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Uncertainty Management in Short-Term Self-Scheduling Unit Commitment Using Harris Hawks Optimization Algorithm

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Abstract— *The present study focuses on the harris hawks optimizer. harris hawks optimization (HHO) is introduced based on population and nature patterns. The HHO algorithm imitates harris hawks attacking behavior and includes two phases called exploration and exploitation, which can be modeled with three strategies, 1) discovering the prey, 2) surprising attack, and 3) prey attack. The main purpose of using this type of algorithm is to optimally solve the short-term hydro-thermal self-scheduling (STHTSS) problem with wind power(WP), photovoltaic (PV), small hydro (SH) and pumped hydro storage (PHS) powr plants while considering uncertainties such as energy prices, ancillary services prices, etc, in the energy market. It will be shown how energy generation companies can use this algorithm and other algorithms and innovative methods that will be introduced in the future to achieve profit maximum with careful scheduling. It is worth mentioning that in this study, the effect of the presence and absence of two important factors, namely valve load cost (VLC) effect and prohibited operating zones (POZs) (with linear modeling) that can affect the profit of units (power plants) has been pointed out. Finally, as shown in this study, several tests perfomed on the IEEE118-bus system validate the precision and credibility of the harris hawks optimization algorithm.*

Keywords—Uncertainty Management In Short-term Self-scheduling Unit Commitment Using Harris Hawks Optimization Algorithm

NOMENCLATURE

Abbreviations

BC	Bilateral contract
BP	Bilateral price
EM	Energy market
FCF	Fuel cost function
HHO	Harris Hawks optimization
HHO-A	Harris Hawks optimization algorithm
HTWSS	Hydro-thermal-wind self-scheduling
ISOs	Independent system operators
MILP	Mixed-integer linear programming
MP	Market prices
NP	Normalized propability
OSSUC	Optimal self-scheduling unit commitment
PHS	Pumped hydro storage
POZs	Prohibited operating zones
SP	Spot market
SR, NSR	Spinning reserve, Non-spinning reserve
TG	Turbine-generator
VLC	Valve loading cost
WP	Wind power

Binary variables

$\chi^{n\,g\,t\,\omega}$	Equals 1 When power out-put of power plant g exceeds block n of VLC effects
$\delta^{n\,g\,t\,\omega}$	Equals 1 when block n from fuel cost curve of power plant g is selected
$\delta^{n\,m\,t\,\omega}$	Equals 1 when the volume of reservoir water is greater than v^n (m)
$I^{d\,g\,t\,\omega}$	Equals 1 when power plant g provides NSR when the power plant = offline
$I^{g\,t\,\omega}$	Equals 1 when power plant g = online
$I^{m\,t\,\omega}$	Equals 1 power plant m = online
$I^{m\,t\,\omega}$	Equals 1 when H power plant m has starts-up
$Y^{g\,t\,s}$	Equals 1 when power plant g shuts down
$Z^{g\,t\,\omega}$, $I^{m\,t\,\omega}$	Equals 1 when G and H power plants g ,m respectively starts up
t ^{sh}	A binary variable showing whether the PHS unit can operate/not operate as a H turbine in scenario s in t ^{sh}

Constants

ΔX^t	The difference between the prey's position vector and its current position at iteration t
ω^{in} , ω^{out}	Cut-in and Cut-out speed (m/s)
ω^r	Rated out-put speed (m/s)
ω_{ws}	Wind speed (m/s)
π^{sh}	Expected price in s, in t$_{sh}$ (\$/MWh)
β^t	Solar radiation (w/m^2)
$\eta^{\,p}_{\,sh}$	Efficiency of the PHS (p.u.)
η^{SH}	Efficiency of TG assembly (0.85)
π^b_t	Bilateral price(BP) (\$/MWh)
$\rho^{\,s}_{\,sh}$	Probability of occurrence of scenario s (p.u.)
ρ^{SH}	Water density (1000 kg/m^3)
c_{su}, c_{su}	Start up/shut down costs of pumping power plants (\$)
$d^{\,p}_{\,min}$, $d^{\,p}_{\,max}$	Pumping power limits for each PHS power plant (MW)
$F(p^u_{n_n-1\ g})$	Upper limit in the fuel cost curve of power plant g (\$/h)
$g^{\,p}_{\,max}$	Generation power limit of each of the PHS units (MW)
$H^{\,SHW}$	Effective pressure head (25m)

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$P^{\,e}_{rp\,o}$	The rated out-put power (PV)
$p^{c\,m}$	Capacity of power plant m (MW)
$p^{min\ g}_{out}$, $p^{max\ g}_{out}$	Min and max out-put power of power plant g (MW)
$p^{min\ m\ n_n}_{out}$	Min out-put power of power plant m for performance curve n_n(MW)
$p_{u_n\ n-1\ g}$	Upper limit of the n_n-1^{th} POZs of power plant g (MW)
$p^{b\ t}$	Power capacity of BC (MW)
$p^{d\ n_n g}$	Lower limit of the $n_n{}^{th}$ POZs of power plant g (MW)
$p^{n_n\ r\ \omega}$	Normalized probability of scenario s
$Q^{\,SHW}$	Water flow rate
$Q^{\,min\ m}_{\,out}$, $Qout^{\,max}_{\,m}$	Min and max water discharge of power plant m (m^3/s)
$RDL^{\,n_n\ g}$, $RUL^{\,n_n\ g}$	Ramp down/up limits of block n_n (MW)
$RDL^{g\ t\ \omega}_{p}$,$RUL^{g\ t\ \omega}_{p}$	Ramping down/ up limits of power plant g (MW)
R^c_r	Irradiance under certain conditions (120 w/m^2)
SUE^g, SDE^g	Start-up / shut-down emission produced by power plant g (lbs)
$SUR^g_{g_g}$,$SDR^g_{g_g}$	Start-up /shut-down ramp rate limits of power plant g (MW/h)
$vol^{\,min\ m}$	Min content of the reservoir for power plant m (Hm^3)
$vol^{\,max\ \ m\,n_n}$	Max content of the reservoir m for the $n_n{}^{th}$ performance curve (Hm^3)
vo^l, vf^l	Initial and final levels in the lower reservoir (MWh)
vo^u, vf^u	Initial and final levels in the upper reservoir (MWh)
$v^{\,l}_{\,min}$, $v^{\,l}_{\,max}$	Capacity limits of the lower reservoir (MWh)
v^u_{min} , v^u_{max}	Capacity limits of the upper reservoir (MWh)
E_F	Escaping energy of the prey
M_u	Number of POZs
$N^{\,sh}$	Number of identical PHS units of the same pond
p_r	Rated out-put power (KW)
P_{TW}	Total wind power (kW)
SDC^g, SUC^m	Shut-down/ Start-up cost of power plants g,h ($)
$W^{\,p\ sh}$	Penalty factor of energy imbalances (p.u.)
$X^{\,t+1}$	Position of the hawk in the next iteration at time t

Indices

Λ	Photovoltaics
ω	Scenario
g	Thermal unit
j	Wind unit
m	Hydro unit
p	Pumped hydro storage
t	Time duration
u	Small hydro

Sets

ω	Scenario
F	Photovoltaic units
G	Thermal units
H	Hydro units
J	Wind units
N	The set of indices for blocks of PL in the hydro unit PC (*L*)
P	Pumped hydro storage units
T	Periods of market time horizon T ={1, 2, . . . , NT}
t^{sh}	Periods PHS t^{sh}={0, . . . , N}
U	Small hydro units

