Multi-Objective Generation Scheduling of Hydro-Thermal System Incorporating Energy Storage with Demand Side Management Considering Renewable Energy Uncertainties

Jena, Chitralekha; Guerrero, Josep M.; Abusorrah, Abdullah; Al-Turki, Yusuf; Khan, Baseem

Published in:
IEEE Access

DOI (link to publication from Publisher):
10.1109/ACCESS.2022.3172500

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 31, 2022, accepted April 23, 2022, date of publication May 3, 2022, date of current version May 19, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3172500

Multi-Objective Generation Scheduling of Hydro-Thermal System Incorporating Energy Storage With Demand Side Management Considering Renewable Energy Uncertainties

CHITRALEKHA JENA[1], JOSEP M. GUERRERO[2], (Fellow, IEEE), ABDULLAH ABUSORRAH[3], (Senior Member, IEEE), YUSUF AL-TURKI[3], AND BASEEM KHAN[4], (Senior Member, IEEE)

[1]School of Electrical Engineering, KIIT University, Bhubaneswar, Odisha 751024, India
[2]Center for Research on Microgrids (CROM), AAU Energy, Aalborg University, 9220 Aalborg, Denmark
[3]Center of Research Excellence in Renewable Energy and Power Systems, K. A. CARE Energy Research and Innovation Center, Department of Electrical and Computer Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[4]Department of Electrical and Computer Engineering, Hawassa University, Hawassa 05, Ethiopia

Corresponding author: Baseem Khan (baseem.khan04@gmail.com)

This work was supported in part by the VILLUM FONDEN through the VILLUM Investigator Grant: Center for Research on Microgrids (CROM) (www.crom.et.aau.dk) under Grant 25920.

ABSTRACT Atmospheric pollutants, mainly produced by thermal power plants compel to utilize green energy sources such as renewable energy sources and hydroelectric plants in a power system. But due to blinking behavior of sources of renewable energy and due to very high rate of outages, it has a detrimental consequence on overall grid. Demand side management (DSM) programs decrease cost and improve power system security. This study proposes non-dominated sorting genetic algorithm-II (NSGA-II) to solve multi-objective scheduling of generation for fixed head hydro-thermal system integrating pumped hydro energy storage and sources of renewable energy taking into consideration the outage and uncertainty in presence of DSM. Numerical results of the test system attained using the proposed technique were compared with strength pareto evolutionary algorithm 2 (SPEA 2).

INDEX TERMS Demand side management, uncertainty, outage, fixed head hydro plant, pumped-hydro storage unit, sources of renewable energy, pumped storage plant(PSP).

NOMENCLATURE

F_c	Function of cost.
$a_{si}, b_{si}, c_{si}, d_{si}, e_{si}$	Co-efficient of cost of ith thermal generator.
$\alpha_{si}, \beta_{si}, \gamma_{si}, \eta_{si}, \delta_{si}$	Co-efficient of emission of ith thermal generator.
P_{sit}	Output power of ith thermal unit at time t.
$P_{si}^{min}, P_{si}^{max}$	Minimum and maximum limits of generation of ith thermal unit.
UR_i, DR_i	Rate of ramp-up and ramp-down limits of the ith thermal unit.
P_{hjt}	Output power of jth hydro unit at time t.
$P_{hj}^{min}, P_{hj}^{max}$	Minimum and maximum limits of generation for j^{th} hydro unit.
$a_{0hj}, a_{1hj}, a_{2hj}$	Co-efficient for water discharge rate function of jth hydro unit.
W_{hj}	Pre-specified volume of water available for generation by j^{th} hydro unit during the scheduling period.
P_{wkt}	At time t, available wind power of kth wind turbine.
$P_{wk}^{min}, P_{wk}^{max}$	Minimum and maximum generation limits for k^{th} wind turbine.
P_{wrk}	Wind power rated for k^{th} wind turbine.
K_{wk}	Direct cost co-efficient for the kth wind turbine.
u_{wk}, o_{wk}	For the kth wind turbine, penalty cost and reserve cost respectively.
v_{in}	Cut-in speed of wind.

The associate editor coordinating the review of this manuscript and approving it for publication was Nagarajan Raghavan.

v_{out}	Cut-out speed of wind.
v_r	Rated speed of wind.
v_{wt}	At time t, forecasted speed of wind.
P_{PVmt}	At time t, output power from m^{th} solar plant.
P_{srm}	Rated power output of mth solar plant.
G	Solar irradiation forecast.
G_{std}	Solar irradiation in standard environment.
R_c	Certain irradiation point.
K_{sm}	Direct co-efficient of cost for m^{th} solar plant.
u_{PVm}, O_{PVm}	For the mth solar PV plant, penalty cost and reserve cost respectively.
P_{ghlt}	At time t, generation of power of lth PSP.
P_{phlt}	At time t, pumping power of lth PSP.
P_{ghl}^{min}, P_{ghl}^{max}	Lower and upper limits of power generation of lth PSP.
P_{phl}^{min}, P_{phl}^{max}	Lower and upper limits of pumping power limits l^{th} PSP.
$Q_{ghlt}(P_{ghlt})$	At time t, discharge rate of lth PSP.
$Q_{phlt}(P_{phlt})$	At time t, pumping rate of lth PSP.
$V_{res,lt}$	At time t, volume of water in upper reservoir of lth PSP.
$V_{res,l}^{min}$, $V_{res,l}^{max}$	Lower and upper limit of upper reservoir storage of lth PSP.
$V_{res,l}^{start}$, $V_{res,l}^{end}$	Specified starting and final stored volume of water in upper reservoir of lth PSP.
Inc^{max}	Maximum load increased in any hour.
$L_{Base,t}$	At time t, forecasted base load.
DR_t	At time t, the percentage of forecasted load engaged in DRP.
DR^{max}	Maximum percentage of base load that can participate in DRP.
Inc_t	Amount of increased load at time t.
Ls_t	Shiftable load at time t.
P_{Lt}	Total transmission line losses at time t.
F	Failure rate (failure times/year).
F_{PV}, F_w	Limit of failure rate of solar unit and wind unit.
$MTTR$	Mean time to repair.
ρ	Rate of forced outage.
ρ_{Repair}, ρ_{Aging}, $\rho_{Weather}$	Rate of forced outage due to repairable, aging, and weather dependent failure.
ρ_{wkt}, ρ_{PVmt}	At time t, rate of forced outage of kth wind turbine and m^{th} solar plant.
λ	Failure probability.
S_{wkt}	'1' if at time t, k^{th} wind power unit is scheduled or '0' otherwise.
S_{PVmt}	'1' if at time t, m^{th} solar PV plant is scheduled or '0' otherwise.
α, β	Scale factor and shape factor of Weibull PDFs.
μ_{log}, σ_{log}	Mean and standard deviation for lognormal PDF.
μ_{Norm}, σ_{Norm}	Mean and standard deviation for normal PDF.
t	Time index.
T	Scheduling period.
H_t	Time in interval t.
T_{gen}	Set containing time intervals where the PSP is operating in generation mode.
T_{pump}	Set containing time intervals where PSP operating in pumping mode.
T_{change_over}	Set containing time intervals where PSP is operated in idle mode i.e. within generating and pumping mode.
N_t	Number of thermal units.
N_h	Number of hydro units.
N_w	Number of wind turbines.
N_{PV}	Number of solar power plants.
$\mathbf{N_{Pump}}$	Number of PSPs.

I. INTRODUCTION

Till today, the power plants based on fossil-fuel are the chief sources of generating power. But, these plants discharge sulfur oxides, nitrogen oxides and carbon dioxide to the atmosphere. These cause lethal damage to flora and fauna and global climate. These result into increased concern over ecological protection with several environmental amendments. For electric utilities, one major challenge is to decrease atmospheric pollution, for reducing acid rain and greenhouse gasses which is the aim of 1990 Clean Air Act. So modern's civilization wants quality electricity not only at low-cost, but pollution free. Many approaches are proposed to reduce pollution in the atmosphere [1].

The rapid increase of electric power demand, gradual reduction of fossil fuel and global warming have pushed energy based research in the direction of green energy. Because of this clean energy sources are achieving to meet the energy demand. Variability and irregularity turn out vital challenges to overcome the problem of scheduling. The grid may have detrimental effect due to this intermittent nature. It is overcome by using pumped hydro energy storage. There is always a possibility of high rate of outage in solar and wind power. Hence it is vital to study possibility of outage during generation scheduling.

Optimal generation scheduling with renewable energy sources of a miniature autonomous system is discussed in [2]. Though, these sources are pollution free but their generation capability is low. Use of amalgam energy system i.e., thermal power integrating wind power [3], thermal power plant-solar PV plant [4], hydro-thermal integrating wind power [5] has swiftly enhanced.

Pumped-storage-hydraulic (PSH) unit is attaining the mammoth attention all over the earth [6] primarily because of characteristic of energy storage. Main function of PSH units is to hoard low-cost excess energy during off-peak load levels as hydraulic potential energy pumping water from lower reservoir to upper reservoir. During peak load levels, stored hydraulic potential energy is utilized. PSH unit ordinarily works in daily or weekly. Operation over a period of a PSH unit reduces the fuel cost [7].

In [8], Gradient search techniques and Lagrangian multiplier is used to get optimum hydro-thermal generation scheduling with PSH unit considering constraints. In [9] evolutionary programming technique has been employed for the same problem in hydrothermal system with PSH units. Mohan *et al.* [10] has shown that a pumped-hydro unit (PHU) can be used as peak-load management unit by shutting down electric power in turn to reduce the large deviation in frequency. Ma *et al.* [11] shows the pumped hydro storage system for solar energy infiltration and for mini sovereign systems.

Multi-objective (MO) hydrothermal generation scheduling problem where cost and emission objectives are optimized simultaneously has been discussed by a number of researchers [12]–[19]. Simab *et al.* [12] have employed MO programming for pumped-hydro-thermal scheduling problem. Narang *et al.* [13] have discussed MO short term hydrothermal generation scheduling utilizing predator-prey optimization. Sun *et al.* [14] have applied an improved quantum-behaved PSO for economic emission hydrothermal scheduling problem. Zhang *et al.* [15] have presented gradient decent based MO cultural DE for short-term hydrothermal optimal scheduling incorporating wind power and photovoltaic power. Dhillon *et al.* [16] applied a fuzzy decision method for deciding generation scheduling of a hydrothermal problem. Fuzzy satisfying method based on EP technique [17] is discussed for MO short-term hydrothermal scheduling problem. Crisscross PSO algorithm [18] is used for MO generation scheduling of pumped storage hydrothermal system incorporating solar units. Basu [20] has applied chaotic fast convergence evolutionary programming (CFCEP) for short-term hydrothermal scheduling. Kaur *et al.* [21] have applied chaotic-crisscross differential evolution (CCDE) algorithm for short-term hydrothermal scheduling. DSM programs have many advantages for example lessening the cost, improving the power system security [22], etc.

