Transmission constraint modelling in Hydrothermal Scheduling using AC load flow model under Deregulated Environment

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Abstract: - This paper addresses the modelling of transmission constraints using full AC load flow model in the context of Hydrothermal Scheduling (HTS) under deregulated environment including multiple objectives, day basis profit and emission. In practical, DC load flow or Optimal Power Flow (OPF) are used in HTS problem as being state of the art but both these techniques has severe cons like DC load flow Model being too erroneous and OPF consumes too much time especially for a deregulated system where time is in short supply. In addition to this, satisfying ramping limitation is highly complicated when using OPF to solve large transmission system. For this purpose in this research AC load flow model is adopted over DC load flow or OPF model and power distribution among the units of GENCOs (Generating Companies) is performed by unit commitment.

As AC load flow model being considered, the intricacies regarding Slack bus is also needed to be handled. The concept of slack bus is born for logical representation of power system by virtually injecting the mathematical unbalances of the system model through that bus. But for a large system where the unbalances exceed slack bus boundary the overall concept tends toward impossibility. Moreover the concept lacks practicality for a problem where multiple inter-related time-intervals is involved as in case of hydrothermal scheduling. In this research the concept of slack bus is extended for more practical depiction of a HTS model in deregulated environment. As the complexity of the problem increases greatly for involving such convolution, a hybridization between Artificial Bee Colony and Grey Wolf Optimization algorithms, i.e. hybrid ABC/GWO algorithm (*h*-ABC/GWO) is proposed which merges the superior exploitation technique of GWO with highly diversified exploration technique of ABC to provide sufficient diversity in the search space of HTS in order to counter additional complexity and to enhance the speed for solving the HTS problem efficiently

Key-Words: - Deregulation, Optimization, hybridization, AC load flow modelling, Hydro-Thermal Scheduling, Slack Bus.

1 Introduction

This paper considers a hydrothermal system in a day ahead electricity market. In deregulated environment Hydrothermal Scheduling (HTS) problem mainly concerns the maximization of total profit of the generating companies (GENCOs) which is defined by the difference between total revenue earned by the GENCOs and the production cost of the generating plants for a speculated duration. In addition, due to substantial environmental impact of thermal power plants, emission is also taken into account as the secondary objective. The intricacies regarding hydrothermal scheduling (HTS) [1] placed in many operational and reliable limitations which includes hydro, thermal and transmission constraints.

There are many researchers who have tried to solve the mentioned problem in conventional as well as deregulated environment in different time frames using efficient solution techniques. Some researchers, due to its non-linear behavior and growing computational burden, has used stochastic optimization approaches such as dynamic programming [2], concept of non-linear network flow [3] etc. to solve such problem. These techniques perform better in non-linear environment but with higher non-convexity in the search space results in reducing the performance of the algorithm considerably. For this nature of HTS few are forced to prefer meta-heuristic algorithms over stochastic optimization technique. Orero et al. [4] solved HTS problem using Genetic Algorithm. This paper demonstrates the basic characteristics of cascaded Hydro network. In literature [5] Sinha et al. incorporated an important practical limitations i.e. prohibited discharge region, in HTS framework and solved the whole system using fast evolutionary algorithm. Lakshminarasimman et al. [6] solved HTS in multi-objective environment using modified Differential Evolution algorithm. Ashutosh et al. [7]

proposed a new solution technique known as epoxy fly ash composite with Taguchi optimization for unit commitment problem. Though their research is performed in conventional environment but the handling procedure of some basic limitations in HTS environment are discussed in detail in this research. The handling procedure shown here lacks heuristic behavior of the algorithm up to some extent as the decision variables are set to boundary value to satisfy equality limitation. Werner et al. [8] used evolutionary strategy for short term hydrothermal Scheduling. However due to the inclusion of non-linear dynamic constraints, the complexity of the algorithm increases considerably.

Kelman et al. [9] demonstrate the wide variation of a market model and asses its effect in hydrothermal system. In literature [10] Ahmadi et al. solve the mentioned problem in deregulated environment with multiple objectives. They have solved the problem with mixed integer programming (MIP) which requires the linearization of all non-linear constraints as well as the objective function. Though this technique works in MIP environment but with a linearized cost function. Further, the authors have not discussed in detail the procedure of handling the transmission line limits. Finally, various optimization techniques that are used to solve HTS problem are discussed in a survey by Farhat et al. [11].

From literature survey it is observed that, comparatively little attention is given to the aspect of transmission constraints in HTS context. In literature [12] the effect of transmission constraint is discussed in regulated environment and recently Martinas et.al [13] have solved the HTS problem considering transmission constraints using primal dual interior point method. As HTS problem is a part of a transmission system, it is an essentiality to incorporate the transmission constraints in system modelling for accurate modelling. In addition to this the amount of demand (which is the summation of required demand and transmission loss) has to be evaluated as accurate as possible as well. The main feature of this paper is to accurately model the transmission and inter temporal limitations in the context of HTS and evaluate exact transmission loss.

In reality, these feats can be reached by incorporating load flow calculation in system modelling and there are many models, which are actually in use as state of the art in different practical power system. HTS problems (with simpler transmission models like direct current load flow model [14]) has been implemented in large power system for decades, but even so, there are still inaccuracies concerning system modelling. The reason behind the mentioned fact is due to adaptation of simpler DC load flow modelling where the load flow problem is considered as linear.

On the other hand the transmission loss can be calculated more effectively using optimal power flow [13] but, the technique is not adopted for two main reasons. As multiple time interval is considered, the loss needed to be calculated multiple times and simulating OPF for each interval consumes considerable amount of time, which in turn make the system inoperative in deregulated environment where the permissible simulation time is considerably low. In addition to this the OPF model being operative on single interval platform, the time depended limitations, like ramp rate of thermal units is highly infeasible with OPF model.