Variables

$\bar{T}$	Max number of repetitions of the algorithm
$\bar{x}_v$	Vector of decision
β^i	A constant value (1.5)
J_p	A random number between 0–1
N^H_t	Total number of hawks
$O_i\left(N^H_t\right)$	Computational complexity of the initial process
r^5	A number simulating the prey's movement
v^i, u^i	Random numbers between 0–1
X^{rabbit}_t	Shows the position of the prey
X^{rand}_t	A random hawk in the current population of hawks
$\nu^{u\ sh}, \nu^{l\ sh}$	Energy storage in the upper/lower reservoir in scenario ω at the end of t^{sh} (MWh)
$\pi^{\ sp\ t\omega}$,$\pi^{\ sr\ t\omega}$, $\pi^{\ ns\ t\ \omega}$	MP for energy, SR, N-SR ($/MWh)
$d^{\,p\ sh}$	Pumping power in-put of the PHS power plant in scenario ω in t^{sh} (MW)
$F^{g\ t\ \omega}$	Fuel cost of power plant g ($)
$G^{\,n\ g\,t\,\omega}_{\,G}$	Generation of block n of fuel cost curve of power plant g (MW)
$g^{p\ sh}$	Discharge power out-put of the PHS power plant in scenario ω in t^{sh} (MW)
$N^{-d\ m\ t\ \omega}$,$N^{-u\ m\ t\ \omega}$	NSR of power plant m in the SM when the power plant is off/on (MW)
$N^{\ d\ g\ t\ \omega}$, $N^{\ u\ g\ t\ \omega}$	NSR of power plant g in the SM when the power plant is off/on (MW)
$p^{\ max\ g\ t\ \omega}_{\ out}$	Max power out-put of power plant g (MW)
$p^{\ sp\ t\ \omega}$	Power for bidding on the SM (MW)
$P^{\Lambda}_{\beta t}$	Power out-put (PV)
p_n	Number of competing objective functions
$p^{\Lambda\ t\ \omega}_{out}$	Power out-put of PV power plant j (MW)
$p^{g\ t\ \omega}_{out}$	Power out-put of power plant g (MW)
$p^{j\ t\ \omega}_{out}$	Power out-put of wind power plant j (MW)
$p^{m\ t\ \omega}_{out}$	Power out-put of power plant m (MW)
$p^{u\ t\ \omega}_{out}$	Power out-put of SH (MW)
P^{SH,Q_W}	SH power plants produce power
$q^{\ P}$	Number of intervals
$Q^{\ n\ m\ t\ \omega}_{out}$	Water discharge of power plant m and block n (m^3/s)
$SR^{g\ \ t\ \ \omega}$, $SR^{m\ \ t\ \ \omega}$	SR of a power plant g and m in the SM (MW)
$SUC^{\ g\ t\ \omega}$	Start up cost of power plant g ($)
$VLC^{\ g\ t\ \omega}$	Valve load cost effects of power plant g ($)
$vol^{\ \ m\ t\ \omega}$	Water content of the reservoir of power plant m (Hm^3)
X^t_i	The position of each hawk in iteration t
D^P	Problem dimension
E_F	The energy of escaping prey
E_i	The initial value of energy in this algorithm is randomly selected between -1, 1
L^B, U^B	Upper and lower limits
L^F	Levy flight function
n_n	block for Ramp down/up limits
r^1, r^2, r^3, r^4, q_i	Random numbers in each iteration between 0–1
r^3	A random coefficient to increase the random nature of the future
r^4	A coefficient very close to 1
S^V	A random vector with the size of component D^P
u^{sh}	The number of power plants in the pumping state scenario ω in $t^{\ sh}$ equal 0,. . . , N
X^m	The average location of hawks in the current population
X^t	Shows the current position of hawks
$y^{\ sh}$, $z^{\ sh}$	The number of start-up/shut-down units in the pumping state scenario ω in $t^{\ sh}$

1. INTRODUCTION

In recent years, novel clean and renewable energies (REs), such as WP-PV-SH, etc. have grown dramatically. Therefore, studying hydro-thermal units with wind power-photovoltaic, small hydro, pumped hydro storage complementary operation is of great significance to promote RESs generation. However, in power systems, as GENCOs are looking for more profit, they are attempting to benefit from the participation of RESs along with

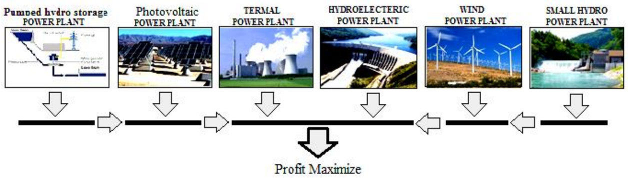


Fig. 1. Schematic diagram of hybrid (H-T,WP, PV ,SH ,PHS units) power system

other generation units to achieve higher profit. Therefore, to maximize the profits of energy GENCOs, this paper presents an optimization algorithm with a specific formulation to solve the problem with the help of mixed-integer programming (MIP).

Reference [1] point outs to ST-HTS as an important topic in power system. Reference [2] presents a stochastic structure of GENCOs that participate in short-term HTSS for simultaneous reserve and energy markets. A study of optimization and a new method using MIP is presented in, Reference [3] to solve the HTSS problem concerning day-ahead joint energy and energy storage. Reference [4] proposes the use of MIP in the day-ahead market aiming to find a solution to the HTSS problem. Problems subject to nonlinearity and inequality constraints, proper solutions are suggested in different. For example, MIP, Reference [5], Benders decomposition (BD), Reference [6], and using different smart methods, Reference [7] have already been presented. References [8, 9] employ the MIP and a deterministic scheduling model for power plant scheduling, in which the effects of the upstream hydropower plant are considered with three efficiency curves in the form of piecewise linear approximation. Taking into account the various uncertainties for problem solving and modeling of hydro-thermal units, a solution related to multiple performances for the day-ahead energy market is presented in, Reference [10]. The authors in [11] point out that the use of renewable energy is increasing due to their suitable properties such as cleanliness, cheapness, etc. Reference [12] introduces pumped storage to store energy. Reference [31] discusses the deficiencies concerning the coordination and planning of hydro-wind units. The authors in [14] propose apporaches to reduce pollutant emissions and strengthen hydro-thermal-wind units. Uncertainty-related issues concerning electrical energy price has also been analyzed Reference [15]. Moreover, energy, fuel, and ancillary services for coordination of power plants based on energy price in a stochastic structure are discussed in [16] in which hourly prices are produced randomly. As generation companies (GENCOs) aim at profit maximization, the authors [17] introduce a stochastic scheduling algorithm to manage hydro-thermal generation units. Reference [18] investigates self-scheduling of hydro-thermal power plants considering stochatic electrical energy prices. Additionally, the HTSS problem using a deterministic method is solved in [19]. A power system with hydro-wind units is scheduled using a stochastic structure [20]. Also, VLC effect is considered by introducing a linearization structure [21]. Reference [22] introduces an HTSS associated with dynamic ramp rate. Self-scheduling (SS) of hydro-thermal-wind (HTW) power plants has been discussed References [23, 24] by adopting a linearization approach. An optimal stochastic model is proposed to schedule a power system (by incorporating MILP method and two-stage structure) concerning the capacity of (hydro) H, (wind power) WP, and PV(photovoltaic) units is presented in, Reference [25]. Concerning the short-term scheduling of energy GENCOs, Reference [26] refers to a structure to solve the HTSS problem with a wind farm. Reference [27] focuses on a multi-stage approach concerning dynamic scheduling of GENCO. GENCOs, in an attempt to maximize their profit from energy and reserve markets, incorporate compressed air energy storage together with wind and heat enrgy, Reference [28]. Reference [29] presents an approach to optimal scheduling and coordination of wind units, PV arrays, thermal units, and fossil fuels to maximize profits and reduce pollution of power plant units. In the United States, the costs of energy and energy storage in power systems using wind energy to generate electricity from energy markets and related energy reserves have been reviewed, Reference [30]. In Reference [31], to determine the efficiency of a power system, an optimization model is proposed that combines a compressed air energy storage system and hydro-thermal, wind turbines, and PV arrays. A modified bacterial algorithm has been used to solve the model. Reference [32] provides a complete description of the technical and economic modeling and optimization of pump hydro storage (PHS) power plants combined with wind and PV units. To minimize energy costs and operation costs in the power system, the authors in [33] have proposed the simultaneous use of energy storage units, wind power, photovoltaics, thermal units, and electric heater. In addition, they used a multi-objective particle swarm optimization (PSO) algorithm to provide a solution to a function with multiple objectives. An optimal method based on stochastic programming (SP) is proposed by the authors in, Reference [34] to maximize the profits of GENCOs which is a combination of wind, thermal, and compressed air energy storage units (CAES). Reference [35] introduces the point estimation method for possible short-term scheduling of GENCOs, which are a combination of H-T-WP-PV units. Reference [36] refers to the optimal solution of a problem related to GENCOs in coordination with wind-pumped storage thermal units in the field of spinning reserve (SR) and daily energy markets by taking into account CO_2 emission and wind energy uncertainty to maximize profits. Reference [37] refers to the modeling of pumped storage hydro-thermal system (PSHTS) with wind energy sources (WES) that adopt mixed decision variables for the scheduling problem. Reference [38] discusses the coordination of unit commitment (UC) and uncertainty of RESs and pumped hydro energy storage (PHEs). It also proposes the use of the binary artificial sheep algorithm (BASA) to improve problem-solving optimization. Several methods have been proposed in, Reference [54] for computationally acceptable solutions in power system operation using relevant analysis and modeling. The Moth Flame Optimization (MFO) and Lévy Flight Search (NSMFLF) methods have been used in, Reference [55] to solve the problem of profit-based unit commitment of power plants in the restructured power system integrated with wind power. Reference [56] has used two-objective optimization to evaluate the reliability in day and night operation (with the presence of PHS-PV) along with investment costs for the entire system. Considering that the Harris Hawks Optimization (HHO) algorithm has fast convergence and low convergence accuracy in solving optimization problems, Reference [57] adopts a heuristic strategy based on a logarithmic spiral and a local search technique to improve the convergence accuracy and increase the local search capability, respectively. Reference [58] presents a new formula with the help of Bernstein polynomials for multi-objective optimization and scheduling to day-ahead minimization of costs and emission of CHP units. Reference [59] carries out a comparative study with multi-objective optimization (minimization of costs and emission) named Hierarchical Particle Swarm Optimization (HPSO) for one-day environmental/economic planning (24 hours) of distributed generation units with renewable energy sources in a grid-connected microgrid. The lightning attachment procedure optimization algorithm (LAPO) has been adopted in ,Reference [60] to solve the short-term hydro-scheduling (STHS) with the presence of renewable energy sources (WP, PV). The main goal of the Reference [61] is to solve the optimal planning (minimizing the total operating costs) problem using modeling methods like Analytical Hierarchy Process (AHP) and considering the Market Clearing Price (MCP) for unit commitment of power plants based on profit maximization. To solve the problem of short-term (day-ahead) planning of the unit commitment of power plants, Reference [62] presents a combination of a dynamic programming optimization method and a genetic algorithm (DP-GA) to compare with different optimization techniques in a day ahead. Moreover,

