which is decreased to zero for offer operation.

6.4 Case Study Multi-region Combined Heat and Power Economic Emission Dispatch:

The recommended WOA is used to solve a complicated MRCHPEED problem. Simulation results have been utilized to coordinate the viability of the suggested WOA along with NSGA II. The populace size, most extreme number of cycles, hybrid and transformation probabilities are preferred like 100, 300, 0.9 and 0.2 separately.

WOA is confirmed to improve different goals for example fuel cost and discharge at the same time. The population size, upper limit of iterations, crossover and mutation probabilities are preferred 20, 30, 0.9 and 0.2 correspondingly in NSGA-II .The WOA and NSGA-II are abused by using MATLAB 7.5 on a PC (Dual core, 1TB, 3.3 GHz).

Section 1 consist of 13 Nos of generation units with restricted effective area and valve point effect, 6 Nos of co-generation units and 5 Nos of heat-only units. The other data of co-generation units is taken from [107].

Section 2 comprises 26 Nos of conventional generation unit restricted effective area and valve point effect, 12 Nos of units which produced power from a particular fuel source, for example, flammable gas, biomass, coal and 10 heat-only units. Records of section 2 are managed by replicating records of section 1.The active power stream border commencing section 1 to section 2 or commencing section 2 to section 1 is 300MW. The heat stream border commencing section 1 to section 2 or commencing section 2 to section 1 is 300 MWth. Whole active powers and heat requirement separated between section 1 and section 2 are 30% and 70% respectively. Total active power requirement is 7500 MW and entire heat requirement is 5000 MWth.

It is examined that ED applicable for both Heat and Power, total cost is 207472 $/hr and emission is 287.1266 Kg/hr. But price boosts to 521942 $/hr and emission reduces to 183.8696 Kg/hr in case of multi-region combined heat and power emission dispatch.

Multi-region combined heat power economic emission dispatch (MRCHPEED) issue is fathomed via using recommended WOA and NSGA II. Contingent upon MRCHPEED using WOA cost is 305630 $/hr and emission is 241.4702 Kg/hr. MRCHPEED using NSGA II , fuel charge is 317390 $/hr and discharge is 241.9414 Kg/hr.

The active power and heat production of section 1 and section 2 accomplished from the multi-area combined heat and power economic dispatch along with others by utilizing WOA and NSGA-II have been pointed out in Table I and II.

Fuel cost, emission, interconnection active power transmission and interconnection heat transmission acquired commencing MRCHPEED problem along with others are accumulated as specified in Table III. The cost convergence and emission convergence characteristics acquired by utilizing WOA have been revealed in Fig. 2 and Fig. 3 respectively.