A variety of classical methods like Newton's method [23], Lagrange multiplier method [24], dynamic programming [8] is employed to solve short-term fixed head hydrothermal scheduling. A variety of meta-heuristic algorithms such as Hopfield neural network [25], artificial immune system [26], cuckoo search algorithm [27], are employed to solve short-term fixed head hydrothermal scheduling problem. Modified cuckoo search algorithm [28] is discussed for MO short-term fixed head hydrothermal scheduling problem. Fast convergence evolutionary programming with time varying mutation scale (FCEP-TVMS) [29] is employed to solve short-term fixed head hydrothermal scheduling problem.

The major aim of MO short-term generation scheduling of fixed head hydrothermal power system incorporating pumped hydro energy storage with and without demand side management (DSM) considering uncertainty and outage of renewable energy sources is to optimize total cost and emission echelon simultaneously over a scheduling period simultaneously satisfying various constraints.

Here, nondominated sorting genetic algorithm-II (NSGA-II) is pertained to solve short-term MO generation scheduling of fixed head hydrothermal power system incorporating pumped hydro energy storage with and without DSM considering uncertainty and outage of sources of renewable energy Simulation outcomes of the test system are matched with that obtained by strength pareto evolutionary algorithm 2 (SPEA 2).

The major contributions of this manuscript can be stated as follows:

- Multi-objective generation scheduling of fixed head hydrothermal system has been considered.
- Ramp rate limit constraints of thermal generators have been taken into consideration.
- Uncertainty and outage of renewable energy sources have been taken into account.
- The problem is solved with and without DSM.

II. PROBLEM FORMULATION

A. UNCERTAINTY MODELING

1) PROBABILITY DISTRIBUTION OF SOLAR PLANT AND WIND TURBINE

Because of intermittency and variability of solar plant and wind turbine, it is difficult to integrate them to the main system. Large reserve capacity margin is caused due to overestimation of renewable power which in turn results instability in the steady state security if there is rise in demand, while underestimation outcomes loss of excess energy. During generation scheduling, both sum up to the total generation and operation costs. As a result, different uncertainty modeling, like Weibull, Beta, Lognormal and Gumbel probability distribution functions (PDFs), is implemented by many researchers to evaluate reserve cost and penalty cost for overestimation and underestimation respectively. Solar irradiation and wind speed are predicted to be well trailed by lognormal and Weibull PDFs respectively as in (1) and (2) [30].

$$f_G(G) = \frac{1}{G \times \sigma_{Log} \times \sqrt{2 \times \Pi}} \times e^{-\left\{\frac{-\left(\ln G - \mu_{Log}\right)^2}{2 \times \mu_{Log}^2}\right\}} \quad \text{for } G > 0 \tag{1}$$

$$f_v(v) = \left(\frac{\beta}{\alpha}\right) \times \left(\frac{v}{\alpha}\right)^{(\beta-1)} \times e^{-\left(\frac{b}{\alpha}\right)^{\beta}} \quad \text{For } 0 < v < \infty \tag{2}$$

2) WIND POWER MODEL

The o/p power [19] of kth wind turbine at time t for a given wind speed is affirmed as:

$$\begin{aligned} P_{wkt} &= 0, \quad \text{for } v_{wt} < v_{in} \quad \text{and } v_{wt} < v_{out} \\ P_{wkt} &= P_{wrk} \times \left(\frac{v_{wt} - v_{in}}{v_r - v_{in}}\right), \quad \text{for } v_i \le v_{wt} \le v_r \\ P_{wkt} &= P_{wrk}, \quad \text{for } v_r \le v_{wt} \le v_{out} \end{aligned} \tag{3}$$

3) SOLAR POWER MODEL

The o/p power [31] from m^{th} solar plant at time t for a given irradiation G is affirmed by

$$\begin{aligned} P_{PVmt} &= P_{srm} \times \left(\frac{G^2}{G_{std} R_c}\right), \quad \text{for } 0 < G < R_c \\ P_{PVmt} &= P_{srm} \left(\frac{G}{G_{std}}\right), \quad \text{for } G \ge R_c \end{aligned} \tag{4}$$

4) POWER PROBABILITIES OF SOLAR PV PLANT

Probability of a PV power is equal to the value of corresponding solar power irradiation probability as in (5).

$$f_{PV}\left(P_{PV}\right) = f_G\left(G\right) \tag{5}$$

5) POWER PROBABILITIES OF WIND TURBINE

For the discrete zones wind power probabilities i.e., for first and third case of (3), is computed using (6) and (7) respectively [32].

$$f_w\left(P_w\right)|_{P_W} = 0 = 1 - e^{-\left(\frac{v_{in}}{\alpha}\right)^\beta} + e^{-\left(\frac{v_{out}}{\alpha}\right)^\beta} \tag{6}$$

$$f_w\left(P_w\right)|_{P_W} = P_{Wr} = -e^{-\left(\frac{v_{in}}{\alpha}\right)^\beta} - e^{-\left(\frac{v_{out}}{\alpha}\right)^\beta} \tag{7}$$

The probability for WT power in the continuous region as second case in (3) is calculated as (8).

$$f_w\left(P_w\right) = \frac{\beta \times (v_r - v_{in})}{\alpha^\beta + P_{wr}} \times \left[v_{in} + \frac{P_w}{P_{wr}} \times (v_r - v_{in})\right]^{(\beta-1)} \times e^{-\left(\frac{v_{in} + \frac{P_w}{P_{wr}} \times (v_r - v_{in})}{\alpha}\right)^\beta} \tag{8}$$

B. OUTAGE MODELING OF SOLAR PV PLANT AND WIND TURBINE

Unavailability of sunshine and wind in the environmental state may force the renewable sources to face forced outage frequently. This forced outage modelling depends on three factors, viz., repairable failure, aging and weather dependency. Repairable forced outage rate is defined as (9) [33].

$$\rho_{Repair} = \frac{F \times MTTR}{8760} \tag{9}$$

Component aging failure model usually follows the normal PDF and during the service time T. Aging failure rate is evaluated as (10).

$$\rho_{Aging} = \frac{1}{\sigma_{Norm} \times \sqrt{2 \times \Pi}} \times e^{-\frac{(T - \mu_{Norm})^2}{2 \times \sigma_{Norm}^2}} \tag{10}$$

Weather dependent failure model can be modelled by exponential distribution as (11) for a time period of Δt.

$$\rho_{Weather} = 1 - e^{-\lambda \times \Delta t} \tag{11}$$

Hence, multi-factor independent outage is involved; the outage rate is estimated using the concept of union set. So, the forced outage rate of any renewable unit is cleared by (12).

$$\begin{aligned} \rho = \rho_{Repair} \cup \rho_{Aging} \cup \rho_{Weather} &= \rho_{Repair} + \rho_{Aging} \\ &+ \rho_{Weather} - \rho_{Repair} \times \rho_{Aging} - \rho_{Aging} \times \rho_{Weather} \\ &- \rho_{weather} \times \rho_{Repair} - \rho_{Repair} \times \rho_{Aging} \times \rho_{Weather} \end{aligned} \tag{12}$$

C. OBJECTIVE FUNCTION AND CONSTRAINTS

The multi-objective generation scheduling of fixed head hydrothermal power system with pumped hydro energy storage and renewable energy sources considering uncertainty and outage in presence of DSM is devised to optimize total cost and emission echelon simultaneously taking variety of constraints. Objective functions and constraints taking into description with DSM and outage possibility.

1) COST

The total cost is affirmed as

$$\begin{aligned} F_C = \sum_{t=1}^{T} H_t \times \Bigg[&\sum_{i=1}^{N_t} \{f_{sit}\left(P_{sit}\right)\} \\ &+ \sum_{k=1}^{N_W} \{K_{wk} \times P_{wkt} + O_{wkt}\left(P_{wkt}\right) + U_{wkt}\left(P_{wkt}\right)\} \\ &\times S_{wkt} \sum_{m=1}^{N_{PV}} \{K_{sm} \times P_{PVmt} + O_{PVmt}\left(P_{PVmt}\right) \\ &+ U_{PVmt}\left(P_{PVmt}\right)\} \times S_{PVmt} \Bigg] \end{aligned} \tag{13}$$

where,

$$S_{wkt} = \begin{cases} 1, & \rho_{wkt} < F_w \\ 0, & otherwise \end{cases}$$

and

$$S_{PVmt} = \begin{cases} 1, & \rho_{PVmt} < F_{PV} \\ 0, & otherwise \end{cases}$$

The cost function of fuel of i the thermal generator at time t, taking valve-point effect [34], is affirmed as

$$\begin{aligned} f_{sit}\left(P_{sit}\right) = a_{si} + b_{si} P_{sit} + c_{si} P_{sit}^2 \\ + \left| d_{si} \times \sin\left\{e_{si} \times \left(P_{si}^{\min} - P_{sit}\right)\right\}\right| \end{aligned} \tag{14}$$

Reserve cost and penalty cost for overestimation and underestimation on dispatchable wind power [31] is given in (15)-(16) respectively.

$$O_{wkt}\left(P_{wkt}\right) = o_{wk} \times \int_{P_{wkt}^{\min}}^{P_{wkt}} \left(P_{wkt} - y\right) \times f_w\left(y\right) dy \tag{15}$$

$$U_{wkt}\left(P_{wkt}\right) = u_{wk} \times \int_{P_{wkt}}^{P_{wkt}^{\max}} \left(y - P_{wkt}\right) \times f_w\left(y\right) dy \tag{16}$$

Reserve cost and penalty cost for overestimation and underestimation on dispatchable solar power [31] is given in (17)-(18) respectively.

$$O_{PVmt}\left(P_{PVmt}\right) = o_{PVm} \times \int_{P_{PVmt}^{\min}}^{P_{PVmtt}} \left(P_{PVmt} - x\right) \times f_{PV}\left(x\right) dx \tag{17}$$

$$U_{PVmt}\left(P_{PVmt}\right) = u_{PVm} \times \int_{P_{PVmt}}^{P_{PVmt}^{\max}} \left(x - P_{PVmt}\right) \times f_{PV}\left(x\right) dx \tag{18}$$

2) EMISSION

For assessment purposes, total emission of these pollutants is affirmed as the summation of a quadratic and an exponential function [35]. Total emission of thermal generators is affirmed as

$$F_E = \sum_{t=1}^{T} H_t \times \left[\sum_{i=1}^{N_t} \alpha_{si} + \beta_{si} P_{sit} + \gamma_{si} P_{sit}^2 + \eta_{si} \exp\left(\delta_{si} P_{sit}\right)\right] \tag{19}$$

Subject to:

(i) Power balance constraints:

$$\sum_{i=1}^{N_t} P_{sit} + \sum_{j=1}^{N_h} P_{hjt} + \sum_{k=1}^{N_w} \left(P_{wkt} \times S_{wkt}\right) + \sum_{m=1}^{N_{PV}} \left(P_{PVmt} \times S_{PVmt}\right) + \sum_{l=1}^{N_{pump}} P_{ghlt} = \left(1 - DR_t\right) \times L_{Base,t} + Ls_t + P_{Lt}, \quad t \in T_{gen} \tag{20}$$

$$\sum_{i=1}^{N_t} P_{sit} + \sum_{j=1}^{N_h} P_{hjt} + \sum_{k=1}^{N_w} \left(P_{wkt} \times S_{wkt}\right) + \sum_{m=1}^{N_{PV}} \left(P_{PVmt} \times S_{PVmt}\right) - \sum_{l=1}^{N_{pump}} P_{phlt} = \left(1 - DR_t\right) \times L_{Base,t} + Ls_t + P_{Lt}, \quad t \in T_{pump} \tag{21}$$

$$\sum_{i=1}^{N_t} P_{sit} + \sum_{j=1}^{N_h} P_{hjt} + \sum_{k=1}^{N_w} \left(P_{wkt} \times S_{wkt}\right) + \sum_{m=1}^{N_{PV}} \left(P_{PVmt} \times S_{PVmt}\right) = \left(1 - DR_t\right) \times L_{Base,t} + Ls_t + P_{Lt}, \quad t \in T_{change\_over} \tag{22}$$

Assuming, $Ls_t = 0$ when load curtailed due to DRP, and when load is moved to base load demand, no load is curtailed.