So for the sake of limited time period and accurate modelling, in this research AC (alternating current) load flow model [13] is adopted which is much more accurate than DC load flow model and consumes lesser time than conventional OPF model. In this research the AC load flow model is evaluated using Newton Raphson Method which effectively satisfy different transmission limitations and calculate network loss within acceptable time with sufficient accuracy. The AC load flow in HTS system modelling did provide these necessary goals but on the contrary it gives birth to another challenge, the inter-temporal limitations of slack bus. In practical scenario managing slack bus is not the problem of GENCOs but in computational point of view as AC load flow model is used for multiple time intervals the above mentioned problem is compulsory to unravel for replicating the system accurately.

In AC transmission network flow analysis, Slack bus is largely an artefact of conventional load flow rather than a physical requirement in a power system. It allows us to converge the solution effectively by providing required mathematical unbalances. But in the context of HTS this method leads to an impractical solution due to the fact that slack bus might not always be able to bear such burden satisfying all the constraints. In addition to that Slack bus management in HTS context is quite complicated as the generation of slack bus depends entirely on system unbalance or in other words load amount and distribution among the generating plants and it may vary greatly with slight input change. There are few methods like multiple slack bus [15], slack to PV bus conversion technique [15] available to manage slack bus in order to reduce the burden but these methods can only be applied efficiently for a particular instant. The satisfaction of all the transmission limitations concerning HTS for a specified time period is completely different scenario as it requires time dependent limitations (for every generated bus, including slack bus) such as ramp rate limitations to be satisfied.

In view of the above, in this research, a novel slack bus management technique is proposed to handle the slack bus power while evaluating the transmission loss using AC load flow model in HTS problem with 24 hours variable load schedule with ramping rate limits, transmission line limits etc. Due to incorporation of these additional realistic features (AC load flow model which is highly non-linear, and non-convex, as the power flow into the loads is a function of square of applied voltage which prevents using conventional optimization techniques), the overall system complexity increases considerably which calls for a solution technique competent enough to provide sufficient diversity in the multi-dimensional search space. For that reason a hybridized algorithm (hybrid-Artificial Bee Colony/ Grew wolf Optimization Algorithm, *h*-ABC/GWO) using Artificial Bee Colony (ABC) [16] Algorithm (2005) developed by D. Karaboga and Grey Wolf Optimizer (GWO) [17], [18], developed by Mirjalil et al. in 2013 is proposed.

ABC algorithm is a swarm based Meta heuristic, optimization algorithm and it has already been used to solve HTS problem as shown in literature [16]. The capability of an algorithm solely depends on the equilibrium between exploitation and exploration based on the behavior of the search space. The exploitation in ABC algorithm mainly done by the onlooker bee phase. But for a problem like HTS the probability value to activate onlooker bees are significantly low resulting poor exploitation capability. So in order to rationally improve the overall performance, GWO algorithm is integrated as a phase of ABC algorithm replacing onlooker bee phase. The basic GWO algorithm is a meta-heuristic population based algorithm which mimics the leadership hierarchy and hunting mechanism of grey wolfs. This diversified technique of grey wolfs provide excellent exploitation capability in multi-dimensional search space with practical problems as shown in literature [17]. For this purpose the superior exploitation capacity of GWO is combined with the diverse solutions of ABC algorithm in order to improve the overall search capability. The performance of the proposed technique is demonstrated on IEEE 118 bus test system and compared with valid published algorithms in order to prove the algorithm proficiency.

In view of the above, the main contributions of this paper are:

1) Full AC load flow model is incorporated in HTS under deregulated environment for higher accuracy and lower time consumption.
2) A novel slack bus management technique is proposed to deal with inter-temporal limitation of slack bus, the complexity is due to the incorporation of full AC load flow model.
3) A new hybridized algorithm (i.e. *h*-ABC/GWO Algorithm) is proposed to solve the mentioned problem with added complexity.
4) The proposed technique is used for solving a moderately large test system under different scenarios.

The rest of the paper is assembled as shown. In the second section the system model for hydrothermal scheduling including unit commitment is discussed. In third section the arrangement of proposed Hybrid-Artificial Bee Colony / Grey Wolf Optimization Algorithm (*h*-ABC/GWO) in single as well as multi-objective environment is demonstrated. In the following section the HTS problem in proposed algorithm is shown. The detailed constraint handling techniques for unit commitment limitations and the technique to embed Newton-Raphson load flow in system modelling is discussed in detail. The fifth section demonstrates the numerical results achieved by the proposed algorithm.

2 System Modelling

HTS problem in deregulated environment can be described as a multi-objective non-linear optimization problem where the economic earnings has to be maximized with minimum environmental impacts in a forecasted time period. For this purpose the system is modeled in multi-objective environment where the two objectives f1 and f2 are taken as profit of the GENCOs involved and emission of corresponding thermal plants.

