Restructured Hydrothermal System: Slack bus management

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Abstract: -. In order to logically represent the power system, it is necessary to develop a concept to compensate various mathematical imbalances, for which the concept of slack bus came into the picture. But when large system is considered, the overall limit of slack bus is not sufficient to compensate the imbalances. In addition to this, the practical depiction of slack bus does not hold when multiple time intervals are considered in HTS problem. In this research, the concept of slack bus is modified and improved so that it can be used for a large power system in restructured hydrothermal system. Furthermore an improved ABC algorithm, i.e. GOABC is proposed, which provides superior diversity and enhanced convergence compared to ABC algorithm.

Key-Words: - Slack Bus, Restructured Power System, Hydro-Thermal Scheduling, ABC Algorithm
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Nomenclature

Vectors,

$f_\tau(X)$ Thermal unit operational cost
R Hydro plant (unit) Set
S Thermal plant (unit) Set
O Time interim Set
X Thermal Power Generation Set
Y Hydro Power Generation Set
A Reservoir total water set of hydro units
B Reservoir water inflows set of hydro unit
F Reservoir water discharges of hydro unit
D Reservoir spillage
$PZ^{h/t}$ Hydro/Thermal Prohibited Region
n_u^α Upstream unit set of a particular Hydro Unit (h^{th}).

Scalars,

h Index for Hydro plant
w Index for Wind power plant
t Index for Thermal power plant
ξ Index for time interval
ξ_m^l Index to consider Time delay from m^{th} upstream hydro power plant to l^{th} hydro plant
X_0 Overall startup cost of thermal power plants
X_Ω Overall shutdown cost of thermal power plant
$\mu_{\beta,1\text{-}5}$ Coefficients of power generation of β^{th} thermal plant
$g_{\beta,1\text{-}5}$ Coefficients of Emission of β^{th} thermal plant
$\varepsilon_\beta^{n/f}$ Minimum time of β^{th} thermal plant
ε_β^c Minimum time for cold start of β^{th} thermal plant
$X_{\beta,\tau}^{n/f}$ β^{th} Thermal plant time period status (on or off) up to τ^{th} hour
ν_β / π_β Ramp rate limit of β^{th} thermal plant
CS_β / HS_β Hot/ Cold Startup cost
ε_β^n Initial status
T net profit
k_τ^b Power capacity as per bilateral contract
k_τ^s Bidding of Power at the spot market
q_τ^b Price decided at bilateral contract
q_τ^{sm} Energy price at Spot market
q_τ^s Price of spinning reserve at spot market.
q_τ^{ns} Price of non-spinning reserve at spot market.
$Y_\tau^{s/ns}$ Contribution of Hydro power in spinning/ non-spinning reserve.
$X_\tau^{s/ns}$ Contribution of Thermal power in spinning/ non-spinning reserve.
$S_\tau^{U/D}$, $S_\tau^{HU/HD}$, $S_\tau^{WU/WD}$ total Startup/ shut down cost
T_L Transmission Loss

Algorithm,

H Population Number
P Number of variable or dimension of the problem
u_y / l_y Upper/lower bound of the concerned variable

1 Introduction

This paper considers a hydrothermal system to be the electricity market of the future. The problem of hydrothermal scheduling (HTS) in a restructured environment is mainly apprehensive with maximizing the total profit of the generating companies (GENCOs). It is the difference between total incomes or revenue of all GENCOs after withdrawing the subsidiary cost of the manufacturing plant for the duration concerned. Additionally considering the pollution now-a-days is a huge concern in the context of power plants, emissions are also considered as secondary objective. Complications related to hydrothermal scheduling (HTS) include a number of functional and reliable constraints, including transmission and plant limits (both hydro and thermal). In transmission network flow analysis, Slack bus plays a valued part in accurately resolving complete transmission network through power flow [1]. This theory permits systematic discrepancies to be included in the network flow model. But it is not possible as slack bus is also a thermal plant and must abide by the practical rules.