Total transmission loss P_{Lt} can be calculated by utilizing B-coefficient affirmed as

$$P_{Lt} = \sum_{i=1}^{N_T} \sum_{j=1}^{N_T} P_{it} B_{ij} P_{jt} + \sum_{i=1}^{N_T} B_{0i} P_{it} + B_{00} \tag{23}$$

Total number of plants $N_T = N_t + N_h + N_w + N_{PV}$ and P_{im} is the respective thermal, hydro, wind power, solar PV unit.

3) CONSTRAINTS OF PUMPED-STORAGE

PSH unit depends entirely on water which is pumped to an upper reservoir from lower one. When the unit changes from generating mode to pumping mode or vice-versa, the unit is made off for an hour, called as change-over time.

$$V_{res,l(t+1)} = V_{res,lt} + Q_{phlt}\left(P_{phlt}\right), \quad l \in N_{pump}, \quad t \in T_{pump} \tag{24}$$

$$V_{res,l(t+1)} = V_{res,lt} - Q_{ghlt}\left(P_{ghlt}\right), \quad l \in N_{pump}, \quad t \in T_{gen} \tag{25}$$

$$V_{res,l}^{(t+1)} = V_{res,l}^{t}, \quad l \in N_{pump} \quad \text{and } t \in T_{change\_over} \tag{26}$$

$$P_{ghl}^{\min} \le P_{ghlt} \le P_{ghl}^{\max} l \in N_{pump}, \quad t \in T_{gen} \tag{27}$$

$$P_{phl}^{\min} \le P_{phlt} \le P_{phl}^{\max} l \in N_{pump}, \quad t \in T_{pump} \tag{28}$$

$$V_{res,l}^{\min} \le V_{res,lt} \le V_{res,l}^{\max}, \quad l \in N_{pump}, \quad t \in T \tag{29}$$

In this problem the initial and final volume of water of upper reservoir of the PSH unit is considered as same.

$$V_{res,l0} = V_{res,lT} = V_{res,l}^{start} = V_{res,l}^{end} \tag{30}$$

4) GENERATION LIMITS

$$P_{hj}^{\min} \le P_{hjt} \le P_{hj}^{\max} j \in N_h, \quad t \in T \tag{31}$$

$$P_{si}^{\min} \le P_{sit} \le P_{si}^{\max} i \in N_t, \quad t \in T \tag{32}$$

5) RAMP RATE LIMITS

$$\begin{aligned} P_{sit} - P_{si(t-1)} &\le UR_i, \quad i \in N_t, \quad t \in T \\ P_{si(t-1)} - P_{sit} &\le DR_i, \quad i \in N_t, \quad t \in T \end{aligned} \tag{33}$$

6) WATER AVAILABILITY CONSTRAINTS

$$\sum_{t=1}^{T} \left[H_t\left(a_{0hj} + a_{1hj} P_{hjt} + a_{2hj} P_{hjt}^2\right)\right] - W_{hj} = 0, \quad j \in N_h \tag{34}$$

7) DEMAND SIDE MANAGEMENT

Demand side management [36] plays an important role in power system. Demand side management alters customers' electricity consumption patterns to produce the desired changes in the load shapes of power distribution systems. The changes in the final consumption profile will depend on the planning objectives and operation of the utility companies. Demand side management focuses on utilizing power saving technologies, electricity tariffs, monetary incentives, and government policies to mitigate the peak load demand

instead of enlarging the generation capacity or reinforcing the transmission and distribution network. To mitigate system instabilities brought about by increasing electricity demand, a suitable objective of demand side management activities could be to change the shape of the load demand curve by reducing the total load demand of the distribution system during peak periods, and shift these loads to be served during more appropriate times in order to reduce the overall planning and operational cost of the network.

Time of use (TOU) demand response (DR) program [22] is the most common price based programs that aims to improve and control subscribers' consumption by changing the electricity price in different time periods. This is actually achieved by motivating the consumers that their electricity price will be reduced. Therefore, this program implements DR programs by informing the consumers about electricity prices. In this type of DR programs, the electricity price depends on when electricity is used. Consumers are heavily charged for power consumption during peak period. Therefore, they are encouraged to reduce their consumption during peak hours and shift their suspended loads to off peak hours. In the TOU program, the electricity tariff varies in different time periods. These tariffs are usually obtained through power generation and transmission cost in these periods. In TOU programs, electricity tariffs are usually pee-determined for several months, years, and different seasons. Here, DR program is used to smooth the load curve by shifting loads from peak hours to off peak hours and, thus, reduce operating costs. As a result the power demand curve is flattened. The TOU program is designated by the equation (35) and constrained by equations (36)–(39).

$$L_t = (1 - DR_t) \times L_{Base} + L_{st} \tag{35}$$

$$\sum_{t=1}^{T} L_{st} = \sum_{t=1}^{T} DR_t \times L_{Base,t} \tag{36}$$

$$L_{Inc_t} = Inc_t \times L_{Base,t} \tag{37}$$

$$DR_t \leq DR^{\max}, \quad t \in T \tag{38}$$

$$Inc_t \leq Inc^{\max}, \quad t \in T \tag{39}$$

III. SOLUTION METHODOLOGY

A. MULTI-OBJECTIVE OPTIMIZATION PRINCIPLE

The majority of the actual-world problems engross optimization of a number of non commensurable and conflicting objective functions simultaneously where a set of optimal solutions is produced in place of one optimal solution because no solution can be looked upon as superior than any other with respect to all objective functions.

The problem of Multi-objective optimization comprises a no. of objectives and a number of equality and inequality constraints and is affirmed as:

$$\text{Minimize} \quad f_i(x), \quad i = 1, \ldots, N_{\text{obj}} \tag{40}$$

$$\text{Subject to :} \begin{cases} g_k(x) = 0, & k = 1, \ldots, K \\ h_l(x) \leq 0, & l = 1, \ldots, L \end{cases} \tag{41}$$

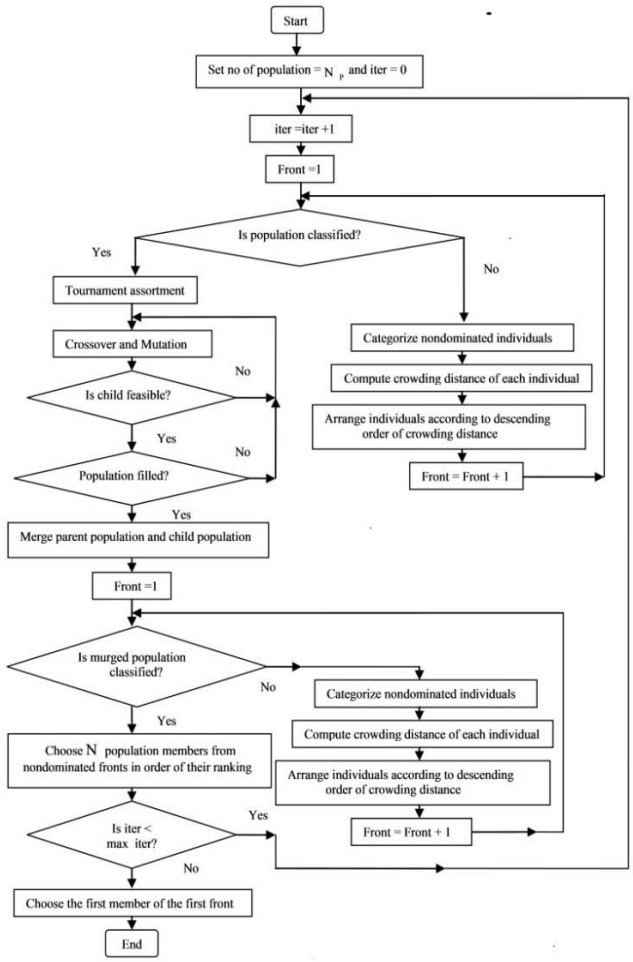

FIGURE 1. Flowchart of NSGA II for the proposed work.

where, f_i is the ith objective function, x is decision vector that represents a solution, and N_{obj} is the no. of objectives.

B. NON-DOMINATED SORTING GENETIC ALGORITHM-II

Srinivas and Deb [37] established nondomoinated sorting genetic algorithm (NSGA). Nondomination is exploited based on grade decisive factor of solutions, and fitness sharing is exploited for diversification control in the explore space. As NSGA depends heavily upon fitness sharing parameters, Deb *et al.* [38] established NSGA-II, which producing more reliable solution than its precursor. NSGA-II flow chart is depicted in Fig. 1.

IV. NUMERICAL RESULTS

Here, the problem is solved with and without DSM. For solving the test system, NSGA-II technique is used. For confirming the efficiency, SPEA 2 [39] is used for solving the problem. The suggested NSGA-II, SPEA 2 and real coded genetic algorithm (RCGA) are done by utilizing MATLAB 7.0 on a PC (Pentium-IV, 1TB, 3.0 GHz).

Two conflicting objective functions, Cost and emission are minimized by RCGA. For the test system, population size,

TABLE 1. Hydro system data of the test system.