Objective Functions:

$$f_1 : \max, V = \sum_{\forall \tau \in \Omega} \begin{bmatrix} D_\tau^b \cdot r_\tau^b + D_\tau^s \cdot r_\tau^s + r_\tau^{sr} \cdot \left(\Lambda_\tau^{sr} + \Pi_\tau^{sr}\right) \\ + r_\tau^{nr}\left(\Lambda_\tau^{sr} + \Pi_\tau^{sr}\right) - \left\{f_\tau(\Pi) + \left(S_\tau^u + S_\tau^D\right)\right\} \end{bmatrix} \tag{1}$$

$$f_2 : \min, Ems = \sum_{\forall \tau \in \Omega} E(\Pi_\tau) \tag{2}$$

Such that, $$\left(\Pi_\tau + \Lambda_\tau\right) \geq \left(D_\tau^b + D_\tau^s\right) + P_L \quad \forall \tau \in \Omega \tag{3}$$

Where, $$f_\tau(\Pi) = \mu_{\beta,1} + \mu_{\beta,2} \cdot \Pi_{\beta,\tau} + \mu_{\beta,3} \cdot \left(\Pi_{\beta,\tau}\right)^2 + \mu_{\beta,4} \cdot \sin\left(\mu_{\beta,5}\left(\underline{\Pi_{\beta,\tau}} - \Pi_{\beta,\tau}\right)\right) \tag{4}$$

$$E = \sum_{\forall \tau \in \Omega} \sum_{\beta \in \Gamma} \begin{matrix} ems_{\beta,1} + ems_{\beta,2}\Pi_{\beta,\tau} \\ + ems_{\beta,3}\Pi_{\beta,\tau}^2 \end{matrix} \tag{5}$$

Eq. 1 represents total profit of the GENCOs. The first term of Eq. 1 signifies the profit due to bilateral contracts ($D_\tau^b \cdot r_\tau^b$), spot market transaction ($D_\tau^s \cdot r_\tau^s$) and spinning and non-spinning reserve (for Hydro and thermal units) and the second term that is, $\{f_\tau(\Pi)+(S_\tau^u+S_\tau^D)\}$ symbolizes the cost comprising production cost (*f:* given in Eq. 4), start up (S_τ^u) and shut down cost (S_τ^D) of concerned thermal units. Eq. 2 suggests the total emission produced. In view of HTS in deregulated environment, the profit, *V*, need to be maximized and the emission, *Ems* needs to be minimized, which in turn defines the problem as Max-Min optimization problem. Eq. 3 suggest that the total generation of all generating units (including Hydal and Thermal units) of respective GENCOs have to be greater than total power transaction (Bilateral and spot market transaction) and system loss. The modeling of HTS problem involves many complex and nonlinear constraints. The limitation mainly involves with generating plants and transmission network.

The hydro power plant is modeled using linearized Hill chart [19] widely demonstrated by Conejo et al. in the literature [20]. The other limitations regarding Hydro units are given below,

Hydro Unit Constraints:

Continuity Equation:

$$\Theta_{\alpha,\tau+1} = \Theta_{\alpha,\tau} + K_{\alpha,\tau} - C_{\alpha,\tau} - S_{\alpha,\tau} + \sum_{\forall m \in R_u^\alpha} \left\{ C_{m,(\tau-\tau_m^l)} + S_{m,(\tau-\tau_m^l)} \right\} \quad (6)$$

$\forall \alpha \in \Delta ; \forall \tau \in \Omega$

Reservoir Water content Limitation:

$$\underline{\Theta_{\alpha,\tau}} \le \Theta_{\alpha,\tau} \le \overline{\Theta_{\alpha,\tau}} \ \ \forall \alpha \in \Delta ; \forall \tau \in \Omega \quad (7)$$

Reservoir Discharge Limitation:

$$\underline{C_{\alpha,\tau}} \le C_{\alpha,\tau} \le \overline{C_{\alpha,\tau}} \ \ \forall \alpha \in \Delta ; \forall \tau \in \Omega \quad (8)$$

Initial/End Volume limitation:

$$\Theta_{\alpha,0} = \Theta_{\alpha,begin} ; \ \Theta_{\alpha,z} = \Theta_{\alpha,end} \ \ \forall \tau \in \Omega \quad (9)$$

Thermal Unit Constraints:

In order to distribute the required demand into available generating plants unit commitment [21] is performed. The related limitations are as follows,

Thermal Generation Limitation:

$$V_{\beta,\tau}\underline{\Pi_{\beta,\tau}} \le V_{\beta,\tau}\Pi_{\beta,\tau} \le V_{\beta,\tau}\overline{\Pi_{\beta,\tau}} \ \ \forall \beta \in \Gamma ; \quad (10)$$

$\forall \tau \in \Omega$

Initial Status:

$$V_{\beta,1} = 0 \ \ if \ T_\beta^{ini} < T_\beta^{OFF} \quad (11)$$

$$V_{\beta,1} = 1 \ \ if \ T_\beta^{ini} < T_\beta^{ON} \quad (12)$$

Minimum On/Off time limitation:

$$\left\{X_{\beta,(\tau-1)}^{on} - T_\beta^{on}\right\} \times \left\{V_{\beta,(\tau-1)} - V_{\beta,\tau}\right\} \ge 0 \quad (13)$$

$$\left\{X_{\beta,(\tau-1)}^{on} - T_\beta^{off}\right\} \times \left\{V_{\beta,\tau} - V_{\beta,(\tau-1)}\right\} \ge 0 \quad (14)$$

$\forall \beta \in \Gamma \ \forall \tau \in \Omega$

Ramp Rate Limitation:

$$\Pi_{\beta,\tau} - \Pi_{\beta,\tau-1} \le UR_\beta \quad (15)$$

$$\Pi_{\beta,\tau-1} - \Pi_{\beta,\tau} \le DR_\beta \quad (16)$$

$\forall \beta \in \Gamma \ \forall \tau \in \Omega$

System Load Balance:

$$\Pi + \Lambda = P_D + P_L \ \forall \tau \in \Omega \quad (17)$$

The transmission loss, P_L is calculated using AC load flow model [13].