Various scholars have tried to solve this problem mentioned in orthodox behavior considering restructured condition in different time frames using effective solution methods. Some scholars, considering its non-linearity and higher analytical liability, have resorted to stochastic optimization methods such as Non-linear network flow [2], DP (Dynamic Programming) [3]. But with increasing search space non-convexity, the efficacy of these methods declines due to the nature of HTS. Many choose meta-heuristic algorithms for the same purpose.

Orero et al. [4] considers various characteristics regarding Hydro network. Although thermal units remains in a very primitive considering various problems concerned. Sinha et al [5] discussed about a concept, Prohibited discharge region in his problem and its related complications. In this paper utilizes Fast Evolutionary [5] Algorithm. A similar problem is solved by Zhang et al. [6] by Small population based PSO algorithm. In this study the problem is considered in conventional and the multi-objective is not considered here. The decision variable here are set to boundary value to satisfy the constraints, which compromises with the natural heuristic behavior of the algorithm. The same problem is solved in multi-objective environment in literature [7] by Lakshminarasimman et al. Werner et al. [8] included the concept non-linear dynamic limitation in evolutionary strategy in the aspect of solution methodology. In the context of HTS problem this process increases the intricacies considerably. The same problem is solved in literature [9] considering restructured scenario.

There are various papers which solves HTS problem, which is shown in the literature by Farhat [10]. The literatures which are related with the work of this paper, are discussed further. Ahmadi et al [11] solved the Hydrothermal Scheduling problem in restructured environment using MIP formulation. Although various constraints are discussed here but linearization is adopted to fit the constraints in MIP formulation. In addition to this various transmission network modelling is not considered here. Also Kelman et al solved the mentioned problem in restructured environment but various complications are not taken into account in the mathematical formulation. Elnaz Davoodi [12] suggested a new method, Benders decomposition algorithm based on decomposition to solve the same problem. Here the problem is solved in GAMS environment.

From all these literature it is quite evident that, although the transmission network constraints are an important consideration along with the control of Slack bus management, but in reality very little effort has been made to incorporate these limitations into HTS formulation. In literature [13, 14] the transmission constraints are discussed and included up to some extent but for a practical perspective these formulation lacks. Also the consideration of Slack bus management method is completely omitted form formulation. There are time dependent constraints involved in HTS modelling such as prohibited discharge region, ramp rate limitation. The methods that usually used to incorporate transmission constraints and slack bus modeling such as, adaption of PV bus as slack bus[15], increasing the number of slack bus when required [15,16], is not appropriate in HTS framework.

From the literatures, it is evident that even though some researchers have solved HTS problem considering transmission constraints into HTS modelling but none has considered the dynamic behavior of transmission losses on slack bus and concerned inter-temporal limitations in the aspect of HTS. In author's view, such an exclusion reduces the practicality of HTS system considerably.

For these reasons, in this paper the problem related to slack bus management is encountered with a novel technique which contemplates the ramp rate and transmission constraints for the entire duration considered in view of variable load demand. These formulation proliferates the intricacies involved in the problem formulation. In order to solve such a complicated problem a novel solution method is also developed, based on Bee swarm optimization [17], which can provide sufficient convergence

exploitation/ exploration in the search space.
Seeing all that mentioned above, the primary aims of this dissertation are,
1) Proposing an innovative technique for managing slack bus to counter the intricacies regarding slack bus in HTS problem under deregulated environment.
(2) An innovative heuristic search algorithm, Generalized Opposition Based Artificial Bee Colony (GOABC) algorithm, is used for solving the HTS problem.
At last, these proposed methods are used to solve a considerably large test system to prove the efficacy of the algorithm.