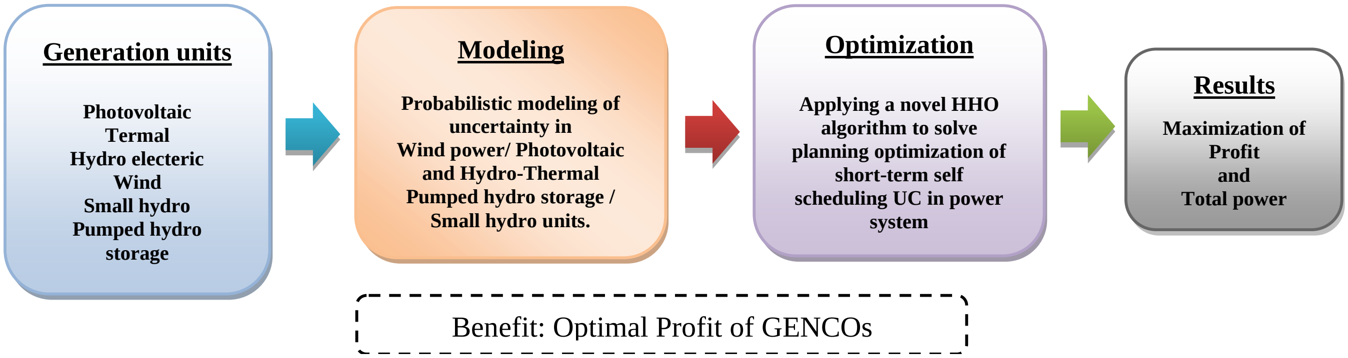


Fig. 2. Procedure of the proposed approach

it also refers to optimal methods of recurrent neural network and a support vector machine (SVM) to predict wind power. Reference [63] refers to the use of a new modified version of the gray wolf optimization algorithm (MGWO) to solve the problem of unit commitment considering the market price change as the main uncertainty.

The most central part of this paper is the presentation of an algorithm called the harris hawk optimization, inspired by nature, to solve the ST-HTSS problem with WP/PV/SH/PHS units and to consider various uncertainties such as energy prices and prices of spinning reserve (SR) and non-spinning reserve (N-SR). However, the purpose of the proposed model, as a practical method for solving the problem based on MIP, is to achieve efficient optimization. Therefore, to consider uncertainty of energy price and other other parameters, in addition to adopting the probability distribution function (to predict price error), LMCS and RWM methods that are also important in predicting error are adopted. In the continuation of the discussion, the conversion of the linearization process in the modeling topic is used to consider the effect of VLC. In general, the formulas presented in this research include various expressions such as VLC, energy price, wind units, photovoltaics, small hydro units, and other constraints that energy GENCOs can consider so that daily scheduling results of upcoming days are found.

The present approach aims to profit maximize subject to meeting several different constraints including uncertain parameters. Fig. 1, depicts a general schematic diagram of a hybrid (WP, PV, SH, PHS units) power system. Fig. 2, depicts the basis of a stochastic single objective (S-SO) function for profit maximization of GENCOs. The key novelties of the present study can be summarized as follows:

- Using the HHO algorithm to generate and select the best solution:
- Achieving the profit maximization simultaneously, taking into account some types of uncertainties and important constraints power plant units.
- Presentation of linear formulation for valve loading cost effect and using dynamic ramp rate limit instead of fix ramp rate limit.
- Using flexible method for multi POZs of thermal units and multi performance curves for hydro units.
- A general linear mathematic expression is incorporated in the OSSUC model with and without WP, PV, SH, and PHS units that consist of MUT, MDT, fuel price, fuel cost function, etc.
- Risk of generating units'intermittency as well as the price and renewable energies (REs) generation uncertainties is modeled in the stochastic optimization framework.

The paper organization is described here. Section 2 presents the SO-SHTSS problem formulation with WP/PV/SH/PHS units. Section 3 explains the stochastic modeling of uncertainties. Section 4 describes the harris hawk optimization algorithm method. Section 5, based on the importance of the proposed algorithm, discusses four studies to investigate the solution of a stochastic single-objective(SO) problem. In addition, four case studies are tested on the IEEE 118-bus test system to investigate the accuracy and validity of the suggested approach. Section 6 refers to the results of the present studies obtained from this study and their comparison with the results of other researchers. Finally, Section 7 summarizes the important conclusions reached.

2. SO-SHTSS Problem Formulation

2.1. Objective function: maximizing expected profit

The single-objective short-term hydro-thermal self-scheduling (SO-SHTSS) with WP/PV/SH/PHS units attempts to maximize the expected profit (E^{PG}) of GENCOs. The formulation of the objective function is expressed in Eq. (1):

$$f^{1\,max}\,|E^{P\,G} = \left\{ \sum_{\omega \in N_s} p^{nr\,\omega}\left(profit^{\omega\,G}\right)\right\} + \left(\pi^{b\,t} p^{b\,t}\right) \tag{1}$$

$$\text{profit}^{\omega\,G} = \sum_{t\in T} \left\{ \begin{array}{l} \sum_{g\in G}\left\{\left(N^{\,u\,gt\omega}+N^{\,d\,gt\omega}\right)\pi^{\,n_s\,t\omega}+\pi^{\,sr\,t\,\omega}\,SR^{gt\,\omega}\right\} \\ -\sum_{g\in G}\left\{Y^{\,gt\,\omega}\,SDC^{\,g}+SUC^{\,gt\omega}+F^{gt\omega}+VLC^{gt\omega}\right\} \\ -(\sum_{m\in M} I^{\,mt\omega}\,SUC^{m})+\,p^{sp\,\,t\,\omega}\,\pi^{\,sp\,t} \\ +\sum_{m\in M}\left\{\left(N^{\,u\,mt\omega}\_+N^{\,d\,mt\omega}\right)\pi^{\,n_s\,t\,\omega}(+\pi^{\,sr\,t\omega}\,SR^{mt\omega})\right\} \end{array} \right\} \tag{2}$$

In short, this equation consists of four parts. The first two parts are related to thermal units and the other two parts include hydro units. In each section, the effect of a bilateral contract to extract fixed income and the presence of each scenario in the income of the units can be seen. The basis of this equation is the starting up cost equation of hydro units obtained from, Reference.[40]. It should be noted that Eq. (2) consists of equality, inequality constraints, and various uncertainties. Total power output of HT/WP/PV/SH and PHS units, which equals the total power transactions in the EM according to the bilateral contract (BC), is another essential constraint, represented by:

$$\begin{array}{c} \sum_{u\in U} p_{out}^{u\,t\,\omega} + \sum_{p\in\,P} p_{out}^{p\,t\,\omega} + \sum_{g\in G} p_{out}^{g\,t\,\omega} \\ +\sum_{m\in M} p_{out}^{m\,t\,\omega} + \sum_{j\in\,J} p_{out}^{j\,t\,\omega} \\ +\sum_{\Lambda\in\,\Lambda} p_{out}^{\Lambda\,t\,\omega} = p^{\,sp\,t\,\omega} + p^{\,b\,t} \\ \forall t\in T, \forall\omega\in\omega,\, \forall p\in P, \\ \forall g\in G\,, \forall m\in M, \forall j\in J\,, \forall u\in U, \forall\Lambda\in\Lambda \end{array} \tag{3}$$

Section 2.2 provides the reset of constraints of thermal (T) units. H units need to be modeled so that H and WP/PV/SH/PHS units can be related to each other. This is stated in sections 2.3 and 2.7.

2.2. Model of Thermal (G) power plant

Linear formulae need to be adopted to change thermal unit equations from nonlinear form to linear form. So, linear forms of relationships given in sections 2.2.1-2.2.5 associated with these units are provided.

A) FCF considering POZs

To find the fuel cost, we use a second-order function is follows for thermal units. As thermal units operate under specific situation, mechanical constraints including vibration of shaft ball bearing prevent thermal units from engaging in separate operation from the rest of areas. The following equations provide the cost function and output cost of thermal units:

$$F^{gt\omega}=\sum_{n_n=1}^{M_u+1}\left[\delta^{n_n\ gt\ \omega}\ F_{(\ P\ _{u\ n_n-1\ g})}+G_G^{n_n\ gt\omega}\ (b^{n_n\ g})\right] \quad \forall g\in G,\ \forall t\in T, \forall\omega\in\omega \tag{4}$$

$$p_{\ out}^{\ g\ t\ \omega}=\sum_{n_n=1}^{M_u+1}[(p_{u\ n_n-1g})\ \delta^{n_n\ gt\omega}+G_G^{n_n\ gt\omega}] \quad \forall g\in G,\ \forall t\in T, \forall\omega\in\omega \tag{5}$$

Moreover, since the FCF(Fuel cost function) of thermal (G) units is a binary variable, this function of power block n and for the *i*-th thermal unit will be. In the rest of the discussion and according to, Reference.[41], the FCFof themral units can be linearized subject to the following constraints:

$$0\leq G_{G}^{\ n\,gt\omega}\ \ ;\ \ n_n=\ 1,\ \ldots,\ M_u+1 \quad \forall g\in G,\ \forall t\in T, \forall\omega\in\omega \tag{6}$$

$$G_G^{n_n\ gt\omega}\ \leq\ (p^{d\,n_n g}-p^{u\,n_n-1\ g})\ (\delta^{\ n_n\ gt\omega}) \quad n_n=1,...,M_u+1 \tag{7}$$

$$I^{\ gt\omega}=\sum_{n_n=1}^{M_u+1}\delta^{n_n\ m\ t\omega}\forall g\in G,\ \forall t\in T, \forall\omega\in\omega \tag{8}$$

Equation (7) presebts the Max $p^{d\ M_u+1\ g}$ equal $p^{\ max\ g}$ and Min $p^{u\ og}$ equal $p^{\ min\ g}$ output power of the thermal plant. Concerning limit (8), generation units are allowed to operate in areas under consideration.