Unit	a_{0h} acre-ft/h	a_{1h} acre-ft/MWh	a_{2h} acre-ft/(MW)^{2}h	W_h acre-ft	P_h^{min} MW	P_h^{max} MW
1	260	8.5	0.00986	62500	0	250
2	250	9.8	0.01140	143000	0	500

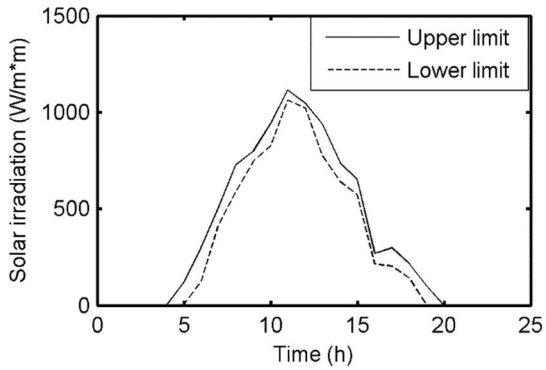

FIGURE 2. Forecast limits of solar irradiation.

crossover and mutation probabilities are taken as 100, 0.9 and 0.2, respectively. The maximum no. of iterations is taken as 300.

NSGA-II and SPEA 2 are employed for cost and emission optimization objectives simultaneously. In NSGA-II and SPEA 2, size of population, maximum no. of iterations, crossover probabilities and mutation probabilities is taken as 20, 30, 0.9 and 0.2 for test system.

It considers two fixed head hydro plants, four thermal plants, one wind turbine, one solar plant and one pumped storage plant. The total scheduling period is 1 day and broken up 24 intervals. The effects of valve point and ramp rate limits of thermal generator have been considered. The data of hydro plants and thermal plants is shown in Table 1 and Table 2. Total hourly load demand is shown in Table 3.

Rating of wind power generator [29] is $P_{wr} = 100$MW. The Cut in, cut out and rated speed of wind are taken as $v_{in} = 4$m/sec, $v_o = 25$m/s and $v_r = 15$m/s respectively. The direct cost coefficient (K_w) for wind power generator is chosen 7. Reserve cost (o_{wk}) and penalty cost (u_{wk}) for the wind power generator are chosen as 2 and 1 respectively. Rating of solar unit [29] is $P_{PVr} = 120$MW. Direct cost coefficient (K_s) for solar unit is chosen 6. The reserve cost (o_{PVm}) and penalty cost (u_{PVm}) for the solar PV unit is taken as 2 and 1, respectively. G_{std} and R_c are taken as 1000 W/m^2 and 120 W/m^2.

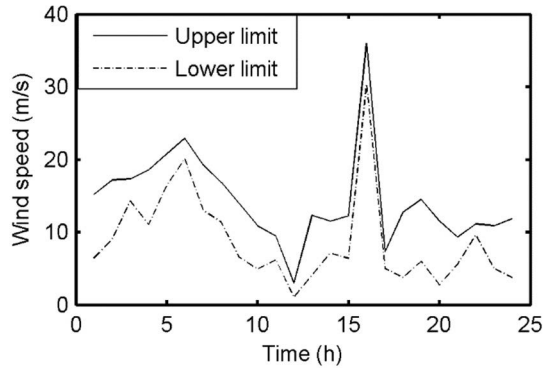

FIGURE 3. Forecast limits of wind speed.

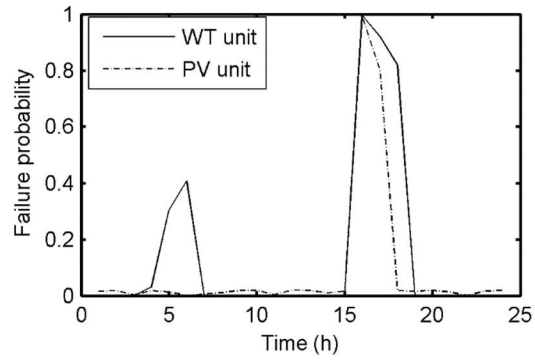

FIGURE 4. The failure probabilities (λ) for WT and PV units.

The minimum and maximum forecast limits of solar irradiation and wind velocity [20] are illustrated in Fig. 2 and Fig. 3 respectively. A sudden change in wind speed can be noticed at 16th hour in Fig. 3. Such high wind speed generally results into turbulent weather condition and causes renewable unit failure. The failure probabilities λ for PV and WT units [20], which can be fetched from weather dependent historical data, are portrayed in Fig. 4. The forced outage rates of PV and WT units [20] are presented in Fig. 5 correspondingly. Obviously from Fig. 5 it shows that, PV unit has high failure rates at 16th and 17th hour and WT unit has high failure rates at 16th, 17th and 18th hour. It is assumed that during DSM, 10% of 15th, 16th and 17th hour load is moved to 3rd, 4th and 5th. Total hourly load demand under DSM is shown in Table 4 hour. The characteristics of pumped hydro storage plant [29] is given below

Generating mode

Q_{ght} is +ve when generating, P_{ght} is +ve and $0 \le P_{ght} \le 100MW$, $Q_{ght}\left(P_{ght}\right) = 70 + 2P_{ght}$ acre-ft/hr.

TABLE 2. Thermal generator data of the test system.

Unit	P_s^{min} MW	P_s^{min} MW	a_s \$/h	b_s \$/MWh	c_s \$/(MW)^{2}h	d_s \$/h	e_s rad/MW	α_s *lb*/h	β_s *lb*/MWh	γ_s *lb* /(MW)^{2}h	η_s *lb* /h	δ_s 1/MW	*UR* MW/h	*DR* MW/h
1	20	125	756.85	38.54	0.1520	300	0.15	13.86	0.327	0.00420	0.220	0.0175	60	60
2	30	175	451.32	45.72	0.1150	400	0.12	14.86	0.328	0.00410	0.270	0.0165	80	80
3	40	250	1243.53	38.30	0.0350	400	0.09	40.26	-0.545	0.00683	0.240	0.0150	100	100
4	50	300	1356.66	38.27	0.0189	400	0.08	43.89	-0.513	0.00460	0.250	0.0150	120	120

TABLE 3. Hourly load demand.

Hour	L_{Base}	Hour	L_{Base}	Hour	L_{Base}
1	1150	9	1390	17	1500
2	1080	10	1380	18	1450
3	1000	11	1400	19	1370
4	1050	12	1450	20	1350
5	1070	13	1410	21	1210
6	1100	14	1450	22	1160
7	1150	15	1500	23	1150
8	1250	16	1550	24	1100

TABLE 4. Hourly load demand under DSM.

Hour	L_t	Hour	L_t	Hour	L_t
1	1150	9	1390	17	1350
2	1080	10	1380	18	1450
3	1150	11	1400	19	1370
4	1205	12	1450	20	1350
5	1220	13	1410	21	1210
6	1100	14	1450	22	1160
7	1150	15	1350	23	1150
8	1250	16	1395	24	1100

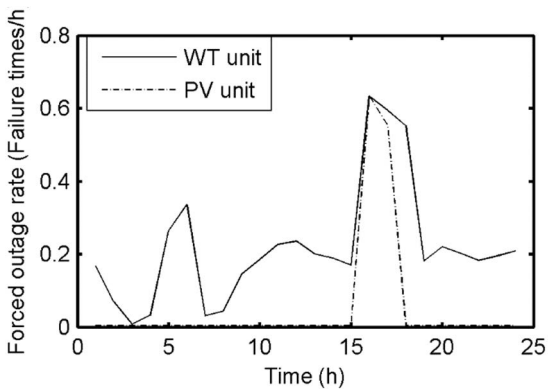

FIGURE 5. The forced outage rates of WT and PV units.

Pumping mode

Q_{pht} is −ve when pumping, P_{pht} is −ve and $-100 < P_{pht} \leq 0MW$, $Q_{pht}\left(P_{pht}\right) = -200$acre-ft/h and $P_{pht} = -100$ MW

Operating limits: PHP is permitted to work at −100 MW while pumping. Reservoir starts at 3000 acre-ft and at the end of 24 hour it must be at 3000 acre-ft. Spillage is not considered and water inflow rate is neglected.

Solar-wind-hydro-thermal-pumped storage generations with DSM acquired from cost minimization and emission minimization by using RCGA are summarized in Table 5 and Table 6, respectively. Solar-wind-hydro-thermal-pumped storage generations with DSM acquired from cost and emission objectives optimized simultaneously by using NSGA-II and SPEA 2 are summed up in Table 7 and Table 8 respectively.

Solar-wind-hydro-thermal-pumped storage generations without DSM acquired from cost minimization and emission minimization by using RCGA are summarized in

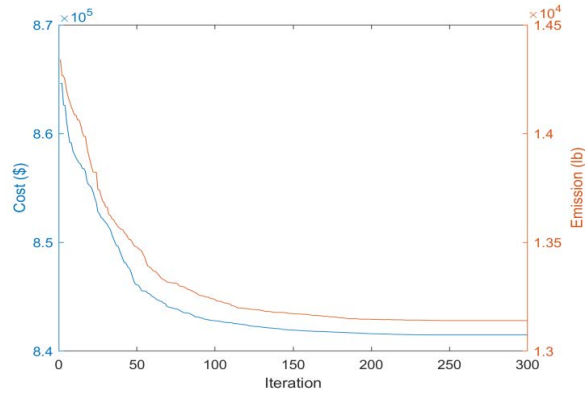

FIGURE 6. Cost emission convergence characteristics with DSM.

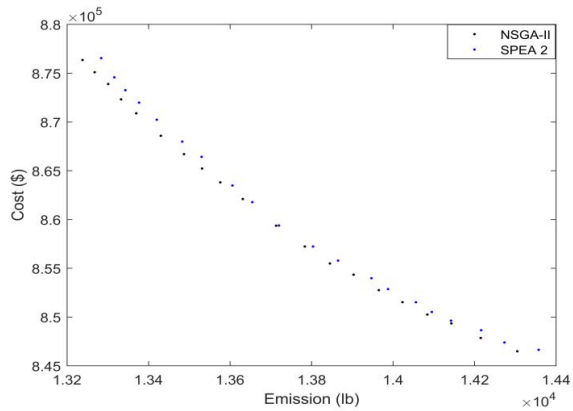

FIGURE 7. Pareto-optimal front of the final iteration with DSM.

Table 9 and Table 10 respectively. Solar-wind-hydro-thermal-pumped storage generations without DSM acquired from cost and emission objectives optimized simultaneously by using NSGA-II and SPEA 2 are summed up in Table 11 and Table 12 respectively.

Cost, emission and CPU time acquired from cost minimization i.e. economic dispatch, emission minimization i.e. emission dispatch and economic emission dispatch where cost and emission objectives are optimized simultaneously with and without DSM are summed up in Table 13. The cost convergence and emission convergence characteristics with and without DSM acquired by utilizing RCGA have been revealed in Fig. 6 and Fig. 8 respectively. Fig. 7 and Fig.9 reveal that the distribution of 20 non-dominated solutions attained from the economic emission dispatch with and without DSM in the final iteration of proposed NSGA-II and SPEA2.

This Fig. 2 represents the upper and lower limit of solar irradiation in W/m^2. The bold line represents the upper limit and the dotted line represents the lower limit of solar irradiation. The upper limit is approximately 1100W/m^2 and the lower limit is around 1000W/m^2.