2 System Modelling

The objective of Hydro-Thermal Scheduling (HTS) problem is to initially maximize the profit deducting various expenditures alongside minimization of total emission for a speculated time duration. So consequently it is a multi-objective problem. The two objectives are represented here by f_1 for profit and f_2 for emission, as shown below,

Objective Function:

$$f_1 : \max, T = \sum_{\forall \xi \in O} \begin{bmatrix} \{k_\xi^b \cdot q_\xi^b + k_\xi^s \cdot q_\xi^{sm} \\ + q_\xi^b \cdot \left(Y_\xi^s + X_\xi^{ns}\right) \\ + q_\xi^n \left(Y_\xi^{sr} + X_\xi^{sr}\right)\} \\ -\left\{ f_\xi\left(X\right) + \left(S_\xi^u + S_\xi^D\right)\right\} \end{bmatrix} \quad (1)$$

$$f_2 : \min, EMS = \sum_{\forall \xi \in o} G\left(X_\xi\right) \quad (2)$$

Such that,

$$\left(X_\xi + Y_\xi\right) \geq \left(k_\xi^b + k_\xi^s\right) + T_L \ \forall \xi \in \mathrm{O} \quad (3)$$

Where, $G\left(X_\xi\right) = \sum_{\forall \xi \in o} \sum_{t \in S} g_{t,1} + g_{t,2} X_{t,\xi} + g_{t,3} X_{t,\xi}^2$

$$f_\xi\left(X\right) = \sum_{\forall \xi \in o} \sum_{t \in S} \begin{bmatrix} \mu_{t,1} + \mu_{t,2} X_{t,\xi} + \mu_{t,3} X_{t,\xi}^2 \\ + \left|\mu_{t,4} \cdot \sin\left\{\mu_{t,5}\left(X_{t,\tau}^{\min} - X_{t,\xi}\right)\right\}\right| \end{bmatrix} \quad (4)$$

The first objective (the profit, f_1) is signifies profit whereas the second objective (emission, f_2) represents the total pollution emission. The negative term in the first equation denotes various cost such as startup/shut down and production cost etc. for the thermal units and the first term denotes total profit for the Generating companies (GENCOs).
The HTS system modelling is subject to many operational and topographical constraints which concerns the cascaded hydro network, multiple thermal plant and transmission network. Many of these constraints are non-convex non-linear in nature. In order to model individual hydro plant widely used Hill Chart [18] is adopted, validated by Conejo et al. [19]. The constraints related to cascaded hydro network are demonstrated below,

Hydro Unit Constraints:

2.1 Continuity Equation

$$A_{\alpha,\xi+1} = A_{h,\tau\xi} - D_{h,\xi} - C_{h,\xi} + B_{h,\xi} + \sum_{\forall m \in n_u^h} \left\{ F_{m,\left(\xi - \xi_m^i\right)} + D_{m,\left(\xi - \xi_m^l\right)} \right\} \quad (5)$$

$\forall h \in R ; \forall \xi \in \mathrm{O}$

2.2 Maximum and minimum water content limitation

$$F_{h,0} = F_{h,begin} ; F_{h,z} = F_{h,end} \ \forall \xi \in \mathrm{O} \quad (6)$$

2.3 Reservoir Discharge Limitation

$$\underline{F_{h,\xi}} \leq F_{h,\xi} \leq \overline{F_{h,\xi}} \ \forall h \in R ; \forall \xi \in \mathrm{O} \quad (7)$$

2.4 Reservoir Water content Limitation

$$\underline{A_{h,\xi}} \leq A_{h,\xi} \leq \overline{A_{h,\xi}} \ \forall h \in R ; \forall \xi \in \mathrm{O} \quad (8)$$

Thermal Unit Constraints:

The procedure of HTS is to first maximize generation from Hydro units as much as possible followed by thermal plants, as the production cost of hydro plant are comparatively cheaper. In order to allocate the rest of the generation among thermal plants, unit commitment (UC) [20, 21] is performed. The constraints regarding UC is discussed below.