B) VLC effects

An VLC function specific to G power plants, References [42], [64], [65] and [66] can be expressed as a nonlinear or nonconvex function.

C) utput limits of the thermal (G) unit

RDL and RUL limits of the thermal plant are given as follows:

$$\{p_{out}^{max\,gt\,\omega}\}\leq\{Y^{g\,t+1\,\omega}\,(SDR_{\omega_\omega}^{\omega})\}+\{(I^{gt\omega}-Y^{\omega\,t+1\,\omega})(p^{max\ g})\} \tag{9}$$

$$\{p_{\ out}^{\ g\ t-1\ \omega}-p_{\ out}^{\ g\,t\,\omega}\}\leq\{(RDL_{\ p}^{\ g\,t\,\omega})+(SDR_{\ g_g}^{\ g}\ (Y^{g\,t\,\omega}))\} \tag{10}$$

$$p_{\ out}^{\ max\ g\,t\,\omega}\ \geq p_{out}^{g\,t\,\omega}\ \geq p^{min\ g}\ (I^{g\,t\,\omega}) \tag{11}$$

$$\{p_{\ out}^{\ g\,t+1\,\omega}-p_{\ out}^{\ g\,t\,\omega}\}\leq\left\{(SUR_{\ g_g}^{\ g}(Z^{g\,t+1\ \omega}))+RUL_{\ p}^{\ g\,t\,\omega}\right\} \tag{12}$$

D) ynamic ramping up / down limit: (RUL) , (RDL)

As per, Reference [23], a function called DRR can be defined for power plants. Hence, Eqs. (13) and (14) are introduced to determine RUL and RDL:

$$RUL_{\ p}^{\ g\,t\,\omega}=\sum_{n_n=1}^{M_u+1}(RUL^{\ n_n\ g})\ (\delta^{n_n\ g\ t\ \omega}) \quad \forall g\in G,\ \forall t\in T, \forall\omega\in\omega \tag{13}$$

$$RDL_{\ p}^{\ g\,t\,\omega}=\sum_{n_n=1}^{M_u+1}(RDL^{n_n\ g})\ (\delta^{n_n\ g\ t\ \omega}) \quad \forall g\in G,\ \forall t\in T, \forall\omega\in\omega \tag{14}$$

The output power generation by thermal unit need to be addressed. Although $\delta_n^{n\ g\ t\ \omega}$ are present, thermal units are successfully related with DRR via $\delta_n^{n\ g\ t\ \omega}$. Eqs. (13) and (14) describe these relationships.

E) ther constraints for G power plant

Power systems operators require some auxiliary and complementary services and actions to equip the system with safety actions. On the other hand, these services are essential for active and reactive powers. Three different categories can be defined for reserve services, Reference [43]: SR, NSR, and alternative or backup reserves. The rest of constraints given in, References [5]–[44] associated with thermal units such as startup cost function, min up time, the min down time ,etc. are described in the following sections.

2.3. Model of hydro units

There is a relationship between the inflow and outflow of water from upstream reservoirs, which results in the power generation by water units. However, these units can communicate with the reservoirs of upstream units (inlet) and downstream units (outlet) through the MIP formulae. Accordingly, in formulating the MIP scheduling problem for the model of hydro units, parameters such as power plant reservoirs with small storage volume, water discharge fluctuations, etc. have also been considered. However, the efficiency curves of hydro units must be carefully considered in the formulae.

A) Piecewise linear formulation of variable head multi-performance curves

This section describes linear relationships and performance curves (L) related to hydro units as follows:

$$\sum_{n_n=2}^{L}\left[(vol^{\ max\ m\ n_n-1})\ (\delta^{\ n_n-2\ \ m\ t\ \omega}-\delta^{n_n-1\ m\ t\ \omega})\right] + \left[(vol^{\ max\ m\ L})\ (\delta^{\ L-1\ m\ t\ \omega})\right]\geq\ vol^{m\ t\ \omega} \tag{15}$$

Performance curves $\delta^{n}{}_{n}^{\ \ m\ t\ \omega}$ depend on the amoutn of water in dam reserves:

$$\sum_{n_n=3}^{L}\ [(vol^{\ max\ \ m\ \ n_n-2})(\delta^{\ n_n-2\ \ m\ t\ \ \omega}-\delta^{\ n_n-1\ m\ t\ \omega})] + [(vol^{\ max\ \ m\ L-1})(\delta^{\ L-1\ m\ t\ \omega})]\leq\ vol^{\ m\ t\ \omega} \tag{16}$$

B) Linear power discharge performance curves (L)

The following equations and sections represent linearized equations, water depletion from dams, hydro (M) power, and their operation curves:

$$[(p_{out}^{m\ t\ \omega})-(p^{min\ m\ k})(I^{mt\omega})]-\sum_{n_n\in N}[(b^{n_n\ m\ k})(Qd^{\ n_n\ mt\omega})] + (p^{c\ m})[\sum_{n_n=k}^{L-1}\delta^{\ n_n\ m\ t\ \omega}+(k-1)-\sum_{n_n=1}^{k-1}\delta^{\ n_n\ m\ t\ \omega}]\geq 0 \quad 1\leq k\leq L \tag{17}$$

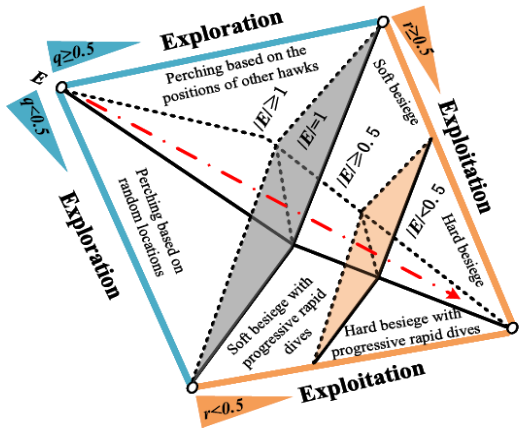


Fig. 3. HHO algorithm steps

$$[(p_{out}^{m\ t\ \omega}) - (p^{min\ m\ k})(I^{mt\omega})] - \sum_{n_n \in N} [(b^{n_n\ m\ k})(Qd^{n_n\ mt\omega})] + [\sum_{n_n=k}^{L-1} \delta^{\ n_n\ m\ t\ \omega} + (k-1) - \sum_{n_n=1}^{k-1} \delta^{\ n_n\ m\ t\ \omega}](p^{c\ m}) \leq 0 \quad 1 \leq k \leq L \tag{18}$$

C) The rest of constraints of hydro power plants

Cases including (1) water overflow of dams, Reference [5], (2) water balance and the initial water storage, References [5, 9] , and operational services, can also be addressed to more precisedly investigate the problem [43].

2.4. Model of pumped hydro storage (PHS) power plants

In, References [53], the pumped hydroelectric storage (PHS) power plant consists of two upstream and downstream sources with reversible pump turbines that can operate in either generator or motor modes. The PHS unit pumps water to the upstream source during the energy consumption period, and at peak consumption times, water is transferred from the upstream source to the downstream source by generating electrical energy. In this case, the water turbine operates in generator mode. This cycle is economically viable because at non-peak times the price of electricity is low and at times of peak consumption the price of electricity is high so that the revenue from the sale of energy offsets the cost of purchasing energy and system losses. The mathematical model of the PHS units in operation is given in (19) and their limitations are provided by (20)-(30):

$$Max \sum_{\omega \in \omega} \rho_{sh}^{\omega} \sum_{m \in M} \left[(g^{p\ sh} - d^{p\ sh})(\pi^{sh}) - c_{su}(y^{sh}) - c_d(z^{sh}) - w^{psh}(\pi^{sh}). \left| g^{psh} - d^{psh} - x^{ph} \right| \right] \tag{19}$$

subject to:

$$\nu^{u\ sh} = \nu^{u\ sh-1} + \eta_{sh}^{p}(d^{p\ sh}) - g^{p\ sh} \quad \forall\omega \in \omega, \forall t \in T \tag{20}$$