This Fig. 3 represents the upper and lower limit of wind speed in m/s with respect to time in hour which is of

TABLE 5. Thermal-hydro-wind-solar-pumped storage generation in MW obtained from Economic dispatch WITH DSM.

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}
1	53.7706	162.7435	157.7247	299.1526	208.8486	348.0908	50.8180	0	-100.0000	31.1488
2	20.4748	118.3487	65.8504	204.5309	237.6826	469.1857	92.9263	0	-100.0000	28.9994
3	36.4858	58.0344	102.3298	282.7332	226.1167	476.1587	100.0000	0	-100.0000	31.8586
4	85.2491	84.3307	139.3986	295.3199	231.7385	422.4519	80.3069	0	-100.0000	33.7956
5	109.0967	158.1464	232.2611	202.8961	209.5173	338.7260	100.0000	0.9746	-100.0000	31.6182
6	56.5745	82.2343	225.6273	154.6244	203.4904	383.0994	100.0000	20.9508	-100.0000	26.6011
7	49.5565	91.1231	250.0000	148.9483	234.0082	356.1578	100.0000	47.8112	-100.0000	27.6051
8	77.3395	56.6737	165.9154	197.7237	223.4581	405.8377	83.0851	67.7084	0	27.7416
9	110.5063	124.9733	224.9888	154.8453	203.9126	420.8120	75.8540	78.8867	27.8941	32.6731
10	69.9179	155.9490	229.7304	274.6224	225.4952	334.9845	22.8846	90.1899	9.9949	33.7688
11	55.4462	85.1482	241.8466	212.3094	209.4115	433.9940	38.8182	111.0972	45.1561	33.2274
12	103.0529	159.6407	220.5776	285.1598	198.6541	369.3696	0	102.8838	46.6273	35.9658
13	62.5536	104.2622	236.5026	285.7270	214.9561	322.1250	34.3800	92.9011	87.3257	30.7333
14	85.2118	90.4554	172.5980	169.4236	249.0342	500.0000	50.5486	73.3984	95.3193	35.9893
15	43.6273	117.4903	170.2868	252.6614	203.5238	399.0937	70.3809	58.3907	64.6246	30.0795
16	82.6442	158.2223	242.7875	241.8038	194.1737	431.8524	0	0	81.5623	38.0462
17	88.1273	133.6159	178.6505	286.7675	195.6572	406.1864	0	0	95.4275	34.4323
18	112.1243	159.9460	239.2163	266.6941	222.5199	399.5417	0	20.5685	69.2038	39.8146
19	98.9903	163.5508	207.2146	214.1977	211.4028	338.0605	71.0125	4.2729	92.1227	30.8248
20	84.5158	117.1479	209.8982	252.2497	230.9645	436.5430	56.0792	0	0	37.3983
21	122.1333	110.3433	234.9254	293.7546	238.1327	315.3957	29.8400	0	-100.0000	34.5250
22	90.8345	69.9285	246.1749	195.3424	215.2318	414.1127	60.8184	0	-100.0000	32.4432
23	87.8062	108.9483	175.9334	272.5396	237.7170	375.4743	24.4663	0	-100.0000	32.8851
24	84.6134	44.8098	170.2502	253.6431	243.8304	422.7718	12.3622	0	-100.0000	32.2809

TABLE 6. Thermal-hydro-wind-solar-pumped storage generation in MW obtained from emission dispatch WITH DSM.

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}
1	67.6293	122.7401	196.6360	206.2622	222.9056	393.3878	71.4442	0	-100.0000	31.0052
2	56.4824	101.5791	132.2691	164.2825	183.8177	469.5674	100.0000	0	-100.0000	27.9982
3	104.5272	157.3053	186.4792	221.4464	180.1277	328.0354	100.0000	0	-100.0000	27.9212
4	124.9158	125.0261	149.5311	221.7665	240.9497	389.9075	85.5059	0	-100.0000	32.6026
5	124.5488	161.2381	134.2831	220.6806	238.8216	371.1060	100.0000	1.5030	-100.0000	32.1812
6	106.7291	101.9583	66.1177	176.2994	180.2731	483.9751	100.0000	13.0228	-100.0000	28.3755
7	123.9147	117.8305	127.4364	215.9706	242.7019	301.1807	100.0000	46.9564	-100.0000	25.9912
8	111.0535	109.9020	87.1969	174.5860	238.6209	402.0771	90.5852	63.3811	0	27.4027
9	124.7475	143.9856	129.1192	211.6322	239.3485	411.9854	52.0177	74.7426	35.8062	33.3849
10	121.6524	144.1838	163.6718	209.4103	216.4728	342.2970	35.6862	92.0986	83.7132	29.1861
11	116.3575	162.9490	153.8589	227.9712	226.7139	330.1518	31.8639	110.6150	69.5100	29.9912
12	118.2106	110.2259	170.0210	219.5597	231.9355	457.9291	0	103.8000	74.8071	36.4889
13	88.7005	126.3640	203.0412	237.4903	198.1393	435.9349	58.1808	83.5373	13.6867	35.0750
14	121.1633	126.7280	178.1124	217.2092	243.6229	415.6466	39.9986	70.8289	72.1606	35.4705
15	124.1920	110.9491	200.6895	228.9243	179.4932	360.9741	39.1690	64.3148	70.8668	29.5728
16	108.7045	163.5730	188.9430	236.0553	227.4234	418.8391	0	0	88.8412	37.3795
17	124.3897	166.5440	147.1638	234.0509	216.5653	486.6531	0	0	14.8213	40.1881
18	112.1012	172.0280	195.4263	224.5454	226.0362	447.4641	0	20.5649	91.4659	39.6320
19	85.8818	173.5834	188.2472	218.6305	216.0327	361.1801	57.7778	0.5899	99.8198	31.7432
20	118.3502	165.7239	203.8393	238.1631	240.8355	411.9421	10.2178	0	0	39.0719
21	123.5917	144.9941	172.4822	216.4226	231.8384	412.2394	43.6450	0	-100.0000	35.2134
22	115.6023	150.7564	135.9570	205.3147	203.5401	428.0043	53.2847	0	-100.0000	32.4595
23	122.8510	164.9201	193.9261	246.2907	199.5938	332.3795	21.6766	0	-100.0000	31.6378
2 4	92.3214	169.0560	142.6887	194.3302	240.2739	322.4715	66.5979	0	-100.0000	27.7396

24 interval. The solid line represents the upper limit and dotted line represents the lower limit of Wind speed. A sudden change in wind speed is noticed at 16th hour of load. The upper limit of wind speed is around 35m/s and lower limit is around 30m/s.

The probability of failure of WT and PV unit is shown in Fig. 4. The failure probabilities λ for PV and WT units in correspond to time in hr which is of 24 interval is shown. The dotted line represents the failure probability of PV unit whereas the bold line shows the the failure probability of WT unit. The maximum failure probability is 1 for both Wind turbine as well as PV unit.

This Figure 5 shows, the forced outage rate in Failure times/hr with respect to time in hr which is of 24 interval. The bold line shows the forced outage rate of Wind Turbine unit where as the dotted line shows the forced outage rate of

TABLE 7. Thermal-hydro-wind-solar-pumped storage generation (MW) acquired from Economic emission dispatch using NSGA-II WITH DSM.

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}
1	78.1343	47.2259	181.0381	276.6473	229.3621	369.6011	97.6335	0	-100.0000	29.6423
2	57.4306	86.9970	121.1559	217.8833	204.7569	443.2759	76.9992	0	-100.0000	28.4988
3	111.7246	136.5404	134.8251	233.7300	233.3942	328.1306	100.0000	0	-100.0000	28.3449
4	123.1028	167.3434	180.0515	226.2897	218.5660	331.9057	88.9632	0	-100.0000	31.2223
5	101.6741	134.4842	229.1785	216.5330	200.5325	366.1933	100.0000	3.3132	-100.0000	31.9088
6	65.6838	93.1523	208.9693	98.1519	208.0866	435.8469	100.0000	18.0223	-100.0000	27.9131
7	67.2939	159.5045	121.5388	156.4660	216.2190	409.3550	100.0000	47.5278	-100.0000	27.9050
8	101.6530	117.9388	64.3443	210.5606	197.4917	454.6912	70.0147	62.4254	0	29.1197
9	118.5563	144.1114	121.1776	181.0794	207.9762	426.7387	79.3498	75.5074	66.2572	30.7540
10	80.0251	152.0822	184.8660	241.1226	199.1537	379.4473	47.1486	86.8020	40.9600	31.6075
11	62.1979	112.6162	225.9512	136.7349	230.8048	460.0750	31.6804	109.1313	64.4040	33.5957
12	121.2151	162.4256	149.4579	208.3145	210.8440	428.4900	0	103.6485	100.0000	34.3956
13	93.8435	169.8774	84.7375	256.3291	246.9145	387.2056	68.1335	85.5800	49.6382	32.2593
14	115.2713	148.6534	164.0044	292.3867	230.3870	350.8171	28.5832	70.2193	83.8674	34.1898
15	68.9390	126.9513	246.7652	213.9681	214.7032	335.6808	58.4207	59.4337	55.1392	30.0012
16	92.5907	170.5587	206.3971	298.5431	225.7320	397.9448	0	0	42.7188	39.4852
17	107.3778	136.1259	174.7762	292.9923	207.5294	381.6527	0	0	84.0467	34.5010
18	87.3706	140.0044	243.1152	291.5153	250.0000	401.1570	0	18.4175	59.4380	41.0180
19	120.0471	127.3205	227.9660	233.8047	215.4334	327.4947	80.4587	0.3789	68.5728	31.4768
20	108.5377	168.1714	145.5696	284.4257	216.6297	408.4166	54.7609	0	0	36.5116
21	94.2846	161.4086	159.3090	281.1084	230.2315	391.9220	27.5067	0	-100.0000	35.7708
22	82.5372	89.8630	131.3769	276.9579	231.1222	426.5295	54.5251	0	-100.0000	32.9118
23	73.9636	149.3108	126.1462	196.1277	237.2366	455.2902	45.4434	0	-100.0000	33.5185
24	85.7614	89.6885	192.4787	158.4917	207.5245	432.1511	63.6480	0	-100.0000	29.7439

TABLE 8. Thermal-hydro-wind-solar-pumped storage generation (MW) acquired from EED using SPEA 2 WITH DSM.