Spinning Reserve:

If spinning reserve, P_R is considered the total generation should provide required spinning reserve along with required demand and transmission loss.

$$(\Pi + \Lambda) \ge (P_D + P_L + P_R) \quad (18)$$

Hot Start/ Cold Start:

$$\Pi_{\beta,\tau}^D = CS_\beta \times \left\{V_{\beta,\tau} - V_{\beta,\tau-1}\right\} \times \left\{V_{\beta,\tau}\right\} \quad if \ \left(X_{\beta,\tau}^{off} - T_\beta^{COLD}\right) \ge 0 \quad (19)$$

$$\Pi_{\beta,\tau}^D = HS_\beta \times \left\{V_{\beta,\tau} - V_{\beta,\tau-1}\right\} \times \left\{V_{\beta,\tau}\right\} \quad if \ \left(X_{\beta,\tau}^{off} - T_\beta^{COLD}\right) < 0 \quad (20)$$

$$\Pi_D = \sum_{\forall \beta \in \Gamma} \sum_{\forall \tau \in \Omega} \Pi^D \quad (21)$$

In addition to this several transmission limitations such as, Line Flow limit, Active and Reactive power Injection, Bus Voltage limitation, Transformer tap setting limitation etc. [25] are also incorporated for real world representation.

3 Hybrid-Artificial Bee Colony (ABC) / Grey Wolf Optimization (GWO) (hABC/GWO) Algorithm

The main drawback regarding metaheuristic algorithms is extensive random search where there is a high possibility of searching same position repeatedly while few places in the vast multi-dimensional search space did not get any attention at all. Superior non-linearity and non-convexity increases the effect of this phenomena even further. In order to search such a complex search space it is necessary to balance between the local and global search capability of the acting algorithm or in other word the exploitation and exploration capability according to the search space behavior. For this purpose a hybridized algorithm that is Hybrid-Artificial Bee Colony / Grey Wolf Optimization Algorithm (*h*-ABC/GWO) is adopted. In this algorithm the superior exploitation capability of GWO algorithm is merged with diversified exploration capability of ABC algorithm.

The challenge of an algorithm in constrained environment is very much complicated than in unconstrained environment. Algorithm performance also greatly depends on the technique used to handle the acting constraints. Before explaining the function evaluation method and constraint handling process of HTS problem, the key arrangement of *h*-ABC/GWO algorithm is discussed in this section.

3.1 Initialization

The initial population will be created using Eq. 22 where *i* and *j* signifies the dimension of the problem and population size.

$$x_{ij} = l_i + rand\ (0,1)\times(u_i - l_i) \tag{22}$$

3.2 Employed Bee Phase

The employed bees will search the neighborhoods of the initial positions, in hopes of better position using Eq. 23 and modify the initial population with better positions.

$$v_{ij} = x_{ij} + \phi_{ij} \times (x_{ij} - x_{il}) \tag{23}$$

3.3 Grey Wolf Phase

Social Hierarchy: In GWO algorithm gray wolfs are categorized among α-Alpha wolf (Fittest Solution of the population), β-Beta wolf (Second Best Solution of the population), δ-Delta wolf (Third Best Solution of the population) and ω-Omega wolfs (All other solutions). The hunting for prey (the optimum solution) is guided by alpha, beta and delta wolfs with the help of omega wolfs [17].

Encircling the prey: In the next stage the according to gray wolfs the pray will be encircled and these specific behavior can mathematically replicated by Eq. 26 and Eq. 27.

$$D_{ij} = \left|C_i(t)\times X_{ij}^{p}(t) - X_{ij}(t)\right| \tag{24}$$

$$X_{ij}(t+1) = X_{ij}(t) - A_i(t)\times D_i(t) \tag{25}$$

Where, $A_i(t) = 2\times a_i(t)\times r_{i1} - a_i(t), C_i(t) = 2\times r_{i2}$.

The components of $A_i(t)$ are reduced from 2 to 0 with respect to iterations and r_{i1}, r_{i2} are vectors of random number within *[0,1]*.

Hunting:

In optimization perspective, the pray is actually refer to the global optima. But in practical scenario it is almost impossible to find global best solution. So in order to imitate the hunting mechanism of grew wolf the best, second and third best solution is considered as alpha, beta and delta wolf and used for hunting. The first step is to create distance vectors using *α, β* and *δ* wolfs by Eq. 26 followed by Eq. 27 which gives three different positions for a particular individual of the population. The modified position will be evaluated using Eq. 28.

$$D_{ij}^{\alpha} = \left|C_i^1 \times X_{ij}^{\alpha} - X_{ij}\right|;\ D_{ij}^{\beta} = \left|C_i^2 \times X_{ij}^{\beta} - X_{ij}\right|;$$
$$D_{ij}^{\delta} = \left|C_i^3 \times X_{ij}^{\delta} - X_{ij}\right|; \tag{26}$$

$$X_{ij}^1 = X_{ij}^{\alpha} - A_i^1 \times D_{ij}^{\alpha};\ X_{ij}^2 = X_{ij}^{\beta} - A_i^2 \times D_{ij}^{\beta};$$
$$X_{ij}^3 = X_{ij}^{\delta} - A_i^3 \times D_{ij}^{\delta} \tag{27}$$