$$\nu^{l\ sh} = \nu^{l\ sh-1} + g^{psh} - \eta_{sh}^{p}(d^{p\ sh}) \quad \forall\omega \in \omega, \forall t \in T \tag{21}$$

$$\nu_{min}^{u} \leq \nu^{u\ sh} \leq \nu_{max}^{u} \quad \forall\omega \in \omega, \forall t \in T \tag{22}$$

$$\nu_{min}^{l} \leq \nu^{l\ sh} \leq \nu_{max}^{l} \quad \forall\omega \in \omega, \forall t \in T \tag{23}$$

$$\nu^{u\ sh} = \nu f^{u} \quad , \nu^{l\ sh} = \nu f^{l} \quad \forall\omega \in \omega, \forall t \in T \tag{24}$$

$$u^{sh+1} = u^{sh} + y^{sh} - z^{sh} \quad \forall\omega \in \omega, \forall t \in T \tag{25}$$

$$d_{min}^{p}(u^{sh}) \leq d^{p\ sh} \leq d_{max}^{p}(u^{sh}) \quad \forall\omega \in \omega, \forall t \in T \tag{26}$$

$$\left\{(1 - \tfrac{1}{N}).u^{sh}\right\} \geq t^{sh}\ , t^{sh} \in \{0, 1\} \quad \forall\omega \in \omega, \forall t \in T \tag{27}$$

$$N(g_{max}^{p}) \geq x_{h}^{p} \geq N(-d_{min}^{p}) \quad \forall\omega \in \omega, \forall t \in T \tag{28}$$

$$u^{sh}, y^{sh}, z^{sh} \ \in \{0, 1, dots, N\} \quad \forall\omega \in \omega, \forall t \in T \tag{29}$$

$$N(t^{sh})(g_{min}^{p}) \geq g_{sh}^{p} \geq 0 \forall\omega \in \omega, \forall t \in T \tag{30}$$

In these relationships, the output variables $g^{p\ sh}$ and $d^{p\ sh}$ are the consumption variables of the PHS power plant, and z^{sh} and y^{sh} are the on and off units in each scenario and hour, respectively. Variable x^{ph} is proposed so that a PHS power plant can produce power at each hour. Variable ν shows the volume of source energy in each of the upstream and downstream sources.

The maximum and minimum volume ν_{max}^{l}, ν_{max}^{u} and ν_{min}^{l}, $\nu_{min}^{u}$of the resource capacity are considered 80 MW and 0 MW, respectively, which are considerable. The capacity of the two sources is obtained from Eq. (31):

$$(g_{max}^{p}.(N) + g_{max}^{w}) \geq x^{wp\ h} \geq -(d_{min}^{p}.(N)) \quad \forall\omega \in \omega, \forall t \in T \tag{31}$$

The efficiency of the PHS unit system is 80%. Equation (19) shows the objective function of the PHS power plant. The first term in Eq. (19) represents the revenue from the sale of energy and the second and third terms show the cost imposed on the unit due to switching on and off, respectively. The fourth sentence shows the cost of an imbalance in energy production or consumption. Eq. (24) reprsents the energy storage at the end of period. Assuming that for T=1, $\nu^{l\ sh-1}$ equals νo^{l} and $\nu^{u\ sh-1}$ equals νo^{u}, variable u^{sh} gives the number of pumps per hour. Water balance of dams is provided by constraints (20)-(21), and the dependencies between these variables can be found in Eq. (25). These capacities and limitations in the energy market are given by Eq. (28).

2.5. Model of wind units

Dependency of output power of wind turbine to wind speed has already been investigated by some, References [49, 50]. To provide a solution to SO-STHTSS problems, the intermittent nature of wind power should be considered and analyzed first, Reference [50]. As we know, v represents wind speed and C > 0 and K > 0 represent scale and shape, respectively. Probability density function (PDF) can be obtained from Eq. (32) and cumulative distriburion funciton (CDF) is derived from Eq. (35) considering constraints (33) and (34):

$$pdf_j^J = (\frac{\omega_{in}}{c})\left[\frac{\omega_{in}}{c}(1+\frac{((\omega_r\ /\omega_{in})-1)J}{j^r})\right]^{k-1}.exp\left\{-\left[(\frac{\omega_{in}}{c})(1+\frac{((\omega_r\ /\omega_{in})-1)J}{j^r})\right]^{k}\right\}(\frac{k((\omega_r\ /\omega_{in})-1)}{j^r}) \tag{32}$$

$$p_{|j=0} = \ p_r(\omega_{in} > \omega_{\omega_{\omega S}}) + p_r(\omega_{\omega_{\omega S}} > \omega_{out}) = 1 - exp(-(\frac{\omega_{in}}{c})^k) + exp(-(\frac{\omega_{out}}{c})^k) \tag{33}$$

$$p\,|_{j=j_r} \ = \ p_r(\omega_{out} \geq \omega_{\omega_{\omega s}} \geq \omega_{in}) = 1 - exp(-(\frac{\omega_{in}}{c})^k) + exp(-(\frac{\omega_{out}}{c})^k) \tag{34}$$

$$cdf_j^J = \left\{ \begin{array}{cc} 0 & (0 > j) \\ (\frac{\omega_{in}}{c})\left[(1+\frac{((\omega_r/\omega_{in})-1)J}{j^r})(\frac{\omega_{in}}{c})\right]^{k-1}.exp\left\{-\left[(1+\frac{((\omega_r/\omega_{in})-1)J}{j^r})(\frac{\omega_{in}}{c})\right]^{k}\right\}.(\frac{k((\omega_r/\omega_{in})-1)}{j^r}) & (j^r > j \geq 0) \\ 1 & (j^r \leq j) \end{array} \right\} \tag{35}$$

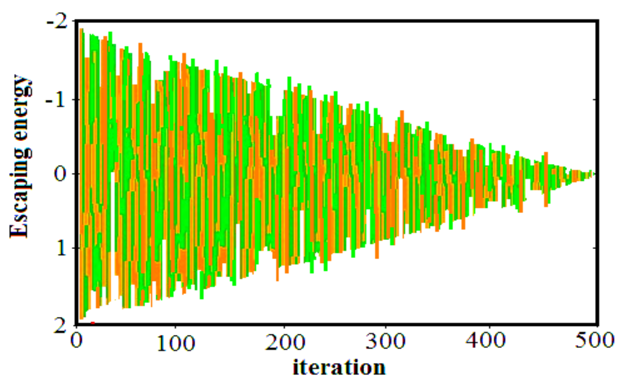


Fig. 4. Depiction of E_F for three runs and 500 iterations

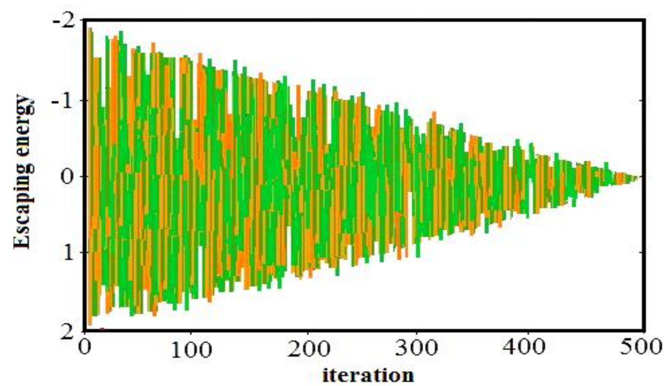


Fig. 5. E_F for three runs and 500 iterations for case 1

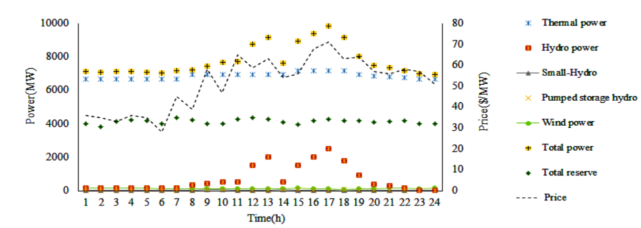


Fig. 6. Results of total generation power (HT-WP-PV-SH-PHS) and price for case study 1

2.6. Model of small hydro(SH) units

According to, Reference [51], the power generation of small hydro units(power plant) is obtained based on Eq. (36). The power production by this type of power plant relies on water flow and water pressure.

$$P^{SH,Q_W} = H^{SHW}.\,Q^{SHW}.\,g^{SH}.\,\rho^{SH}.\,\eta^{SH} \tag{36}$$

2.7. Model of photovoltaic(PV) units

In general, according to, Reference [52], the required power of PV cells is obtained from solar radiation, and according to Eq. (37):

$$p^{\Lambda}_{\beta t} = \left\{ \begin{array}{cc} P^e_{rpo}[\frac{(\beta^t)^2}{\beta^{s\ rs}.R^c_r}] & R^c_r > \beta^t > 0 \\ P^e_{rpo}[\frac{\beta^t}{\beta^{s\ rs}}] & \beta^t > R^c_r \end{array} \right\}, \qquad t = 1, ...T \tag{37}$$

3. Stochastic Modeling of Uncertainties

According to, Reference [39], the Lattice Monte Carlo Simulation (LMCS) has suitabley been used to solve various problems, including the coordination and planning of power plants, some of which "have a (price) prediction error or various types of uncertainty (wind power/solar irradiation). In the discussion of the standard deviation for each time interval, according to the price prediction error (σ), References [40, 41] refer to it. However, References. [41] and [42] refer to price prediction levels using PDF and RWM to create different scenarios per hour. However, the process of reducing scenarios (elimination of weak scenarios or low probability scenarios) has been used in ,References [40] and [41]. Therefore, after eliminating the weak scenarios, strong scenarios for solving the problem will remain.