2.5 Thermal Generation Limitation

$$\underline{X_{t,\xi}} \leq X_{t,\xi} \leq \overline{X_{t,\xi}} \quad (9)$$

$$j_{t,\xi} = 0 \, or \, 1 \quad (10)$$

$$j_{t,\xi} \underline{X_{t,\xi}} \leq j_{t,\xi} X_{t,\xi} \leq j_{t,\xi} \overline{X_{t,\xi}} \quad \forall t \in S ; \forall \xi \in \mathrm{O} \quad (11)$$

2.6 Initial Status

$$j_{t,1} = \begin{cases} 0 & if \ \varepsilon_t^n < \varepsilon_t^f \\ 1 & if \ \varepsilon_t^n < \varepsilon_t^n \end{cases} \quad (12)$$

2.7 Min On Off time constraint

$$\left\{X_{t,(\xi-1)}^{on} - \varepsilon_t^n\right\} \times \left\{ j_{t,(\xi-1)} - j_{\xi,\tau} \right\} \geq 0 \quad (13)$$

$$\left\{X_{t,(\xi-1)}^{on} - \varepsilon_t^f\right\} \times \left\{ j_{t,\xi} - j_{t,(\xi-1)} \right\} \geq 0 \quad (14)$$

$\forall t \in S ; \forall \xi \in \mathrm{O}$

2.8 Ramp Rate Limit

$$X_{t,\xi} - X_{t,\xi-1} \leq \nu_t \ \forall t \in S ; \forall \xi \in \mathrm{O} \quad (15)$$

$$X_{t,\xi-1} - X_{t,\xi} \leq \pi_t \ \forall t \in S ; \forall \xi \in \mathrm{O} \quad (16)$$

2.9 System generator and Load Balance

$$X + Y + \Phi = P_D + P_L \ \forall \xi \in \mathrm{O} \quad (17)$$

2.10 Spinning/Non- Spinning Reserve

$$X \geq Y = \left(P_D + P_L + P_R\right) - \left(Y + \Phi\right) \quad (19)$$

2.11 Hot and Cold Start

$$X_{t,\xi}^{D} = CS_t \times \left\{ j_{t,\xi} - j_{t,\xi-1} \right\} \times \left\{ j_{t,\xi} \right\} \quad if \; \left(X_{t,\xi}^{f} - \varepsilon_t^{c} \right) \geq 0 \quad (20)$$

$$X_{t,\xi}^{D} = HS_t \times \left\{ j_{t,\xi} - j_{t,\xi-1} \right\} \times \left\{ j_{t,\xi} \right\} \quad if \; \left(X_{t,\xi}^{f} - \varepsilon_t^{c} \right) < 0 \quad (21)$$

$$X_D = \sum_{\forall t \in S} \sum_{\forall \xi \in \Omega} X_{t,\xi}^{D} \quad (22)$$

Various transmission line constraints like

1. Limit of bus voltage at each bus
2. Active and Reactive power balance after injection
3. Line power flow limit
4. Tap setting of transformer etc. are included.

3 Slack Bus Management

Slack bus is more of a mathematical concept rather than a practical aspect. But as it is used to provide the mathematical imbalances such as transmission loss in to the system, it has practical implication. It is also necessary to keep the generation and load plus loss equality. It is for this reason, the plant that is most reliable and has ample reserve considered to be the slack bus. The hydro plants although extremely fast reacting to system imbalances are not suitable for this purpose because of topographical and geographical limitations. So in general, thermal power plant which has more flexibility after satisfying the concerned limitation (as shown in Eq. 11-23), serve this purpose. Satisfying all these limitations and increasing the flexibility of a thermal plant optimally is a great challenge. One other problem related to the mentioned topic is the maximum limit of thermal plant as a slack bus. For smaller system the limit of slack bus is sufficient however for a big system the limit of slack bus is not sufficient to incorporate the loss of entire system. Satisfying the ramp rate limitation (Eq. 15-16) also pose difficulty.

In the following section upper mentioned problems are tackled.

1. Instead of lumping the entire loss it is found that distributing the loss into all the available generated bus based on their rating provide much more feasibility into the system. For including this mentioned concept into the system modelling the loss (P_L^*) is predicted which modifies the demand (P_D^*) using the following equation.

$$P_D^* = P_D + P_L^* \;\; \forall \tau \in \Omega$$

2. Then demand P_D^* will be distributed among all the generators using unit commitment, which satisfies related thermal plant limitations. In this method the slack bus will not be allocated as it is preserved for imbalances. This condition is valid for large system where there is no room for slack bus after imbalance. But for smaller system the slack bus can be allotted.
3. At last the load flow will be performed to find out the generation of slack bus.