$$X_{ij}(t+1) = \frac{X_{ij}^1 + X_{ij}^2 + X_{ij}^3}{3} \tag{28}$$

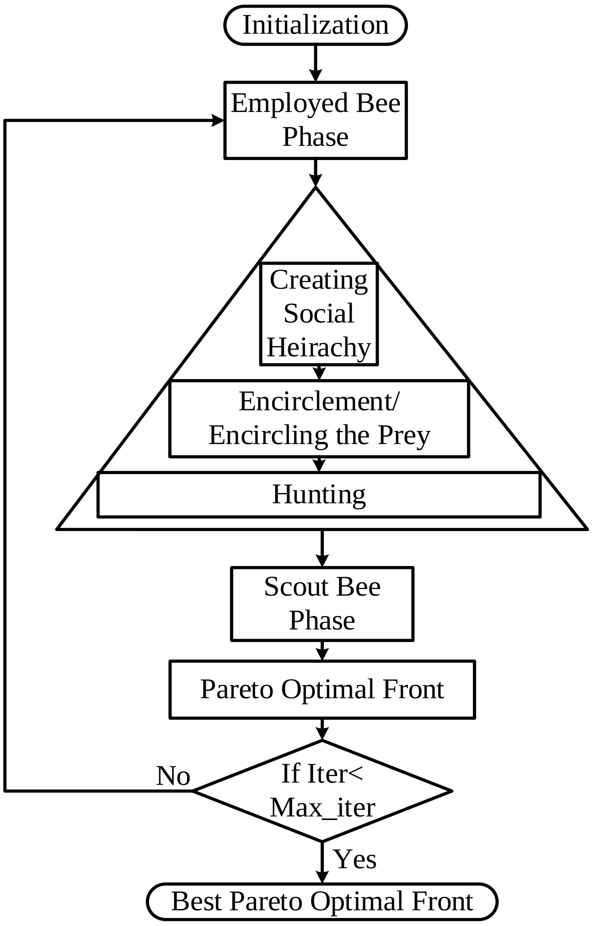


Fig. 1. The detailed flow chart of Hybrid-Artificial

Bee Colony (ABC) / Grey Wolf Optimization (GWO) (*h*-ABC/GWO) Algorithm

3.4 Scout Bee Phase

Consistent individuals that do not improve its position, will be converted to scout based on a predefined parameter, *limit* and forced to search the search space without any guidance using Eq. 29.

$$w_{im} = l_i + rand(0,1)\times(u_i - l_i) \quad (29)$$

3.5 Selection

The best solution so far is taken as the global best for the next iteration. This process continues until the iteration number reaches the maximum cycle number (M_I). The flowchart for *h-ABC/GWO* is shown in Fig. 1

Multi-objective optimization: As the problem concerned is multi-objective in nature so the algorithm is made suitable for handling multiple objectives simultaneously. A typical multi-objective problem can be stated as,

$$\begin{aligned}&Minimize,\ f_n(X)\quad n=1,2,...obj;\\&Subject\ to\\&\begin{cases}A_p(X)=0 & p=1,...X\\ B_q(X)\le 0 & q=1,...Y\end{cases}\ \text{Constraints}\end{aligned} \quad (30)$$

Where, $f_n(x)$ is the n^{th} objective function and *obj* is the total number of objectives. In order to find best compromise solution the first step is to create Pareto optimal front consisting all non-dominated individual, which can be found by,

$$\begin{aligned}&\forall i\in\{1,2,\cdot\cdot,obj\}:\ f_i(X)\le f_i(Y)\ \text{and}\\&\exists j\in\{1,2,\cdot\cdot,obj\}:\ f_j(X)\le f_j(X)\end{aligned} \quad (31)$$

The individuals *X* and *Y* satisfying Eq. 31 states that *X* dominates *Y*. So, in other words solution *X* is non-dominated over solution *Y*. Among all the solutions, the solutions that are not dominated by any other solution are termed as non-dominated solution. The Pareto optimal front is created by non-dominated solutions only.

Best compromise solution

Among the individuals of Pareto optimal front there is one individual that has to be termed as best individual. For this purpose, a membership function is used to fit all the objectives within unity bound so that *obj* number of objectives can be compared accurately. The membership function, g^j_n for j^{th} individual with respect to n^{th} objective function can be calculated as,

$$g_n^j=\begin{cases}1 & for\ \ f_n^j\le f_n^{\min}\\ \dfrac{f_n^{\max}-f_n^j}{f_n^{\max}-f_n^{\min}} & for\ \ f_n^{\min}<f_n^j<f_n^{\max}\\ 0 & for\ \ f_n^j\le f_n^{\max}\end{cases} \quad (34)$$

Where, *M* is the size of Pareto optimal front and $f_n^{\min}$ and $f_n^{\max}$ is the lowest and highest function value of n^{th} objective function. In order to find the best compromise solution another normalized function for each individual is found using,

$$h^j=\sum_{n=1}^{obj}\sqrt{\left(g_n^j\right)}\Bigg/\sum_{j=1}^{M}\sum_{n=1}^{obj}\sqrt{\left(g_n^j\right)} \quad (35)$$

The individual with minimum h^j is taken as the best compromise solution.

4 *h*-ABC/GWO HTS Environment

In HTS problem, the decision variables consists hydro discharges and thermal production along with binary variables in order to define the commitment status of thermal units. So each individual of the population can be defined as,

$$\begin{aligned}&X=\begin{bmatrix}C & \Pi & B\end{bmatrix}^T\ \text{and}\\&C=\left[C(j,1)\ C(j,2)\cdots C(j,T\times N_h)\right]^T;\\&\Pi=\left[\Pi(j,1)\ \Pi(j,2)\cdots\Pi(j,T\times N_T)\right]^T;\\&B=\left[B_S(j,1)\ B_S(j,2)\cdots B_S(j,T\times N_T)\right]^T\end{aligned} \quad (36)$$

Where, *C*, and *B* is the randomly generated hydro discharges for every hydro unit (N_h) for each hour (*T*), Thermal power generation and randomly generated binary variable for every thermal unit (N_T) for all hour (*T*). The decision variables are generated using Gaussian random generator so it is highly unexpected the solutions to be feasible as there are many limitations concerned (especially equality limitations) regarding HTS. So for the sake of simplicity, the hydro problem is solve at first followed by unit commitment calculation.

Handling technique for hydro units: The hydro sub-system involved many complex topographical limitations so the system is solved without the interferences of load flow calculation. The hydro power generation is simply calculated and used for load flow solution. The pseudo code used to handle hydro limitations is shown in Fig. 2.