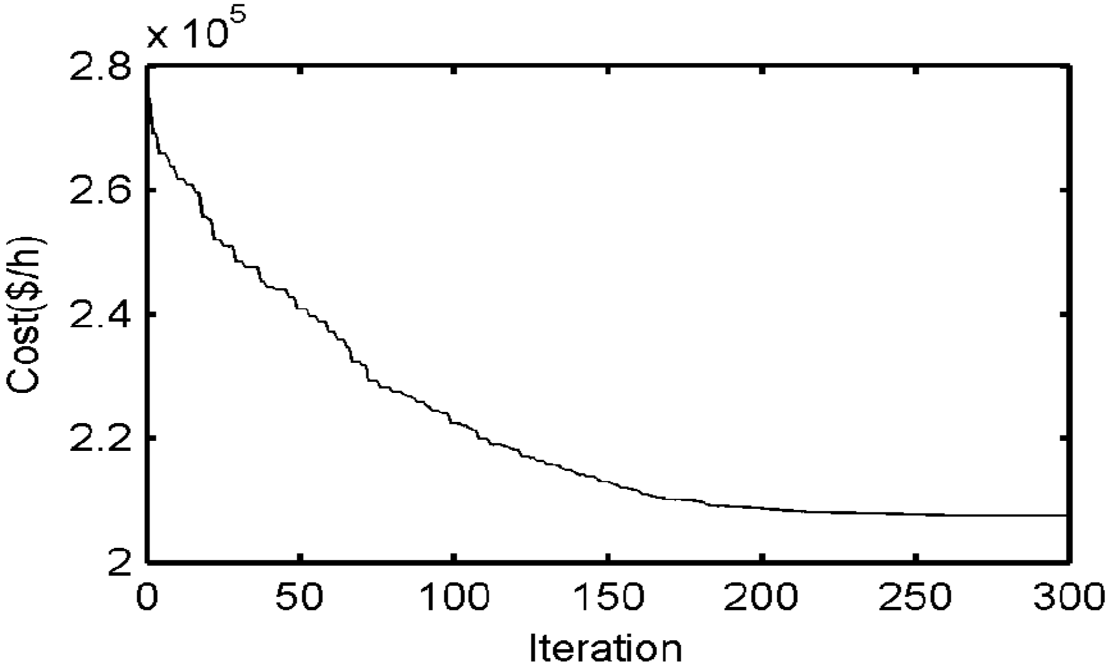

Fig. 2. Cost convergence characteristic.

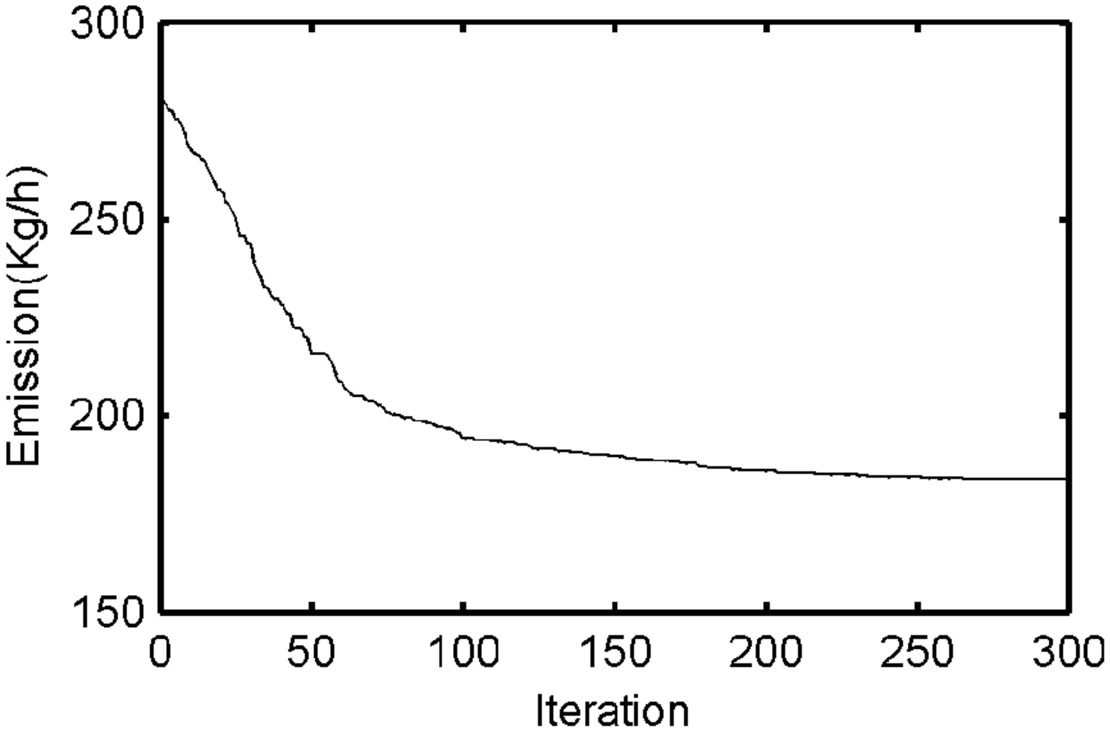

Fig. 3. Emission convergence characteristic

Table III: Assessments of concert

Parameter	Multi-region combined heat and power economic dispatch	Multi-region combined heat and power emission dispatch	Multi-region combined heat and power economic emission dispatch	
			WOA	NSGA II
Cost ($/h)	207472	521942	305630	317390
Emission(Kg/h)	287.1266	183.8696	241.4702	241.9414
T_{12} (MW)	42.1859	246.8647	200.0926	100.9626
H_{12} (MWth)	173.3398	116.7972	-271.5332	149.8350

Table I: Power manufacturing (MW) and Heat- manufacturing (MWth) of section 1 acquired from multi-region combined heat and power dispatch.