4. Harris hawks optimization algorithm method

According to studies in, Reference [48], the Harris hawk is one of the intelligent and most unique predators among birds in nature. The hunting method begins with an "amazing attack". This attack is called the "seven kills" strategy, in which harris hawks (HHs) attempt to beseige the preys and identify them as they converge during the hunting. But sometimes the ability to escape and the

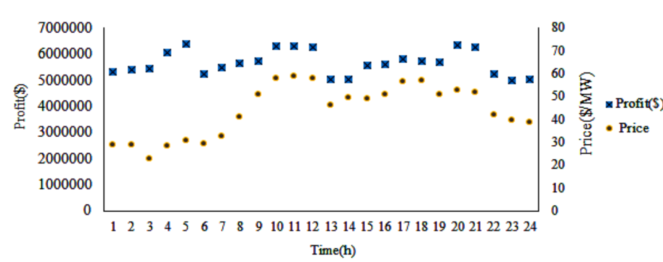


Fig. 7. Hourly energy price and expected profit of GENCOs for case study 1

Table 1. The HHO-A solution to S-SO-STHTSS problem (Case study 1)

Objective function	Total power (MW)	Total reserve (MW)	Profit($)	Computation time (s)
Expected profit($)	181899.38	3321	5421648.01	85

Table 2. The HHO-A solution to S-SO-STHTSS problem (Case study 2)

Objective function	Total power (MW)	Total reserve (MW)	Profit($)	Computation time (s)
Expected profit($)	184800.29	4071.02	5843083.07	72

Table 3. The HHO-A solution to S-SO-STHTSS problem (Case study3)

Objective function	Total power (MW)	Total reserve (MW)	Profit($)	Computation time (s)
Expected profit($)	181961.27	3956.85	5424418.01	63

Table 4. The HHO-A solution to S-SO-STHTSS problem (Case study4)

Objective function	Total power (MW)	Total reserve (MW)	Profit($)	Computation time (s)
Expected profit($)	184864.4	4386.87	5845853.17	59

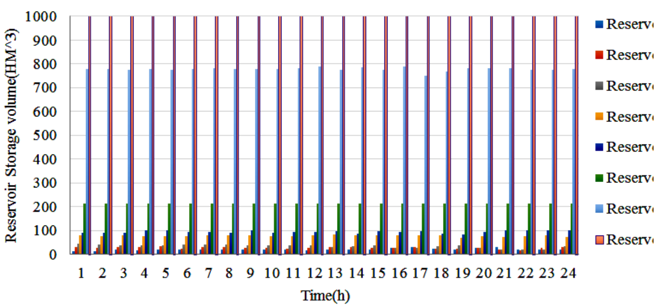


Fig. 8. The water contents of reservoir storage for case study 1

behavior of the prey in this strategy may take a few minutes, this is due to the rapid and short dive behavior near the prey from different directions. The most important advantage of this method is the cooperation of Harris hawks in identifying prey, which can increase the vulnerability of prey. In short, Each of the steps (4-1)–(4-3-3) (as shown in Fig. 3) need to be considered when trying to provide a solution to the optimization problem when using the HHO algorithm.

4.1. Exploration phase

This section focuses on describing the exploraiton phase of the HHO algorithm. HHO can detect, track and hunt prey. In this algorithm, hawks wait in different random places until they may be able to detect the prey using strategies (with equal chances). According to Eq. (38), strategies consist of two categories:
Strategy 1: HHs specify their place with respect to those of other HHs and the prey (rabbit) (provided that $q_i < 0.5$).
Strategy 2: HHs are randomly placed in long random locations (on tall trees) (provided that $q_i \geq 0.5$).

$$X^{H+1}=\left\{\begin{array}{ll} X_t^{\text{rand}}-r^1\left|X_t^{\text{rand}}-2r^2X^t\right| & q_i\geq 0.5 \\ \left(X_t^{\text{rabbit}}-X_t^m\right)-r^3\left(L^B+r^4\left(U^B-L^B\right)\right) & q_i\leq 0.5 \end{array}\right\} \tag{38}$$

One can also consider a simplified model to randomly produce places between (L^B, U^B). Equation (39) can also be used to determine the average location of the total number of HHO.

$$X_t^m=\left(\frac{1}{N_t^H}\right)\sum_{i=1}^{N_t^H}X_i^t \tag{39}$$

4.2. Transition from exploration to exploitation

HHO-A can be transferred from exploration to exploitation phase and, among various exploitation behaviors, it can select prey using the remaining energy. The prey's escape energy will decrease over time. Equation (40) is used to model this:

$$E_F=2E_i\left(1-\frac{t}{T}\right) \tag{40}$$

When E_i increases from -1 to 0, the prey (rabbit) becomes weaker, while if E_i increases from 0 to 1, the prey becomes stronger. The important point is that if the escape energy of the prey is constrained as $|E_F|>1$, HHO will search for the prey's location, so the algorithm is in the exploration phase. Additionally, if $|E_F|<1$, the algorithm is in the exploitation phase. For example, Fig. 4 shows the escape energy of the prey E_F with respect to the number of iterations.

4.3. Exploitation phase

At the exploitation phase, HHs attack the prey detected in the previous stage, and they form different tracking behaviors in different situations. If the prey successfully escapes (0.5> r) or the escape is failed (0.5≤ r), there is the chance of prey before the sudden attack of the hawk. When the prey is escaping, the hawks use a hard or soft siege to catch it. However, after a few minutes, they lose their energy gradually, after which the prey becomes tired and gets into trouble. The soft siege occurs when it $|E_F|>0.5$ and the hard siege is formed take $|E_F|<0.5$.

A) oft besiege

Prey will have enough energy when conditions$|E_F|>0.5$ and 0.5≤ r are established, but in the end, the attempt to escape will not work. During this effort, the hawks will make a surprise attack. They run softly and surround the prey. In the meanwhile, the prey also gets more tired. The soft siege is modeled according to Eq. (42):

$$\Delta X^t-X_t^{\text{asbt}}-X^t \tag{41}$$

$$X^{-11}=\Delta X^r-ET_p\left(X_r^{\text{motet}}\right)-X' \tag{42}$$

In this case, hawks severely encircle their prey by surprise attack, and its formula is given as Eq. (43):

$$X^{=11}=X_z^{\infty m}-E_r\left|\Delta X^t\right| \tag{43}$$

Table 5. Results summary of different References

Discription	**Our article**	Reference [31]	Reference [32]	Reference [33]	Reference [34]	Reference [36]
Generation unit type	H-T-WP-PV-SH-PHS	H-T-WP-PV-CAES	H-PV-PHS-CAES	WP-PV-T-EH	T-WP- CAES	WP-T- PHS
Multi-objectiv function	✗	✗	✗	✓	✗	✓
Single-objectiv function	✓	✓	✗	✗	✓	✗
Uncertaite number	5	2	✗	2	4	3
Max.profit	✓	✗	✗	✗	✓	✓
Min.emission	✓	✗	✗	✗	✗	✓
Min.cost	✗	✓	✗	✓	✗	✗
Case stady number	4	2	✗	3	3	2
Uncertainty modeling	✓	✓	✗	✓	✓	✓
Simulat random method	✓	✓	✗	✓	✗	✗
Algorithm	✓	✓	✗	✓	✗	✓
Other optimization	✓	✗	✗	✗	✓	✓
Consider the load	✗	✗	✗	✗	✗	✗
Solution method	HHO	MBFA	✗	PSO	✗	GA
Operation	GENCOs	GENCOs	GENCOs	GENCOs	GENCOs	ISO
Review article	✗	✗	✓	✗	✗	✗

B) Soft besiege with progressive rapid dives

Nonetheless, when conditions $|E_F| \geq 0.5$ and $r < 0.5$ are met, the prey has the potential of escaping, but the soft siege will remain. In this case, for prey escape patterns and mutant movements, a mathematical modeling known as levy flight or L^F is adopted. In fact, hawks make several quick group laps around the prey and try to modify their location as per the deceiving movements of the prey.