This process will be performed on every hydro units least depended to most depended unit. After every limitation is satisfied, the hydro power generation will be calculated.

Constraint handling technique for Thermal units:

After calculating hydro generation the thermal generation has to be provided according to required demand (P_D) and transmission loss (P_L). As AC load flow model (Newton Raphson technique) is used to model the transmission network and calculate transmission loss, the slack bus management is a highly complicated issue along with unit commitment.

1. Using unrefined hydro discharges, calculate erroneous end volume, and mismatch of unit α will be calculated using,

2. $$\Theta^0_{\alpha,T} = \Theta_{\alpha,1} + \sum_{\tau\in\Omega} K_{\alpha,\tau} - \sum_{\tau\in\Omega} C_{\alpha,\tau} \sum_{\tau\in\Omega} \sum_{m\in R^{\alpha}_{u}} \left\{C_{m(\tau-\tau^{\alpha}_{m})}\right\};$$
$$mis_{\alpha} = \Theta^0_{\alpha,T} - \Theta_{\alpha,1}$$

3. If mis_α > tolerance
4. Generate, z (randomly), providing (z is a dependent time, integer variable).
5. Heuristically improve discharge of z^{th} hour on the concerned unit within higher and lower limit to reduce mismatch.
6. Calculate mis_α.
7. Else save hydro discharge

Fig. 2. Pseudo code for handling the Hydro limitation (Eq. 6-9)

The consideration of slack bus intuitively, as widely believed, is a requirement for mathematical description of transmission network, which virtually has no affiliation of practical systems. One of the main purposes of this concept is to provide the necessary unbalances (losses of transmission network) regarding power of the network in power flow calculation is the reason for most reliable generator of the network to be treated as the slack bus in general. But being a generator (or thermal power plant) the restrictions of practical constraints (as shown in Eq. 10-21) are operative in slack bus also. In addition to that, for a big practical power system it is literally impossible to inject all the unbalances of the network through one bus. Even if sometimes the plant does provide necessary attributes, it is highly unlikely to ignore some important limitations such as Ramping rate etc. in the process. Considering HTS where the mentioned facts needed to be satisfied for an entire horizon make the problem even more complicated. In this research a theory is demonstrated in order to incorporate the remedy for the complexity mentioned in system modeling of the HTS problem. Considering the highly complex topographical limitations of hydro units, the units do not have much liberty to accept such burden, and because of that the buses including thermal power plants are considered. The procedure to get such a feat is demonstrated below:

Required Thermal generation,
$\Pi_{req} = P^{*}_{D} - \sum \Lambda$
Letting, N^{a}_{τ} is the set of available Thermal units for a particular time interval based on previous hours.
$for\ \ \tau = 1\ to\ T$
Calculate total generation from unrefined individual of the population.
Calculate, $\text{mis}_{\tau} = \Pi_{req} - \sum \Gamma\left(N^{a}_{\tau}\right)$
While $\backslash mis_{\tau} \backslash >$ tolerance (typically 10^{-3})
$k = floor\{rand(0,1) \cdot N^{a}_{\tau}\} + 1$
update the upper and lower limit of k^{th} thermal unit based on up/down ramp rate and previous hour generation.
$\Gamma(k) = \underline{\Gamma(k)} + rand(0,1) \cdot (\overline{\Gamma(k)} - \underline{\Gamma(k)})$
end, (while)
end, (for)

Fig. 3. Pseudo code for handling the Thermal limitation

1. In a practical power system the transmission loss of the network is given through all available generators. Considering the fact as very difficult, if not impossible, the transmission loss in AC load flow model is given through slack bus. But for a large system, it is highly complicated considering the unpredictability of transmission loss and multiple time interval. In order to do such an action a predicted value is made for transmission loss, P_L*. Which makes the demand as,
Where, P_D is the Required Load Demand.

2. Then unit commitment is performed to distribute this renewed demand, P_D* among all the available generators excluding slack bus using as slack generator is reserved specifically for unbalances. The pseudo code used to deal thermal limitations is shown in Fig. 3. This action is performed on each individual of the population. This is also worth mentioning that the slack bus could take part in unit commitment provided there is sufficient room for the slack bus generator to supply necessary unbalances. Such a condition arrives more often in smaller system where transmission loss is comparatively low with respect to generator limit.

3. In order to correct the transmission loss and find slack bus generation, Newton Raphson load flow technique is used over the entire time span.

Though this procedure will satisfy the power balance with sufficient accuracy but the satisfaction of ramping limitation concerning slack bus will not satisfy as the generation from slack bus is totally depend on system unbalance. In order to satisfy this limitation, the generation of slack bus is increased according to ramp rate.

The pseudo code for slack bus management is given in Fig. 4.

Let, $[H_\tau]$ is the vector of slack bus generation over the entire time horizon.

Considering, $[H_{\hat{\tau}}]$ is the maximum slack bus generation at time $\hat{\tau}$. The complete algorithm is divided in two part. The first algorithm is to take care the interval from first to $\hat{\tau}$ and second algorithm for the remaining.

```
For i=τ̂ to 2
        if Hτ(i-1) - Hτ(i)>URslack
                Hτ(i)=Hτ(i-1) – URslack
        elseif Hτ(i-1) - Hτ(i)>DRslack
                for j= i to τ̂
                        if Hτ(j-1) - Hτ(j)>DRslack
                                Hτ(j)=Hτ(j-1) – DRslack
end, end,end,end
```

```
For i=τ̂ to (T-1)
        if Hτ(i+1) - Hτ(i)>DRslack
                Hτ(i+1)=Hτ(i) – DRslack
        elseif Hτ(i+1) - Hτ(i)>URslack
                for j=τ̂ to i
                        if Hτ(j+1) - Hτ(j)>URslack
                                Hτ(j)=Hτ(j+1) – URslack
end, end,end,end
```

Fig. 4. Pseudo code for the algorithm used to control Slack bus where, UR_{Slack}/ DR_{Slack} is the up and down ramp limit for the slack bus generator.