Economic Dispatch	Emission Dispatch	Economic Emission Dispatch	
		WOA	NSGA II
P_{t1} 175.3269	131.3751	238.6961	121.4263
P_{t2} 240.2568	220.0097	169.3303	269.6463
P_{t3} 262.1979	225.0039	252.0785	259.3150
P_{t4} 122.4446	148.1775	137.6074	165.9348
P_{t5} 171.2847	149.4530	180.0000	100.9899
P_{t6} 106.1885	151.0677	107.4919	139.3710
P_{t7} 137.3948	76.0717	86.5014	60.0000
P_{t8} 143.3005	76.1873	136.9679	60.0000
P_{t9} 131.5079	75.4632	120.3673	71.5266
P_{t10} 77.5608	96.4404	101.4402	106.8052
P_{t11} 75.2351	97.5335	119.5742	120.0000
P_{t12} 55.0000	77.5996	57.8323	94.8652
P_{t13} 55.9525	77.0394	57.3955	81.6566
P_{c1} 147.0936	246.9580	177.5651	185.7836
P_{c2} 87.0206	125.7733	93.0103	82.0021
P_{c3} 170.5433	247.0000	225.3918	239.8347
P_{c4} 83.6526	125.7509	119.4748	72.5157
P_{c5} 10.7658	60.0000	33.4432	39.6768
P_{c6} 39.4589	89.9604	35.9243	79.6128
H_{c1} 141.7551	0	65.3837	53.9485
H_{c2} 115.5269	32.3889	48.3176	80.0202
H_{c3} 154.8795	0	0	0
H_{c4} 112.6807	32.1705	13.4316	50.2808
H_{c5} 40.3284	0	0.0941	28.3155
H_{c6} 21.9781	24.1873	5.1975	0.0005
H_{h1} 60.0000	1.4000	36.7000	56.7000
H_{h2} 59.9822	0	60.0000	44.7000
H_{h3} 119.9857	0	105.1000	87.2000
H_{h4} 119.9984	1.0000	120.0000	112.2000
H_{h5} 726.2247	1525.60	774.3	1136.4

Table II: Power manufacturing (MW) and heat manufacturing (MWth) of section 2 acquired from multi-region combined heat and power dispatch

Economic Dispatch	Emission Dispatch	Economic Emission Dispatch	
		WOA	NSGA II
P_{t1} 175.1141	131.2701	47.8544	125.2241
P_{t2} 242.6539	220.0054	157.7517	270.0507
P_{t3} 304.6120	225.0104	285.2191	243.0064
P_{t4} 147.6799	147.5379	147.5379	176.5720
P_{t5} 166.2134	150.3602	124.0388	163.4945
P_{t6} 136.7123	149.5807	180.0000	133.8819
P_{t7} 173.7326	76.4833	60.0000	117.9709
P_{t8} 154.9804	77.1193	179.4743	60.0577
P_{t9} 121.5496	74.9862	91.3939	125.0197
P_{t10} 40.3942	95.6814	108.0711	80.5614
P_{t11} 40.4158	95.9912	40.2763	119.9426
P_{t12} 56.2225	76.1652	61.9070	55.0000
P_{t13} 55.0172	55.0118	107.3403	55.8733
P_{t14} 421.4253	135.3546	243.2763	257.7605
P_{t15} 234.3023	90.2354	284.8780	266.3629
P_{t16} 252.2307	225.0035	236.0131	227.6083
P_{t17} 146.8343	148.1660	180.0000	63.6185
P_{t18} 147.2141	149.1256	120.8225	152.0744
P_{t19} 174.7218	150.1015	126.8398	153.4561
P_{t20} 161.7564	73.8703	60.0000	79.5739
P_{t21} 148.2109	76.5604	119.8093	135.8604
P_{t22} 180.0000	73.7084	154.0689	76.2866
P_{t23} 55.4384	95.7966	78.8220	120.0000
P_{t24} 41.4238	97.1463	120.0000	120.0000
P_{t25} 57.7860	76.1090	88.2034	98.9655
P_{t26} 55.5977	76.2695	112.2056	74.3555