In addition, L^F-based patterns have been identified in animal tracking activities such as monkeys and sharks. Therefore, Harris hawks are gradually choosing the best position to attack the prey. If it is assumed that the hawks can make the necessary decision to make a soft siege in the next move, Eqs. (44) will be used in this regard:

$$Y^i = X_t^{\text{rabbit}} - E_F \left| J_P \left(X_t^{\text{rabbit}} \right) - X^t \right| | \tag{44}$$

Next, HHO compare the possible outcome of their movement with their previous dive to validate the dive. The hawks are thought to dive using the following rule (Eqs. (45)–(47)) based on L^F-based patterns:

$$Z = Y' \times S^v \left(D' \right) \tag{45}$$

$$\sigma^i = \left[\frac{\Gamma\left(1+\beta^i\right) \times \sin\left(\frac{\pi \beta^i}{2}\right)}{\Gamma\left(\frac{1+\beta^i}{2}\right) \times \beta^i \times 2^{\frac{\beta^i - 1}{2}})} \right]^{\frac{1}{\beta^i}} \tag{46}$$

$$LF_x = 0.01 \times \left[\frac{(u' \times \sigma')}{| v''} \right]^1 \tag{47}$$

Equation (48) can be used for the final strategy so that HHs' locations are updated:

$$X^{t-1} = \left\{ \begin{array}{l} Y^i \text{ if } F\left(Y^i\right) < F\left(X^t\right) \\ Z^i \text{ if } F\left(Z^i\right) < F\left(X^t\right) \end{array} \right\} \tag{48}$$

C) Hard besiege with progressive rapid dives

If conditions $|E_F| < 0.5$ and $r < 0.5$ are considered, the prey cannot escape because it does not have enough energy. At this point, before the hawks suddenly attack the prey to hunt and kill the prey, a severe siege ensues.

In this step, the hawks are trying to get closer to the prey. Hence, in case of a severe besiege, Eq. (49) is used:

$$X^{t+1} = \left\{ \begin{array}{l} Y^i \text{ if } F\left(Y^i\right) < F\left(X^t\right) \\ Z^i \text{ if } F\left(Z^i\right) < F\left(X^t\right) \end{array} \right\} \tag{49}$$

Where Y^i and Z^i are calculated from Eqs. (44)–(45) in Eq. (44) and X_t^m can be found from Eq. (39).

4.4. Computational complexity in harris hawks optimization algorithm

There are three factors impacting the complexity of the HHO algorithm: (1) initialization, (2) competency assessment, and (3) hawks update.

The calculation of the complexity of this mechanism is based on the update, which consists of looking for the most suitable position as well as updating HHs locations. Thus, the computational complexity equation of this algorithm is obtained from Eq. (50).

$$C_C = O_i \left(N_t^H \times \left(\overline{T} + \overline{T} D^P + 1 \right) \right) \tag{50}$$

4.5. HHO algorithm for optimization

The steps to solve the optimization problem of this paper by adopting the HHO algorithm are described here.

Step 1: Read the input data of the power system (including parametersof the model and initial estimation of electrical enegy price, WP and PV power, etc).

Step 2: RWM and LMCS for random scenario produce, also PDF is used to predict their errors (wind speed/photovoltaic power/price, etc).

Step 3: Define including parameters of HHO, control variable and their limits, and objective function to be optimized.

Step 4: Generate a set of N solutions of dimension D between the max and min limits of the control variables.

Step 5: Set N^{inter}=1.

Step 6: Is network constraints are satisfied if Yes go to step 7, if No go to step 8.

Step 7: Calculate the objective function value (profit) for all agents, go to step 9.

Step 8: Discard the results.

Step 9: Calculate the smallest fitness and related best solution.

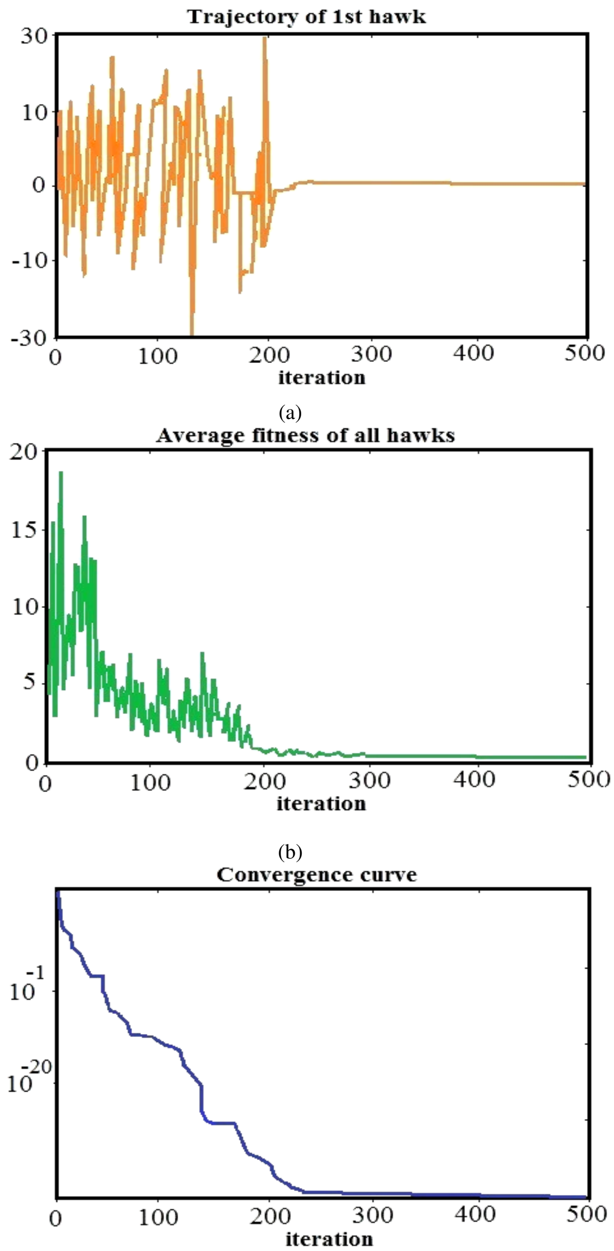
Step 10: Compute the probability of the fitness value as per Eq. (46) .

Step 11: Check if $N^{iter,max} \geq N^{iter}$, if Yes go to step 12, if No go to step 12.

Step 12: N^{iter} = N^{iter}+1 go to step 6.

Step 13: Print report the optimal results(profit (M- G power , photovoltaic power, wind power, SH power, and pumped hydro storage)).

Step 14: End.



(a) (b) (c)

Fig. 9. Qualitative analysis results for case study 1

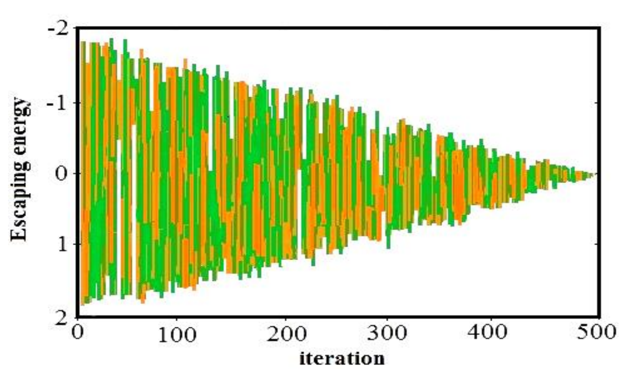


Fig. 10. The behavior of E_F during three runs and 500 iterations for case 2

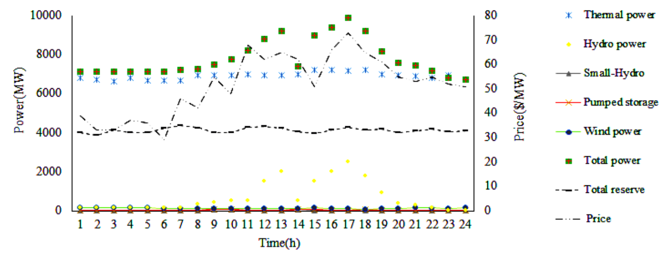


Fig. 11. Results of total generation power (HT-WP-PV-SH-PHS) and price for case study 2

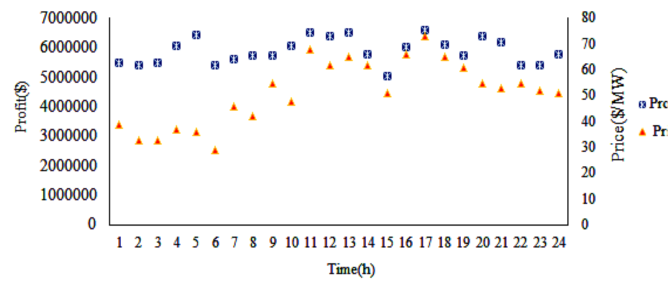


Fig. 12. Hourly energy price and expected profit of GENCOs for case study 2

4.6. Pseudocode of HHO algorithm

The HHO algorithm can be summarized as follows:

Inputs: The population size N and maximum number of iterations T.

Outputs: The location of the rabbit and its fitness value

Initialize the random population X_i (i = 1, 2, . . . ,N).

while (termination criteria is not satisfied) do

Calculate the fitness values of the HHs

Set X^{rabbit} as the location of the rabbit (best location).

for (each hawk (X_i)) **do**

Update the initial energy E_i and jump strength J_p

Update E_F based on Eq. (48).

If ($|E_F| \geq 1$) **then** → Exploration phase

Update the location vector using Eq. (46).

If ($|E_F| < 1$) **then** → Exploitation phase

If (r ≥0.5 and $|E_F| \geq 0.5$) **then** → Soft besiege

Update the location vector using Eq. (50).

Else if (r ≥0.5 and $|E_F| < 0.5$) **then** → Hard besiege

Update the location vector using Eq. (**??**).

Else if (r <0.5 and $|E_F| \geq 0.5$) **then** → Soft besiege with progressive rapid dives

Update the location vector using Eq. (**??**).