Further, it is worth noting that the power management of slack bus does have financial implication under deregulated environment.

Table 1. The parameters used for the modeling

Bilateral Contract=1000 MWH
Bilateral contract price=40 $/MWh
Maximum cycle number (M_l)=2000
'*limit*'=60
Population Size=250
Iteration Number = 3000

5 Numerical Result

Table 2. The Optimal Solution in case I

Objective function	Profit ($)	Emission (lbs)
h-ABC/GWO	5713809.78	95201.19
ABC	5621395.26	139568.48
GWO	5354684.48	236987.26
MIP [10]	5553834.30	162820.22

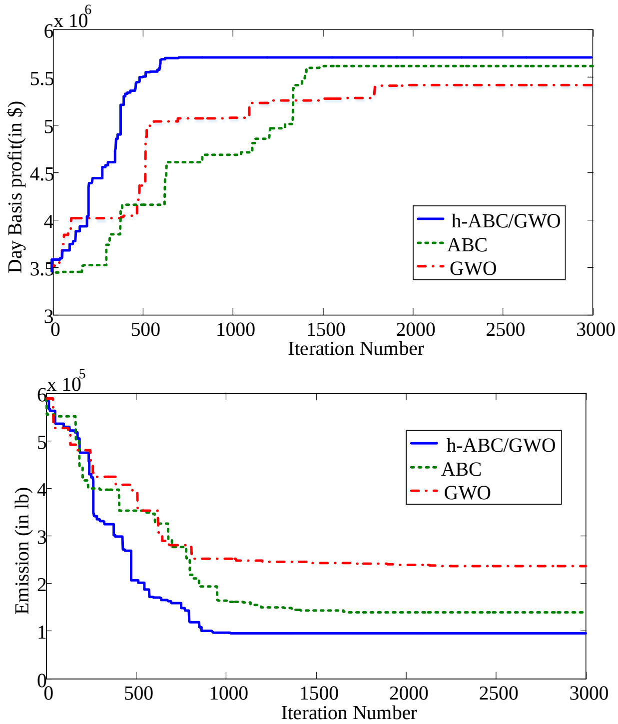
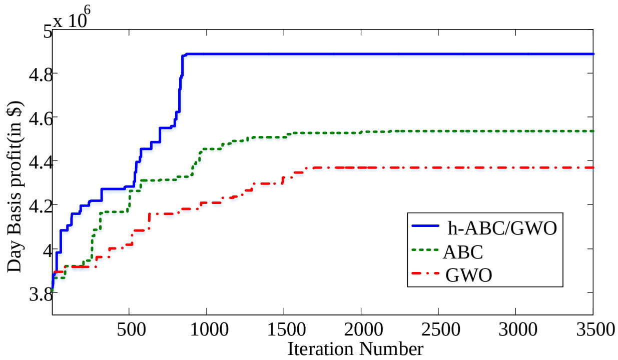


Fig. 5. Convergence characteristics for profit and Emission for Case I

For demonstrating the performance of the proposed technique, a large test system, that is IEEE 118 bus test system, is considered in this study. The system [10] comprises 54 thermal units, and eight cascaded hydro reservoirs. The data for Hydro network is taken from ref. [19]. The revenue mainly involved two types of transactions such as bilateral contract and spot market bidding. The data regarding thermal units and transmission network along with hour basis prices of energy, spinning and non-spinning reserve is provided in [22]. The proposed technique is implemented in MATLAB (Version: 8.1.0.604(R2013a)) environment version: 6.2(R2013a) and simulated on Dell XPS15 (2760QM®) with 3.2GHz processor speed. The total time horizon is one day with 24 hourly periods. The proposed technique is demonstrated on two different scenarios: (i) solving the test problem under multi-objective environment without considering slack bus management technique; and (ii) solving the same test problem considering multiple objectives with slack bus management technique.



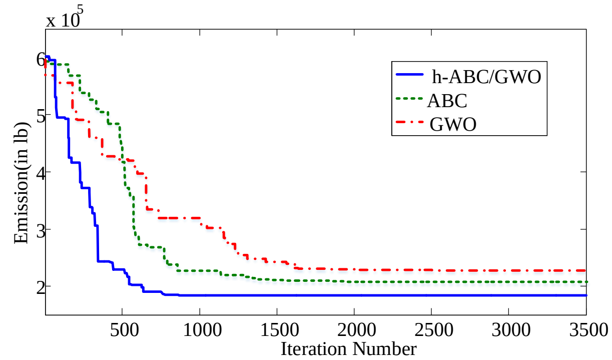


Fig. 6. Convergence characteristics for profit and Emission for Case II.

Case I: In this case the test problem is solved with multiple objectives, maximizing the profit of GENCOs and minimizing the emission from thermal power plants, using *h*-ABC/GWO algorithm with the forecasted transmission loss as given in [22]. The parameters used to solve the system are shown in Table I. The results obtained with *h*-ABC/GWO algorithm is compared with that reported in [10] and given in Table II. The convergence characteristic of *h*-ABC/GWO algorithm is shown in Fig. 5 along with ABC and GWO algorithm with respect to profit and emission. From Table II and Fig 5, it is evident that the performance of the proposed algorithm is better than the recently reported results in terms of profit and emission. This case is considered for validating the performance of the proposed algorithm in HTS problems.