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}
1	78.6816	39.7901	179.1488	283.1842	228.1045	373.2024	97.6335	0	-100.0000	29.7451
2	62.5186	84.7083	118.3975	222.9891	199.6607	443.1553	76.9992	0	-100.0000	28.4287
3	112.6283	136.5555	140.3287	233.0777	230.6158	325.0570	100.0000	0	-100.0000	28.2630
4	122.8886	167.6275	172.8764	225.2533	222.5722	336.1433	88.9632	0	-100.0000	31.3245
5	106.5559	135.0428	222.5048	218.3429	198.6494	367.4514	100.0000	3.3132	-100.0000	31.8604
6	67.9158	90.7362	208.5313	102.1845	207.6364	432.7798	100.0000	18.0223	-100.0000	27.8063
7	67.6017	157.9772	120.7734	161.7432	218.4625	403.7057	100.0000	47.5278	-100.0000	27.7915
8	100.0805	113.6535	66.1721	219.0484	199.6589	447.9385	70.0147	62.4254	0	28.9920
9	120.9839	144.4526	121.4263	171.9557	213.2965	426.1093	79.3498	75.5074	67.6521	30.7336
10	82.5776	151.6090	187.2808	242.0349	204.4691	372.1398	47.1486	86.8020	37.6007	31.6625
11	59.9836	113.5543	223.5015	135.9053	231.8038	463.4196	31.6804	109.1313	64.6985	33.6783
12	119.3558	161.8868	148.5274	221.1208	202.2186	429.5627	0	103.6485	98.1087	34.4293
13	90.0919	172.2996	85.0615	256.7916	250.0000	387.6424	68.1335	85.5800	46.8580	32.4585
14	114.3252	150.8154	158.2415	285.1832	233.2742	360.6695	28.5832	70.2193	83.1005	34.4120
15	57.6919	128.7433	245.1547	232.3526	217.4204	330.5890	58.4207	59.4337	50.4259	30.2322
16	96.9908	174.9102	206.4434	287.1862	222.3025	398.2496	0	0	48.0476	39.1303
17	108.0672	135.4168	172.8165	299.9008	202.8870	381.7849	0	0	83.6220	34.4952
18	96.1508	139.9839	242.0475	290.4064	250.0000	392.4584	0	18.4175	61.2174	40.6819
19	120.0656	127.5955	226.4100	222.4274	213.8404	336.4292	80.4587	0.3789	73.7549	31.3606
20	108.1040	166.2717	146.1687	286.5443	211.9467	412.7656	54.7609	0	0	36.5619
21	92.2738	156.7802	162.3355	289.0882	227.3339	390.4235	27.5067	0	-100.0000	35.7418
22	84.2569	92.5592	127.0793	277.8975	232.7045	423.8373	54.5251	0	-100.0000	32.8598
23	69.1262	151.0513	124.2038	193.0939	239.8890	460.9067	45.4434	0	-100.0000	33.7143
24	84.7844	95.1462	201.8729	138.6632	211.5983	434.2115	63.6480	0	-100.0000	29.9245

PV unit. PV unit has high failure rates at 16th and 17th hour and WT unit has high failure rates at 16th, 17th and 18th hour. The PV unit as well as the WT unit is having maximum failure times/hr around 0.6.

The cost and emission convergence characteristics using RCGA with Demand Side Management is shown in the Fig. 6. The number of iteration taken is 300. It is observed that the cost as well as emission curve converge around 200 iterations.

This Fig. 7 shows the distribution of 20 non-dominated solutions obtained from the economic emission dispatch with DSM in the final iteration by using NSGA-II and

TABLE 9. Thermal-hydro-wind-solar-pumped storage generation in MW obtained from economic dispatch without DSM.

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}	
1	104.8860	82.3450	110.5133	246.3843	249.9601	394.8624	91.2524	0	-100.0000	30.2035
2	79.0433	54.7539	109.4401	245.8789	197.8284	441.7667	79.5824	0	-100.0000	28.2937
3	123.6493	56.1803	114.1364	129.2027	233.8241	365.9466	100.0000	0	-100.0000	22.9394
4	123.4340	55.7899	52.0498	175.7862	218.5274	485.6960	67.2711	0	-100.0000	28.5544
5	63.4363	59.4656	52.1553	291.7431	217.1031	407.9806	100.0000	4.7634	-100.0000	26.6474
6	101.2665	107.0061	111.9228	246.3529	223.9009	319.9430	100.0000	15.0509	-100.0000	25.4431
7	82.8361	107.9762	116.3243	246.3913	198.2091	378.9307	100.0000	46.3754	-100.0000	27.0431
8	101.0193	128.6467	61.2319	285.6156	198.8495	339.4369	91.2938	69.7763	0	25.8700
9	124.7200	170.8105	148.3925	294.3067	206.8680	341.1536	59.1745	75.6851	1.9482	33.0591
10	103.7904	107.8954	154.3692	246.4912	233.4601	363.6014	36.8428	86.4524	77.4258	30.3287
11	103.7217	133.8293	239.1126	246.3270	236.8361	326.2626	24.8417	108.0612	14.3540	33.3462
12	61.6070	134.6758	230.9934	276.9098	208.0151	377.8082	0	104.1771	90.1658	34.3522
13	61.6454	154.5201	179.2485	246.2625	209.3230	396.8207	11.5108	93.4674	89.8378	32.6362
14	82.7482	160.6274	150.6440	207.1018	235.8374	426.0415	54.8455	66.2272	99.9035	33.9765
15	103.0310	134.4231	249.5916	289.2654	205.9804	394.3691	57.7911	64.7418	39.3393	38.5328
16	119.3293	157.0577	249.0833	285.6149	240.8650	444.8821	0	0	99.0621	45.8944
17	124.6999	160.9031	249.2942	285.6270	218.8758	470.5187	0	0	36.9838	46.9025
18	102.9829	164.9217	249.3087	285.6201	204.7809	362.4634	0	17.7783	99.7459	37.6019
19	61.8057	133.0575	179.6428	246.3478	221.7988	471.8977	25.0497	1.0293	66.7315	37.3608
20	103.7716	92.7926	214.5569	219.1353	211.6365	488.3324	58.0273	0	0	38.2526
21	82.5141	118.2169	249.9452	288.7633	241.5026	345.0758	19.7817	0	-100.0000	35.7996
22	103.7185	136.2230	151.1315	247.2410	231.0243	361.0742	60.7236	0	-100.0000	31.1361
23	103.6964	159.0111	168.3255	147.6722	204.1214	442.1524	57.4022	0	-100.0000	32.3812
24	53.2789	134.4075	217.6102	167.8181	221.3598	371.3682	63.1253	0	-100.0000	28.9680

TABLE 10. Thermal-hydro-wind-solar-pumped storage generation in MW obtained from emission dispatch without DSM.

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}	
1	117.5390	123.4483	107.6890	201.1245	218.6154	420.5680	91.2524	0	-100.0000	30.2366
2	122.8799	63.4000	111.3402	189.1334	199.3955	442.3334	79.5824	0	-100.0000	28.0648
3	90.6699	80.8849	119.2628	165.8308	211.3350	354.5182	100.0000	0	-100.0000	22.5016
4	110.6315	70.8922	81.3436	182.7034	199.9747	465.0544	67.2711	0	-100.0000	27.8709
5	80.9385	92.6979	102.0893	189.4985	214.5962	411.6067	100.0000	4.7634	-100.0000	26.1905
6	96.0883	120.5814	129.1187	194.6017	239.3760	330.9215	100.0000	15.0509	-100.0000	25.7385
7	93.7851	129.2925	129.3450	213.9966	218.8879	344.8500	100.0000	46.3754	-100.0000	26.5325
8	125.0000	141.7350	93.0398	224.6183	212.9014	316.9560	91.2938	69.7763	0	25.3206
9	122.7853	162.7478	156.5839	235.7519	222.8030	361.0392	59.1745	75.6851	25.7825	32.3532
10	124.7180	108.7749	136.4992	236.1609	239.1181	369.6534	36.8428	86.4524	72.3908	30.6105
11	124.8165	140.7365	197.3018	236.8200	226.1856	355.4622	24.8417	108.0612	19.0029	33.2284
12	106.2707	150.1617	196.3953	239.5174	215.6606	380.4415	0	104.1771	91.3455	33.9698
13	102.6675	157.7839	193.1434	213.2597	204.7833	394.9608	11.5108	93.4674	71.6005	33.1773
14	105.6783	168.7428	128.7179	241.4989	227.0554	402.0573	54.8455	66.2272	88.9418	33.7651
15	123.8544	174.5649	221.0420	246.3044	195.2586	415.0625	57.7911	64.7418	39.9639	38.5836
16	123.9465	174.6737	234.2807	265.4243	239.2032	463.7146	0	0	95.2063	46.4493
17	125.0000	166.5045	224.1884	256.4784	232.1079	492.9131	0	0	49.6130	46.8053
18	122.8593	167.9159	230.0380	244.4635	213.6652	392.4322	0	17.7783	98.9466	38.0990
19	89.2551	135.7455	167.6736	228.7506	220.0781	477.9147	25.0497	1.0293	62.0067	37.5033
20	101.7490	119.0003	204.8892	220.4345	213.6596	470.0102	58.0273	0	0	37.7701
21	110.8851	144.9325	217.5370	231.9029	247.1776	373.7616	19.7817	0	-100.0000	35.9784
22	117.4005	149.1395	162.5436	236.0096	235.6116	329.1592	60.7236	0	-100.0000	30.5876
23	92.4156	150.3413	163.8772	186.7414	213.8843	417.1809	57.4022	0	-100.0000	31.8429
24	82.3571	122.5374	203.5322	212.3231	209.4216	334.5920	63.1253	0	-100.0000	27.8887

SPEA 2. Red dot represents the distribution with SPEA 2 and the blue dot shows distribution with NSGA-II. It is observed that NSGA-II provides better results compared to SPEA-2.