Economic Dispatch	**Emission Dispatch**	**Economic Emission Dispatch**	
		WOA	**NSGA II**
P_{c1} 117.6495	246.9607	195.6818	215.7340
P_{c2} 70.9362	125.7974	60.4244	74.7606
P_{c3} 148.8926	246.9461	222.8787	130.2030
P_{c4} 103.4972	125.8000	97.6660	118.7039

6.5 Conclusion

In the current work, WOA is recommended to solve complex multi-region combined heat and power economic emission dispatch problem. For testing purpose, two plants are considered from each type. All plants are taken in cascaded form. This mixed system is tested to verify the performance of WOA. The result obtained from the proposed WOA is compared with NSGA II. The numerical results obtained from the comparison shows that the value of fuel cost and cost of emission are minimum for the proposed method. It is also verified from the results that very less CPU time is required for this method as compared to other method. Hence, the proposed WOA method provides a more robust and efficient technique to solve the EED problem. It is seen that the recommended technique proffers a cutthroat performance.

CHAPTER-7

Conclusion & Future Scope

(a) Overall Conclusion

In these premise intelligent techniques like Non-Dominated sorting genetic Algorithm, Whale Optimization Algorithm etc. are projected to solve many complex power system optimization problems such as economic dispatch, economic emission dispatch, combined heat and power economic dispatch, Multi-objective Economic Environmental Dispatch of Variable Hydro-Wind-thermal Power System. Accrued result corresponding to different module is also contrasted with other computational intelligent technique from the literature. It has been found that here the results are competitive and quite encouraging.

Chapter wise conclusion has been presented below.

Chapter-2

In this chapter, NSGAII is used to solve a economic emission dispatch of hydro thermal power system, in which three objectives,namely cost, NOx emission, and SO2 emission, are optimized simultaneously while taking into account wind power uncertainty, cascaded hydro plants with water transport delays, valve point effect of thermal generators, and other constraints. The proposed approach's experimental results were compared to those obtained from SPEA 2. The comparativeanalysis clearly demonstrates that the current proposal outperforms SPEA 2.

Chapter-3

NSGA-II has been defined as the process of determining the most cost-effective and environmentally friendly way to dispatch a wind-coal-fired generating unit. The challenge has been designed as a multi-objective optimization problem with difficult fuel charge, NOx, and SO2 discharge targets. The results of the analysis obtained from the proposed proposal were compared to those acquired through SPEA 2. The resemblance shows that the suggested approach provided a viable presentation in terms of explanation.

Chapter -4

A Nondominating Sorting Genetic Algorithm II (NSGA II) is proposed in this approach with th egoal of resolving the economic environmental dispatch of a coal-wind-sun

based power system with a battery vitality stockpiling system. The problem is formulated as a multi objective optimization problem with difficult price, NOx, and SO2 objectives. The efficiency of the proposed system has been verified by extensive experimental assessment and comparison analysis using experimental approaches. The results of the tests performed on the suggested system are compared to those obtained using the Strength Pareto Evolutionary Algorithm 2(SPEA 2). In comparison to the present algorithm employed for comparison, the results of the testing clearly show that the proposed approach provides more combative recital with respect to the answer

Chapter -5

To handle a difficult multi-region combined heat and power economic emission dispatch problem, NSGA-II is recommended. The recommended technique's simulation results are compared to SPEA 2's simulation findings. It can be shown that the suggested technique delivers a ruthless performance

Chapter -6

The use of WOA to handle a difficult multiregion combined heat and power economic emission dispatch problem is advocated in the current study. Two plants from each type are considered for testing purposes. All of the plants are taken in a sequential order. This mixed system is put to the test to see how well WOA performs. The projected WOA's outcome is compared to the

NSGAII result. The numerical results of the comparison demonstrate that the proposed method has the lowest value of fuel cost and pollution cost. The results also show that this method requires significantly less CPU time than other methods. As a result, the suggested WOA method for solving the EED problem is more robust and efficient. It can be shown that the presented approach delivers a ruthless performance.