These method will satisfy the load and generation balance but for the ramp rate limitation to be satisfied the generation of slack bus generator will be increased based on ramp rate.

In this method although individually the GENCO concerning slack bus may face deficit up to some extent, but overall profit would gain.

4 Solution Procedure

Here opposition based ABC algorithm is used to solve the problem. Normal ABC algorithm although capable but for the proposed problem and concerned enhanced complexity the required exploitation and exploration capability is not bounteous.

Initial population based on the principle of opposition:

In the following subdivision theory regarding opposition is described. The theory of opposition is based on the principal that the population is initially created heuristically in the space but it is also possible to have better solution in the opposite side [14] as well so the after creating the initial population, it is simply reversed so as to increase the volatility of algorithm search process more capable. The opposition based population is created by Eq. 23 and 24.

$$a_{xy} = l_y + rand \times \left(u_y - l_y\right) \;\; \forall x \in H \;\; \forall y \in P \quad (23)$$

$$\hat{x}_{xy} = u_y + l_y - a_{xy} \quad (24)$$

Followed by, based on the principal of ABC algorithm the populations (the first (initial) and second (opposite)) are modified using fitness value which can be found using the following section. The ABC Algorithm is, based on population, stochastic and meta-heuristic in nature utilizes the "foraging behavior of honey bee swarms" [17] for searching out the best individual. The steps regarding ABC algorithm is discussed below.

1. *Initialization:* Discussed under in Eq 23.
2. *Employed Bee:* These bees are used to improve the initial position found in initialization. It pursuits the better position in the vicinity or the neighborhood of the position of initial position and modify the initial population (u_{xy}).

$$u_{xy} = a_{xy} + \theta_{xy} \times \left(a_{xy} - a_{ky}\right) \; \forall x \in H \;\; \forall y \in P \quad (25)$$

Here, x and k is stochastically selected solution from

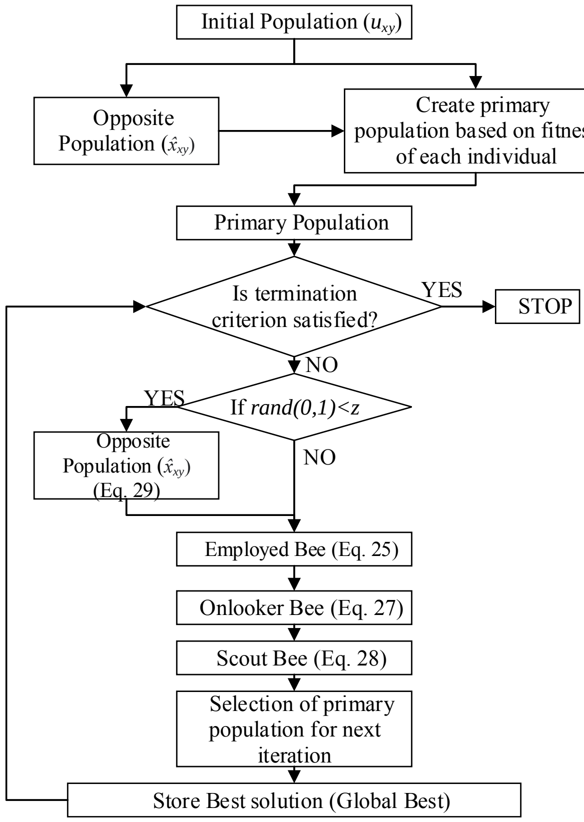

Fig. 1 Flowchart for GOABC algorithm in single environment

initial population and $\theta_{xy}\left(\in|0\quad 1|\right)$ represents randomly generated number using normal distribution. Next the concerned fitness, $L\left(u_{xy}\right)$ value will be calculated using Eq. 26.

$$L\left(u_{xy}\right)=1\Big/\left\{1+I\left(u_{xy}\right)\right\} \qquad (26)$$

Where, $I\left(u_{xy}\right)$ represents concerned objective (Profit or Emission in the context of HTS problem) function.