The cost and emission convergence characteristics using RCGA without Demand Side Management is shown in Fig. 8. The number of iteration is taken as 300. It is observed that the cost curve converge near about

TABLE 11. Thermal-hydro-wind-solar-pumped storage generation (MW) acquired from economic emission dispatch without DSM using NSGA-II

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}	
1	116.6694	104.7758	125.2403	220.2357	236.3512	385.2103	91.2524	0	-100.0000	29.7351
2	99.1705	33.5046	119.0789	241.7358	211.8096	423.1284	79.5824	0	-100.0000	28.0102
3	110.0291	59.5711	108.9736	176.3241	211.8349	355.7691	100.0000	0	-100.0000	22.5019
4	108.4918	43.8769	55.1371	202.0860	207.7284	494.1476	67.2711	0	-100.0000	28.7389
5	81.4686	73.1945	67.6251	233.4446	216.5353	419.4461	100.0000	4.7634	-100.0000	26.4776
6	108.3883	112.7671	124.3798	205.6543	236.1723	323.1205	100.0000	15.0509	-100.0000	25.5332
7	98.2883	115.9476	110.7577	218.1887	226.0083	361.3045	100.0000	46.3754	-100.0000	26.8705
8	112.2319	141.5923	97.4019	212.5241	189.7971	361.2573	91.2938	69.7763	0	25.8747
9	125.0000	174.3040	155.3807	243.5012	241.6039	334.1629	59.1745	75.6851	13.8576	32.6699
10	104.8553	117.6646	152.0590	223.6233	232.5278	386.1166	36.8428	86.4524	70.8413	30.9831
11	102.2653	128.8168	225.3716	254.8902	232.5700	349.4898	24.8417	108.0612	7.6568	33.9634
12	72.8003	142.4879	218.6762	270.3258	201.6865	392.1286	0	104.1771	82.5090	34.7914
13	78.4064	157.5328	179.4773	241.3525	200.0754	390.8527	11.5108	93.4674	89.6444	32.3197
14	88.7300	167.9848	177.8384	229.6208	215.8199	386.3069	54.8455	66.2272	95.7810	33.1545
15	113.8322	148.5408	247.7877	240.2448	214.7758	410.4231	57.7911	64.7418	40.6378	38.7751
16	113.3454	175.0000	246.2293	287.9583	241.5532	436.4239	0	0	95.4391	45.9492
17	120.7469	164.7286	217.5094	272.1711	224.9330	498.9004	0	0	47.9883	46.9777
18	125.0000	166.0207	250.0000	267.2847	204.6250	357.5588	0	17.7783	99.1260	37.3935
19	80.9681	143.8243	189.2019	217.5186	212.9114	464.5541	25.0497	1.0293	71.6941	36.7515
20	121.8386	111.5758	211.2432	187.2215	212.9581	485.2524	58.0273	0	0	38.1169
21	88.1746	140.6729	229.9969	265.5057	244.7596	356.9574	19.7817	0	-100.0000	35.8488
22	96.8533	148.6694	187.6376	193.1620	245.8279	358.5024	60.7236	0	-100.0000	31.3762
23	110.3792	165.1571	169.5521	150.0815	198.1119	431.3815	57.4022	0	-100.0000	32.0655
24	60.5989	128.8608	191.1872	219.0909	208.6299	356.8678	63.1253	0	-100.0000	28.3608

TABLE 12. Thermal-hydro-wind-solar-pumped storage generation (MW) acquired from EED WITHOUT DSM using SPEA 2.

Hour	P_{s1}	P_{s2}	P_{s3}	P_{s4}	P_{h1}	P_{h2}	P_w	P_{PV}	P_{gh}	P_{loss}	
1	120.6107	92.5889	114.0120	247.7675	235.7944	377.6122	91.2524	0	-100.0000	29.6381
2	84.8616	59.9547	115.1998	214.0597	207.3436	447.3948	79.5824	0	-100.0000	28.3966
3	120.5938	75.0535	112.0881	149.4976	216.8572	348.2961	100.0000	0	-100.0000	22.3863
4	116.1474	82.9365	52.6764	167.7706	211.0591	480.4823	67.2711	0	-100.0000	28.3434
5	92.1759	55.3891	79.9278	227.7084	228.3551	408.0171	100.0000	4.7634	-100.0000	26.3368
6	114.8918	120.6765	104.9533	232.1981	218.0910	319.4196	100.0000	15.0509	-100.0000	25.2812
7	109.4462	131.4982	107.9245	182.4053	224.9835	374.4161	100.0000	46.3754	-100.0000	27.0492
8	84.3812	135.7796	80.3598	240.1798	213.3755	361.1095	91.2938	69.7763	0	26.2555
9	123.4431	166.5371	171.7673	257.4404	213.7140	341.0684	59.1745	75.6851	13.6808	32.5107
10	101.7340	106.5669	161.8395	222.7311	236.2572	376.5273	36.8428	86.4524	81.4568	30.4080
11	105.5220	161.8792	231.3167	233.7623	227.3318	341.4072	24.8417	108.0612	0	34.1221
12	84.6434	138.5743	220.8758	246.7341	193.6482	400.0088	0	104.1771	95.4904	34.1521
13	78.6706	167.8187	170.5286	220.4150	221.1259	399.4101	11.5108	93.4674	80.1858	33.1329
14	85.8698	168.4449	149.4878	239.0740	220.4131	406.1199	54.8455	66.2272	93.2176	33.6998
15	88.3236	154.3876	212.9095	276.6095	219.7705	401.7085	57.7911	64.7418	61.4046	37.6467
16	121.9457	172.5598	238.1607	279.8525	233.5270	449.7677	0	0	100.0000	45.8134
17	124.1243	174.3450	232.4712	282.7843	216.1400	486.0692	0	0	31.5856	47.5196
18	117.3721	174.8008	241.3024	287.9128	213.9163	346.3590	0	17.7783	88.4290	37.8707
19	70.8121	128.6862	184.4636	227.9060	223.3118	475.9422	25.0497	1.0293	70.0477	37.2486
20	107.2464	122.0680	213.0403	210.4939	200.0352	476.9115	58.0273	0	0	37.8226
21	84.8858	159.6512	246.7208	226.1762	250.0000	358.8240	19.7817	0	-100.0000	36.0397
22	109.5762	159.7544	158.2676	215.1809	236.1486	351.3469	60.7236	0	-100.0000	30.9982
23	94.5063	164.0937	165.6104	177.6447	203.3885	419.1827	57.4022	0	-100.0000	31.8285
24	48.0465	131.3383	202.7782	204.4329	206.7253	372.3102	63.1253	0	-100.0000	28.7567

250 iterations whereas the emission curve converge near to 100 iterations.

Fig. 9 shows the distribution of 20 non-dominated solutions obtained from the economic emission dispatch without DSM in the final iteration by using NSGA-II and SPEA2. Red dot represents the distribution with SPEA2 and the blue dot shows distribution with NSGA-II. It is observed that NSGA-II provides better results compared to SPEA-2.

TABLE 13. Assessments of concert.

Analysis			Cost ($)	Emission (lb)	CPU time (s)
With DSM	Economic dispatch		841488	14391	20.43
	Emission dispatch		876614	13140	19.96
	Economic emission dispatch	NSGA-II	859369	13713	7.27
		SPEA 2	859387	13720	9.45
Without DSM	Economic dispatch		845868	14286	18.58
	Emission dispatch		872138	13378	18.61
	Economic emission dispatch	NSGA-II	865542	13787	6.94
		SPEA 2	865796	13789	8.67

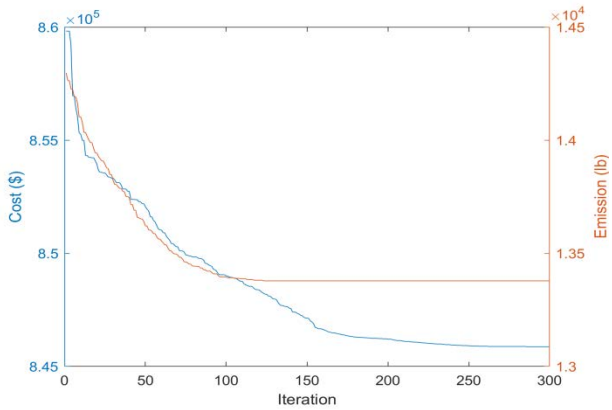

FIGURE 8. Cost emission convergence characteristics without DSM.

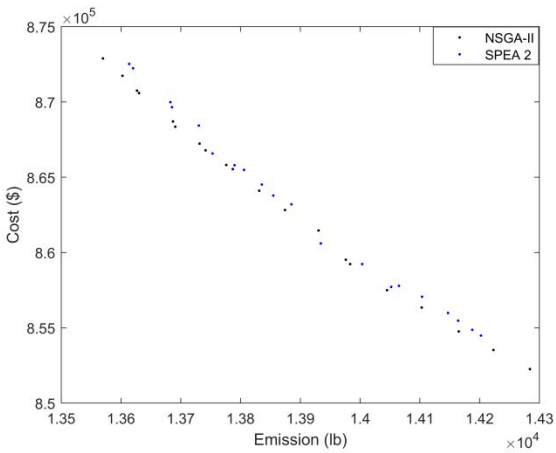

FIGURE 9. Pareto-optimal front of the final iteration without DSM.

Power generation in MW obtained from economic dispatch with DSM using RCGA of four thermal, two fixed head hydro plants, one wind turbine, one solar plant and one pumped storage plant at each interval or hour within a scheduling period of 1 day is shown in Table 5. The power loss in MW at each hour for each unit is also shown. The power loss is maximum at 18th hour. At some hour one of the PV unit or the Wind Turbine or the Pumped-Hydro-Storage doesn't generate power. At some hour also two units doesn't generate power simultaneously.

Power generation in MW obtained from emission dispatch with DSM using RCGA of four thermal plant, two fixed head hydro plants, one wind turbine, one solar and one pumped storage plant at each interval or hour within a scheduling period of 1 day is shown in Table 6. The power loss in MW at each hour for each unit is also shown. The power loss is maximum at 17th hour. At some hour one of the PV unit or the Wind Turbine or the Pumped-Hydro-Storage doesn't generate power at some hour also two units doesn't generate power simultaneously.

Power generation in MW obtained from economic emission dispatch with DSM using NSGA-11 of four thermal plant, two fixed head hydro plants, one wind turbine, one solar and one pumped storage plant at each internal or hour within a scheduling period of 1 day is shown in Table 7. The power loss in MW at each hour for each unit is also shown. The power loss in MW at each hour for each unit is given. The power loss is maximum at 18th hour.

Power generation in MW obtained from economic emission dispatch with DSM using SPEA-2 of four thermal plant, two fixed head hydro plants, one wind turbine, one solar and one pumped storage plant at each internal or hour within a scheduling period of 1 day is shown in Table 8. The power loss in MW at each hour for each unit is also shown. The power loss in MW at each hour for each unit is also shown. It is maximum at 18th hour.

Power generation in MW obtained from economic dispatch without DSM using RCGA of four thermal, two fixed head hydro plants, one wind turbine, one solar plant and one pumped storage plant at each internal or hour within a scheduling period of 1 day is shown in Table 9. The power loss in MW at each hour for each unit is also shown. It is maximum at 17th hour.

Power generation in MW obtained from emission dispatch without DSM using RCGA of four thermal, two fixed head hydro plants, one wind turbine, one solar plant and one pumped storage plant at each internal or hour within a scheduling period of 1 day having 24 hour is shown

in table 10. The power loss in MW at each hour for each unit is also shown which is maximum at 16th and 17th hours.

Power generation in MW obtained from economic emission dispatch without DSM using NSGA-II of four thermal plant, two fixed head hydro plants, one wind turbine, one solar and one pumped storage plant at each internal or hour within a scheduling period of 1 day is shown in Table 11. The power loss in MW at each hour for each unit is also shown. It is maximum at 17th hour.

Power generation in MW obtained from economic emission dispatch without DSM using SPEA 2 of four thermal plant, two fixed head hydro plants, one wind turbine, one solar and one pumped storage plant at each internal or hour within a scheduling period of 1 day having 24 interval is shown in Table 12. The power loss in MW at each hour for each unit is also shown. It is maximum at 17th hour.