(b) Future Scope

1. For multi area technique, more region can be incorporated which indicates better accuracy of the whole system.
2. Some new optimization techniques may also be implemented in multi area combined heat power and dispatch for large system

The proposed Artificial Intelligence (AI) techniques are capable of providing global optimal solutions to the generation scheduling problems for variable with almost hundred percent success rates. However, further research is to be carried out by adopting load changing scenario. The development of methodology for multi-objective along with multi area generation scheduling with coordination of other performance indices such as reliability, start-up and shut-down of generating units and spinning reserves should be aimed at in future. Further research is to be carried out by adopting complex short-term hydrothermal scheduling problems using AI and RES. In future, attempts should also be made for the solution of multi- objective generation dispatch with various constraints such as loss, security, reliability and reactive power allocation in the dispatch algorithm by the application of AI with integrates to RES.

CHAPTER-8
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Chapter 9
Appendices

Table A.1: Data of section 1

Thermal generators								
Unit	P^{min}	P^{max}	a	b	c	μ	κ	π
1	0	680	160	3.6	0.0021	5.4289	0.0351	0.00024
2	0	360	130	3.8	0.0017	4.2895	0.0411	0.00040
3	0	360	130	3.8	0.0017	4.2895	0.0411	0.00040
4	60	180	100	4.0	0.0023	4.2669	0.0545	0.00028
5	60	180	100	4.0	0.0023	4.2669	0.0545	0.00028
6	60	180	100	4.0	0.0023	4.2669	0.0545	0.00028
7	60	180	120	3.5	0.0035	4.2669	0.0254	0.00036
8	60	180	120	3.5	0.0035	4.2669	0.0254	0.00036
9	60	180	120	3.5	0.0035	4.2669	0.0254	0.00036
10	40	120	150	4.6	0.0105	1.3859	0.0327	0.00032
11	40	120	150	4.6	0.0105	1.3859	0.0327	0.00032
12	55	120	140	3.8	0.0015	1.4385	0.0232	0.00034
13	55	120	140	3.8	0.0015	1.4385	0.0232	0.00034
Cogeneration units								
Unit	α	β	γ	δ	ε	ξ	τ	
1	2650	14.5	0.0345	4.20	0.030	0.031	0.00165	
2	1250	36.0	0.0435	0.60	0.027	0.011	0.00220	
3	2650	14.5	0.0345	4.20	0.030	0.031	0.00165	
4	1250	36.0	0.0435	0.60	0.027	0.011	0.00220	
5	2650	34.5	0.1035	2.20	0.025	0.051	0.00140	
6	1565	20.0	0.0720	2.34	0.020	0.040	0.00110	
Heat-only units								
Unit	H^{min}	H^{max}	φ	η	λ	ρ		
1	0	60	950	2.0109	0.038	0.0018		
2	0	60	950	2.0109	0.038	0.0018		

3	0	120	480	3.0651	0.052	0.0017
4	0	120	480	3.0651	0.052	0.0017
5	0	2635.2	950	2.0109	0.038	0.0016

Table A.2: Restricted effective area of l thermal generators of section 1.

Unit	Precinct 1, MW	Precinct 2, MW	Precinct 3, MW
1	[180, 195]	[260, 335]	[390, 420]
2	[30, 40]	[180, 220]	[305, 335]
3	[30, 45]	[190, 225]	[305, 335]
10	[45, 55]	[65, 75]	-
11	[45, 55]	[65, 75]	-