3. Onlooker Bee: The Onlooker bees are used for searching the neighborhood vicinity of the point already selected by employed bee by stochastic value *(k_m)* using,

$$K_x=L\left(u_{xy}\right)\Big/\sum_{x=1}^{H}L\left(u_{xy}\right) \quad \forall x\in H \ \ \forall y\in P \qquad (27)$$

Using Eq. 27 the K_x can be calculated easily and based on a random number the onlooker bee can be activated to improve the exploitation capability.

4. *Scout Bee:* In normal circumstances it is normal for some bees to be incapable to improve its fitness after a certain number of iteration which reduces the effectiveness of the capability of that bee. In order to not waste the capability of that bee that bee is converted into a scout which randomly search beyond the vicinity of population. In order to mathematically model this a new variable is added '*trial*' which signifies the number of iteration a bee can become idle before becoming a scout bee. The exploration of scout bee is done by (29). Scout bee are defined by s_{xy} defined by, x̂

$$s_{xy}=a_{xy}+\theta_{xy}\times\left(a_{xy}-a_{ky}\right) \ \forall x\in H \ \ \forall y\in P \qquad (28)$$

In this basic algorithm structure the opposition is incorporated firstly in the initial stage in the initial population and secondly in multiple iteration number based on the performance. For this reason the "Jumping Rate" (z) is considered.

$$a_{xy}^{o+1}=\hat{x}_{xy} \quad iff \ \ rand^{o}\geq z^{o} \qquad (29)$$

Where o is the iteration counter, $\hat{x}_{xy}$ is the opposition based population and a_{xy}^{o+1} is the initial population at $\left(o+1\right)^{st}$ iteration. In Fig. 1 the detailed flowchart for GOABC algorithm is shown.

Multi-objective optimization: A typical multi-objective problem can be stated as,

$$Minimize, G_n\left(A\right) \quad k=1,2,...K;$$

$$Subject\ \ to \ \begin{cases} P_p\left(A\right)=0 & p=1,...X \\ Q_q\left(A\right)\leq 0 & q=1,...Y \end{cases} \qquad (30)$$

$G_k(A)$ represents k^{th} objective function among K number of objectives. For best compromise solution firstly the set of non-dominated solutions from all should be established. The Pareto optimal front satisfies the following equation,

$$\forall x\in\{\ 1,2,\cdot\cdot,K\ \}:G_x\left(P\right)\leq G_x\left(Q\right)\&$$

$$\exists y\in\{\ 1,2,\cdot\cdot,K\ \}:G_y\left(P\right)\leq G_y\left(Q\right) \qquad (31)$$

The solutions, P that contents with Eq. 31, can be considered as non-dominated over the solutions Q followed by building the Pareto front which only concerns P. Based on the pareto front all the non-dominated solution will be used to find r_n^j and y^j using Eq. 32 and 33. The solution that will provide

Table 1: Algorithm and deregulation data for solving Test System

Contract at bilateral market=1000 MWH
Contract price at bilateral market=40 $/MWh
Maximum iteration number=2500
"limit"=50
'z'=0.35
Hive size=250/2=125

Table 2: Case I: Optimal Solution

Algorithm	Profit in $	Emission in lb
GOABC	5712345.31 ($)	95192.23 (lbs)
MIP [11]	5553834.30 ($)	162820.22 (lbs)

Table 3: Case II: Optimal Solution

Algorithm	Profit in $	Emission in lb
GOABC	5306068.96	137430.11
ABC	5136089.35	141578.43