Case II: In this case the transmission constraints are incorporated using AC load flow modelling. The 69th bus of the network is treated as slack bus with maximum and minimum power limit as 400 and 30 MW respectively. The transmission loss at each interval is calculated accurately by Newton Raphson Load flow technique [1]. The convergence characteristics of *h*-ABC/GWO algorithm are shown in Fig. 6. Table III depicts the results obtained with *h*-ABC/GWO and compared with ABC and GWO algorithms with respect to profit and emission which proves superior proficiency of *h*-ABC/GWO over other mentioned algorithms.

The power distribution over the entire time period is shown in Table IV. The fifth column of Table IV shows the transmission loss of the system in time basis. In normal transmission network, the amount of transmission loss is fed through slack bus in order to balance necessary unbalances. So it is safe to say that without any management technique the slack bus generation would be the same as column 5 of Table IV which does not satisfy the ramp rate limitation and maximum generation limit. But due to use of slack bus management technique the slack bus generation falls within maximum and minimum limit along with the satisfaction of ramp rate limit.

TABLE III. Optimal Solution for case II

Objective function	Profit ($)	Emission (lbs)
h-ABC/GWO	4884275.73	184294.04
ABC	4536089.35	221578.43
GWO	4300456.36	240258.36

From Table IV it can be observed that the transmission loss of a network differs greatly with slightest differences in the input or different load requirement. Without the effect of Slack bus management the total loss is needed to be fed through slack bus which could practically be impossible by reason of boundary and ramping constraints regarding slack bus. Due to the use of the mentioned technique, it is seen that the generation of slack bus for the entire time period is within its maximum and minimum limitation. In addition, the ramping limit for the slack bus is also satisfied.

6 Conclusion

The hydrothermal scheduling problem is solved in practical scenario as state of the art for at least three decade. Even so the available models can provide accuracy up to an extent and this occurrences can be explained due to exclusion of necessary limitations or simplification. In addition to that, the effect of multiple time depended limitations are often excluded in terms of modelling, which being one of the main reason for limited accuracy. In general, the transmission network is modeled using simple DC load flow model or optimal power flow (OPF) model. Both of these models has pros and cons. But in this paper the mentioned objective is achieved by full AC load flow modelling as this model is much more agile than OPF and much more accurate than DC load flow model. In this paper the HTS problem is solved in deregulated environment with profit and emission as objective functions including transmission system modelling.

As full AC load flow model is considered, the intricacies of slack bus is also need to be considered. The intricacies regarding the handling of power at slack bus in the context of HTS is discussed in this paper and a novel power management technique is proposed to solve the problem. The proposed technique allows the generator attached to slack bus to maintain its limitations even when the required unbalances are much higher than slack generator limitations. The approach is highly effective with large system. Incorporating, such a phenomena increases the model complexity considerably. Further, a hybridization of ABC and GWO algorithm that is hybrid-Artificial Bee Colony/ Gray Wolf Optimization (*h*-ABC/GWO) is used for solving the highly non-linear large HTS problem. The results demonstrate that the performance of *h*-ABC/GWO is superior as compared the ABC algorithm and at the same time all the realistic constraints of HTS problems are satisfied because of slack bus management technique.

Nomenclature

Ψ	Total operational cost of all thermal units
Δ	Set of Hydro Units
Γ	Set of Thermal Units
Ω	Set of Discretized time interval
Π	Set of Thermal Power Generation
Λ	Set of Hydro Power Generation
Θ	Set of water content in hydro unit reservoirs
K	Set of water inflows in hydro unit reservoirs
C	Set of water discharges in hydro unit reservoirs
S	Set of spillage content of hydro unit reservoirs
$PZ^{h/t}$	Prohibited operating region for hydro/ thermal region
R_u^{α}	Set of upstream units of α^{th} hydro unit
α	Hydro unit index
β	Thermal unit index
τ	Time interval index
τ_m^l	Time delay of i^{th} hydro unit from m^{th} upstream unit
Π_0	Total startup cost of thermal units
Π_Ω	Total shutdown cost of thermal units
$\mu_{\beta,1\cdot\cdot5}$	Power generation coefficients of β^{th} thermal unit
$ems_{\beta,1\cdot\cdot5}$	Emission coefficients of β^{th} thermal unit
$\mu_{\beta,1\cdot\cdot6}$	Power generation coefficients of β^{th} thermal unit
$V_{\beta,\tau}$	On/ off status of β^{th} thermal unit at τ^{th} time interval; $V_{\beta,\tau}=0$ if on; $V_{\beta,\tau}=1$ if off .
$T_\beta^{on/off}$	Minimum on/ off time of β^{th} thermal unit
T_β^{cold}	Minimum cold start time of β^{th} thermal unit
$X_{\beta,\tau}^{on/off}$	Time duration for which β^{th} thermal unit has been on/off up to τ^{th} hour
UR_β / DR_β	Up/ down ramp rate limit of β^{th} thermal unit
CS_β / HS_β	Cold/ hot start cost of β^{th} thermal unit
T_β^{ini}	Initial status of β^{th} thermal unit
V	net profit
D_τ^b	Bilateral contract power capacity
D_τ^s	Spot market power bid
r_τ^b	Bilateral contract price
r_τ^s	Spot market energy price
r_τ^{sr}	Spot market spinning reserve energy price
r_τ^{nsr}	Spot market non spinning reserve energy price
$\Lambda_\tau^{sr/nr}$	Total hydro power involved in spinning/ non-spinning reserve at τ^{th} interval in the spot market.
$\Pi_\tau^{sr/nr}$	Total thermal power involved in spinning/ non-spinning reserve at τ^{th} interval in the spot market.
$S_\tau^{U/D}$	Startup/ down cost of all thermal unit at τ^{th} interval
$S_\tau^{HU/HD}$	Startup/ down cost of all thermal unit at τ^{th} interval

$S_{\tau}^{WU/WD}$ Startup/ down cost of all thermal unit at τ^{th} interval

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