Table 13 shows the Cost ($), Emission (lb) and CPU time (s) for Economic dispatch, Emission dispatch and Economic Emission dispatch with and without DSM using NSGA-II and SPEA 2 algorithm. After analysis, It is analysed considering Economic emission dispatch that the cost ($) and Emission (lb) with DSM is less as comparison to without DSM. The CPU time is little higher considering DSM in comparison to without DSM. This Economic Emission Dispatch using NSGA-II provides less cost, less emission as compared to SPEA 2 but the CPU time (s) is slightly higher. So, it is proven that economic emission dispatch using NSGA-II provides better result compared to SPEA 2.

V. CONCLUSION

In this paper (NSGA-II) algorithm is implemented on a test system to solve economic emission dispatch problem for fixed head hydro-thermal system with pumped hydro energy storage and renewable energy sources while considering the outage and uncertainty with and without DSM. The test system consists of two fixed head hydro plants, four thermal plants, one wind turbine, one solar plant and one pumped storage plant. Numerical results of the test system obtained using the proposed algorithm were compared with strength pareto evolutionary algorithm 2 (SPEA 2). The percentage reduction in Cost ($), Emission (lb) is nearly 0.0021 and 0.051 respectively by using NSGA considering DSM II in comparison with SPEA 2. The percentage reduction in CPU time is nearly 23.07 with NSGA-II considering DSM in comparison with SPEA 2, whereas without considering DSM, the percentage reduction in Cost ($), Emission (lb) is nearly 0.03 and 0.0145 respectively by using NSGA-II in comparison with SPEA 2. The percentage reduction in CPU time is nearly 19.95 with NSGA-II in comparison with SPEA 2. So, it is concluded here that suggested technique NSGA II proffers a cutthroat performance.

REFERENCES

[1] J. H. Talaq, F. El-Hawary, and M. E. El-Hawary, "A summary of environmental/economic dispatch algorithms," *IEEE Trans. Power Syst.*, vol. 9, no. 3, pp. 1508–1516, Aug. 1994.

[2] A. G. Bakirtzis and E. S. Gavanidou, "Optimum operation of a small autonomous system with unconventional energy sources," *Electr. Power Syst. Res.*, vol. 23, no. 2, pp. 93–102, Mar. 1992.

[3] S. Mondal, A. Bhattacharya, and S. H. N. Dey, "Multi-objective economic emission load dispatch solution using gravitational search algorithm and considering wind power penetration," *Int. J. Electr. Power Energy Syst.*, vol. 44, no. 1, pp. 282–292, Jan. 2013.

[4] N. A. Khan, A. B. Awan, A. Mahmood, S. Razzaq, A. Zafar, and G. A. S. Sidhu, "Combined emission economic dispatch of power system including solar photo voltaic generation," *Energy Convers. Manage.*, vol. 92, pp. 82–91, Mar. 2015.

[5] H. M. Dubey, M. Pandit, and B. K. Panigrahi, "Ant lion optimization for short-term wind integrated hydrothermal power generation scheduling," *Int. J. Electr. Power Energy Syst.*, vol. 83, pp. 158–174, Dec. 2016.

[6] J. I. Pérez-Díaz and J. Jiménez, "Contribution of a pumped-storage hydropower plant to reduce the scheduling costs of an isolated power system with high wind power penetration," *Energy*, vol. 109, pp. 92–104, Aug. 2016.

[7] S. Fadıl and B. Urazel, "Solution to security-constrained non-convex pumped-storage hydraulic unit scheduling problem by modified subgradient algorithm based on feasible values and pseudo water price," *Electr. Power Compon. Syst.*, vol. 41, no. 2, pp. 111–135, Jan. 2013.

[8] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation and Control*, 2nd ed. New York, NY, USA: Wiley, 1984, ch. 7, pp. 230–239.

[9] S. K. Khandualo, A. K. Barisal, and P. K. Hota, "Scheduling of pumped storage hydrothermal system with evolutionary programming," *J. Clean Energy Technol.*, vol. 1, no. 4, pp. 308–312, 2013.

[10] M. R. Mohan, S. R. Paranjothi, and S. P. Israel, "Use of pumped-hydro as peak-load management plant in optimal scheduling of power systems," *Electr. Mach. Power Syst.* vol. 25, no. 10, pp. 1047–1061, 2007.

[11] T. Ma, H. Yang, L. Lu, and J. Peng, "Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization," *Appl. Energy*, vol. 137, no. 1, pp. 649–659, Jan. 2015.

[12] M. Simab, M. S. Javadi, and A. E. Nezhad, "Multi-objective programming of pumped-hydro-thermal scheduling problem using normal boundary intersection and VIKOR," *Energy*, vol. 143, pp. 854–866, Jan. 2018.

[13] N. Narang, J. S. Dhillon, and D. P. Kothari, "Multi-objective short-term hydrothermal generation scheduling using predator–prey optimization," *Electr. Power Compon. Syst.*, vol. 40, no. 15, pp. 1708–1730, Oct. 2012.

[14] C. Sun and S. Lu, "Short-term combined economic emission hydrothermal scheduling using improved quantum-behaved particle swarm optimization," *Expert Syst. Appl.*, vol. 37, no. 6, pp. 4232–4241, Jun. 2010.

[15] H. Zhang, D. Yue, X. Xie, C. Dou, and F. Sun, "Gradient decent based multi-objective cultural differential evolution for short-term hydrothermal optimal scheduling of economic emission with integrating wind power and photovoltaic power," *Energy*, vol. 122, pp. 748–766, Mar. 2017.

[16] J. S. Dhillon, S. C. Parti, and D. P. Kothari, "Fuzzy decision-making in stochastic multiobjective short-term hydrothermal scheduling," *IEE Proc., Gener., Transmiss. Distrib.*, vol. 149, no. 2, pp. 191–200, 2002.

[17] M. Basu, "An interactive fuzzy satisfying method based on evolutionary programming technique for multiobjective short-term hydrothermal scheduling," *Electr. Power Syst. Res.*, vol. 69, nos. 2–3, pp. 277–285, May 2004.

[18] R. S. Patwal and N. Narang, "Crisscross PSO algorithm for multi-objective generation scheduling of pumped storage hydrothermal system incorporating solar units," *Energy Convers. Manage.*, vol. 169, pp. 238–254, Aug. 2018.

[19] J. Hetzer, D. C. Yu, and K. Bhattarai, "An economic dispatch model incorporating wind power," *IEEE Trans. Energy Convers.*, vol. 23, no. 2, pp. 603–611, Jun. 2008.

[20] M. Basu, "Optimal generation scheduling of hydrothermal system with demand side management considering uncertainty and outage of renewable energy sources," *Renew. Energy*, vol. 146, pp. 530–542, Feb. 2020.

[21] M. Kaur, J. S. Dhillon, and D. P. Kothari, "Crisscross differential evolution algorithm for constrained hydrothermal scheduling," *Appl. Soft Comput. J.*, vol. 93, pp. 1–19, Aug. 2020.

[22] A. Mehdizadeh and N. Taghizadegan, "Robust optimisation approach for bidding strategy of renewable generation-based microgrid under demand side management," *IET Renew. Power Gener.*, vol. 11, no. 11, pp. 1446–1455, Sep. 2017.

[23] M. F. Zaghlool and F. C. Trutt, "Efficient methods for optimal scheduling of fixed head hydrothermal power systems," *IEEE Trans. Power Syst.*, vol. PWRS-3, no. 1, pp. 24–30, Feb. 1988.

[24] A. H. A. Rashid and K. M. Nor, "An efficient method for optimal scheduling of fixed head hydro and thermal plants," *IEEE Trans. Power Syst.*, vol. 6, no. 2, pp. 632–636, May 1991.

[25] M. Basu, "Hopfield neural networks for optimal scheduling of fixed head hydrothermal power systems," *Electr. Power Syst. Res.*, vol. 64, no. 1, pp. 11–15, Jan. 2003.

[26] M. Basu, "Artificial immune system for fixed head hydrothermal power system," *Energy*, vol. 36, no. 1, pp. 606–612, Jan. 2011.

[27] T. T. Nguyen, D. N. Vo, and A. V. Truong, "Cuckoo search algorithm for short-term hydrothermal scheduling," *Appl. Energy*, vol. 132, pp. 276–287, Nov. 2014.

[28] T. T. Nguyen and D. N. Vo, "Modified cuckoo search algorithm for multiobjective short-term hydrothermal scheduling," *Swarm Evol. Comput.*, vol. 37, pp. 73–89, Dec. 2017.

[29] M. Basu, "Optimal generation scheduling of fixed head hydrothermal system with demand-side management considering uncertainty and outage of renewable energy sources," *IET Gener., Transmiss. Distrib.*, vol. 14, no. 20, pp. 4321–4330, 2020.

[30] J. V. Seguro and T. W. Lambert, "Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis," *J. Wind Eng. Ind. Aerodyn.*, vol. 85, no. 1, pp. 75–84, Mar. 2000.

[31] R.-H. Liang and J.-H. Liao, "A fuzzy-optimization approach for generation scheduling with wind and solar energy systems," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1665–1674, Nov. 2007.

[32] S. S. Reddy, P. R. Bijwe, and A. R. Abhyankar, "Real-time economic dispatch considering renewable power generation variability and uncertainty over scheduling period," *IEEE Syst. J.*, vol. 9, no. 4, pp. 1440–1451, Dec. 2015.

[33] W. Li, *Risk Assessment Of Power Systems: Models, Methods, and Applications*. Hoboken, NJ, USA: Wiley, 2014.

[34] D. C. Walters and G. B. Sheble, "Genetic algorithm solution of economic dispatch with valve point loading," *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 1325–1332, Aug. 1993.

[35] M. R. Gent and J. W. Lamont, "Minimum-emission dispatch," *IEEE Trans. Power App. Syst.*, vol. PAS-90, no. 6, pp. 2650–2660, Nov. 1971.

[36] A. Yousefi, H. H.-C. Iu, T. Fernando, and H. Trinh, "An approach for wind power integration using demand side resources," *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 917–924, Oct. 2013.

[37] N. Srinivas and K. Deb, "Muiltiobjective optimization using nondominated sorting in genetic algorithms," *IEEE Trans. Evol. Comput.*, vol. 2, no. 3, pp. 221–248, Sep. 1994.

[38] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 182–197, Jan. 2002.

[39] E. Zitzler, M. Laumanns, and L. Thiele, "SPEA2: Improving the strength Pareto evolutionary algorithm," Swiss Federal Inst. Technol. (ETH), Zurich, Switzerland. Tech. Rep. TIK- Rep. 103, May 2001.

[40] S. S. Reddy, "Optimal scheduling of thermal-wind-solar power system with storage," *Renew. Energy*, vol. 101, pp. 1357–1368, Feb. 2017.