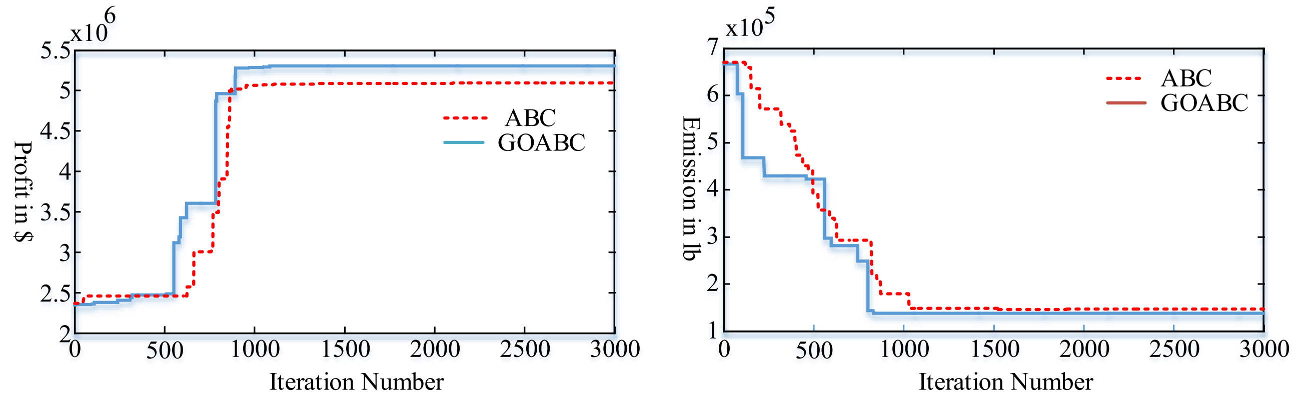

Fig. 2 Case II: Convergence characteristics (Profit and Emission)

the minimum y^j will be considered the best compromising solution.

$$r_n^j = \begin{cases} 1 & for \;\; s_n^j \le s_n^{\min} \\ \dfrac{s_n^{\max} - s_n^j}{s_n^{\max} - s_n^{\min}} & for \;\; s_n^{\min} < s_n^j < s_n^{\max} \\ 0 & for \;\; s_n^j \le s_n^{\max} \end{cases}$$

$$\forall j \in 1 \cdots M; \;\; \forall n \in 1 \cdots k \qquad (32)$$

M signifies number of solution in the Pareto front and $s_n^{\min}$ and $s_n^{\max}$ is the concerned maximum and minimum value on n^{th} solution.

$$y^j = \sum_{n=1}^{k} \sqrt{\left(r_n^j\right)} \Bigg/ \sum_{j=1}^{M}\sum_{n=1}^{k} \sqrt{\left(r_n^j\right)} \qquad (33)$$

4 Numerical Result

In order to verify the capability of the proposed model and mentioned algorithm IEEE 118 bus system is considered. The model comprises almost all the practical aspect of a real network such as irrigation. The 54 thermal plants including the transmission network constraints [22] and 8 cascaded hydro reservoirs [18] poses sufficient complexity in the multi-dimensional search space. The complete problem is solved in a day ahead electricity price market with 24 hourly discretized period.

The platform used to solve the problem is MATLAB 8.1 and solved using Lenevo G80, 2.8GHz i5 processor.

The proposed model is executed firstly without the slack bus management followed by inclusion of the mentioned method to understand the effectiveness of the method. In both scenarios the problem is solved in multi-objective environment.

Case I: After solving the problem in the mentioned

Table 4: Power Distribution among Hydro Plant and Thermal Power Plants for Case II

hour	Hydro Power	Thermal Power without slack bus	Total Gen without slack bus	Load	Transmission Loss	Slack bus Generation	Spinning reserve	Non-spinning reserve
1	1184.416	3370.683	4555.099	4200.000	250.099	490.199	340.101	210.000
2	941.866	3329.913	4271.779	3960.000	212.779	530.199	417.420	198.000
3	1779.733	2185.756	3965.489	3480.000	398.489	570.199	271.711	174.000
4	2109.672	959.389	3069.061	2400.000	609.061	610.199	794.811	120.000
5	1435.583	1906.609	3342.192	3000.000	267.192	650.199	483.007	150.000
6	815.028	3029.231	3844.259	3600.000	154.259	690.199	635.940	180.000
7	1216.480	3370.372	4586.852	4200.000	281.852	730.199	548.347	210.000
8	1306.577	3866.112	5172.690	4680.000	375.690	770.199	494.510	234.000
9	1434.732	4231.510	5666.241	4920.000	623.241	810.199	286.958	246.000
10	632.232	5163.085	5795.317	5280.000	383.317	850.199	566.882	264.000
11	1331.755	4918.277	6250.031	5340.000	776.531	890.199	213.668	267.000
12	1466.506	4603.693	6070.199	5040.000	904.199	930.199	126.000	252.000
13	710.942	4760.971	5471.913	4800.000	551.913	911.333	459.421	240.000
14	1426.124	4176.280	5602.404	4560.000	928.404	951.333	122.929	228.000
15	480.828	5401.255	5882.083	5280.000	470.083	991.333	621.250	264.000
16	1539.733	4991.600	6531.333	5400.000	996.333	1031.333	135.000	270.000
17	303.054	5311.746	5614.800	5100.000	387.300	991.333	704.033	255.000
18	92.950	5644.685	5737.635	5340.000	264.135	951.333	787.198	267.000
19	388.318	5604.286	5992.603	5640.000	211.603	911.333	799.730	282.000
20	100.204	6087.521	6187.725	5880.000	160.725	871.333	810.608	294.000
21	119.382	6223.341	6342.723	6000.000	192.723	831.333	738.610	300.000
22	108.151	5618.341	5726.493	5400.000	191.493	791.333	699.841	270.000
23	106.266	5458.276	5564.542	5220.000	214.042	751.333	637.291	261.000
24	73.392	5191.723	5265.115	4920.000	222.115	711.333	589.219	246.000

condition, the simulated result is given in Table II. The data for regarding bilateral and spot market price are given in Table I. the data regarding the transmission network and loss is given in [22].

The final result found using GOABC is given in tabular form in Table II with comparative performance with MIP algorithm [11]. It is evident that the proposed algorithm managed to provide an increase of 2.79% in net profit while reducing the overall pollution by 41.02%. This validates the capability of GOABC over MIP algorithm. It is also worth mentioning that, as the solution methodology does not involve the slack bus management technique, the solution although, for all the buses satisfies the ramp rate and prohibited discharge region (Eq. 15 and 16) constraint, slack bus does not satisfies the mentioned limitations.

Case II: The proposed slack bus management technique is adopted here. In this case also the solution provide similar result compared to ABC algorithm which can be verified from Table III. In this case it is seen that compared to ABC, the proposed GOABC algorithm increase the profit by 3.2% whereas decreasing the emission by 2.9%. Fig. 2 which exhibits the convergence characteristics of GOABC and ABC algorithm, prove the superiority of GOABC algorithm once more. From all these characteristics and result it is evident that the proposed algorithm is superior to ABC or MIP algorithm. As in case II the slack bus management technique is used, the slack bus should meet related constraints of thermal units (Eq. 9-23) which can be verified from Table IV where the sharing of power is among hydro and thermal plants are shown along with the generation of slack bus (bus 69).

It is also worth noting that due to inclusion of the management method the solution tends to be shallower in case II compared to case I, which proves the increased complexity in case II. But as the mentioned algorithm, GOABC used the concept of opposition increased the efficacy and thus able to provide an acceptable solution. In addition to this, the capability of management technique should be commended as it manages to keep the generation of slack bus within ramp rate limit and boundary condition considering the fact that the loss of transmission network fluctuates exceedingly with minimum load or generation variation.

5 Conclusion

In this dissertation, an innovative technique in order to manage the slack bus is discussed which is capable to make the slack bus deal with various complicated limitation such as ramp rate, prohibited discharge region etc. in a multi-dimensional discretized time dependent search space in the perspective of hydro thermal scheduling problem. The problem is modeled is two different scenarios without and with management technique and it is shown that the problem with management technique vastly increases the model complexity. In order to counter that a newly proposed algorithm, GOABC, inspired by ABC and opposition based learning methodology is developed. The performance of the algorithm is demonstrated and compared with recently published MIP algorithm and basic ABC algorithm.

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