Else if (r <0.5 and $|E_F| < 0.5$) **then** Hard besiege with progressive rapid dives

Update the location vector using Eq. (**??**).

Return X^{rabbit}

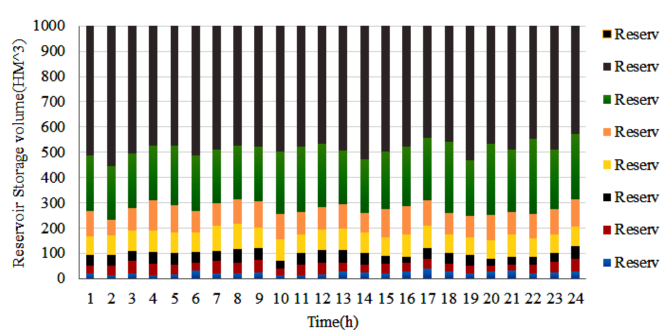
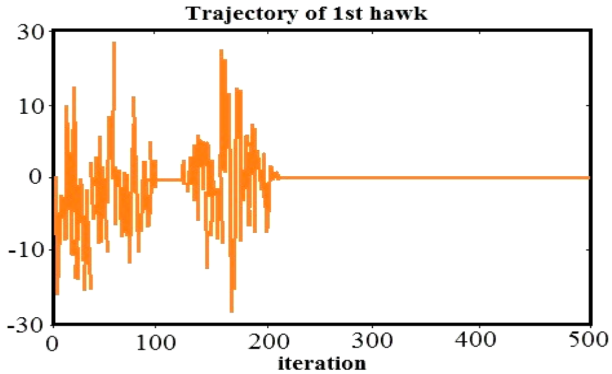
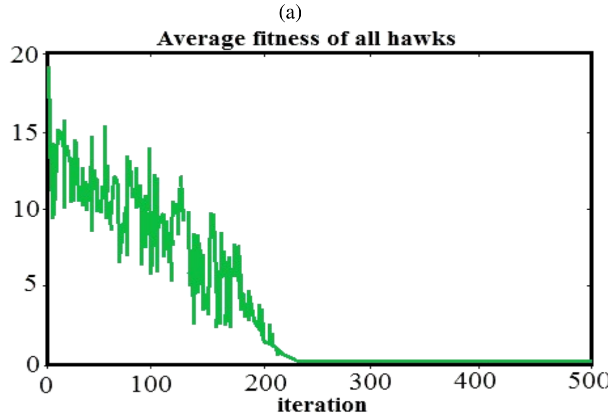


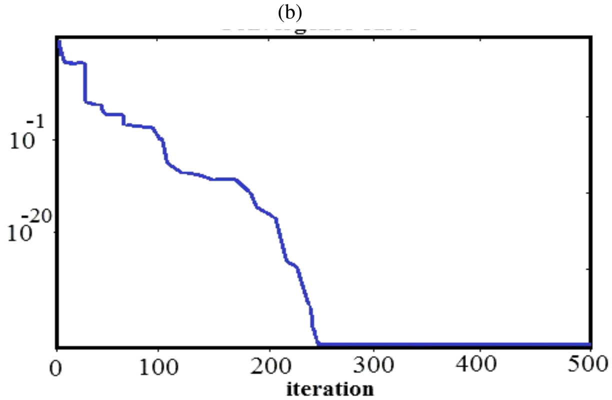
Fig. 13. The water contents of reservoir storage for case study 2



(a)



(b)



(c)

Fig. 14. Qualitative analysis results for case study 2

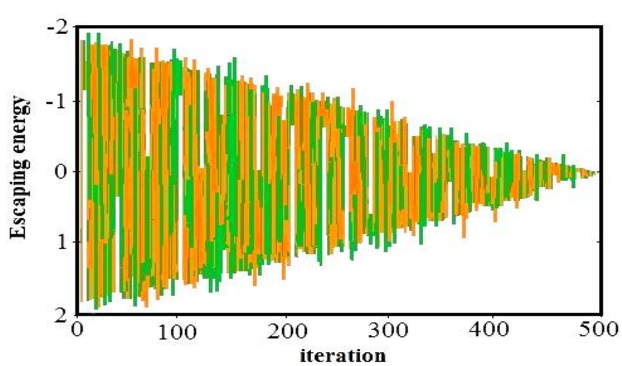


Fig. 15. The behavior of E_F during three runs and 500 iterations for case 3

5. Description of the Test Systems and Case Studies

The stochastic HTSS and case studies are tested on the IEEE 118-bus system. The system consists of 54 thermal (T) units that operate with different types of fuel, including ten power plant with cruel oil fuel, eleven power plant with gas fuel, and thirty-three units with charcoal fuel. Reference [9] provides the data related to 8 hydro units. The following assumptions are made: (1) As ramp rates are known, the data is not changing, (2) When scheduling and unit commitment of generation units, several thermal units, like 33, 41, 46, and 49 are not incroporated because of thir high costs, (3) In BC of electricity pricing, the energy amount and price per hour are set 1000 MW and 45$/hour, respectively, (4) Water head in the dam, water depletion from the dam, and power generation establish the three paramters of the hydro power plant model, (5) As per Reference [45], the amount of fuel consumption and hydro units costs will be equal to the energy consumed at the startup time, (6) The data required for scheduling wind turbines is Reference to [46], (7) The data associarted with thermal power plants sych as POZs and coefficients of VLC are Reference to [47], and (8) to plan G and M power plants, the data of References [9, 46] is used. So, the single-objective stochastic optimization method is used here to solve self-scheduling problem of generation power plants concerning the effects of VLC, POZs, etc with and without WP, PV, SH, and PHS units when maximizing the profits of energy GENCOs. The cases investigated in this paper include:

- Stochastic HTSS problem of WP/PV/SH/PHS with VLC and POZs.
- Stochastic HTSS problem of WP/PV/SH/PHS without VLC and POZs.
- Stochastic HTSS problem of WP/PV/SH/PHS with VLC.
- Stochastic HTSS problem of WP /PV/SH/PHS without VLC.

5.1. Case study

1 This section investigates an optimal solution to the Stochastic-SO-STHTSS (S-SO-STHTSS) problem by adopting the HHO-A to maximize GENCOs' profit. The present paper focuses on analyzing the impacts of uncertainties associated with energy price, operating services price, and WP and PV by considering SH and PHS units and VLC, POZs. Only the best scenario out of 500 scenarios produced by LMCS and RWM will remain. The result in Fig. 5 shows the important point that if $|E_F| \geq 1$, HHO will search different areas to find the prey's location. So, the algorithm is in the exploration phase, and when $|E_F| < 1$, the algorithm is in the exploitation phase. Fig. 5 (escaping energy-iteration) shows the behavior of E_F for three runs and 500 iterations.

HT, WP, PV, and PHS units generate a total of 181899.38 MW of electrical power. Hence, as per Table 1, the profit expected from a stochastic solution of the S-SO-STHTSS problem in the presence of WP/PV/SH/PHS units will be 5421648.01 $ with a calculation time of 85 s.

Fig. 6 shows how energy price and the total power output of H-T, WP, PV, SH, and PHS units(power plants) are related. With increased energy price in the spot market (SP), a majority of G units participate in power generation to gether with the rest of generation power plants.

Fig. 7 depicts the imapct of energy price changes on the profit of GENCOs.

Fig. 8 shows the hourly water contents of reservoir storage.

In summary, Fig. 9 show the results include three well-known metrics: the trajectory of the first hawk, average fitness of population, and convergence behavior. The search history diagram reveals the history of those positions visited by artificial hawks during iterations. The map of the trajectory of the first hawk monitors how the first variable of the first hawk varies during the steps of the process (Fig. 9(a)). The average fitness of hawks monitors how the average fitness of whole population varies during the process of optimization (Fig. 9(b)). The convergence metric

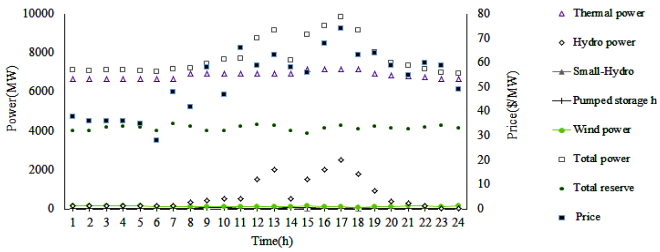


Fig. 16. Results of total generation power (HT-WP-PV-SH-PHS) and price for case study 3

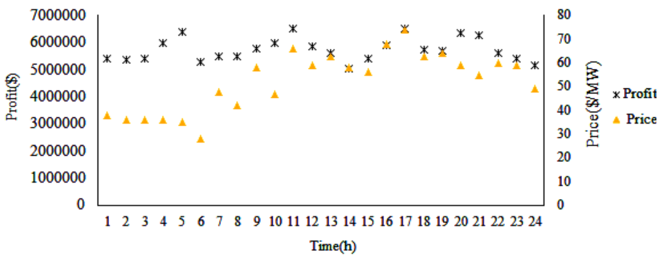


Fig. 17. Hourly energy price and expected profit of GENCOs for case study 3

also reveals how the fitness value (best solution) varies during the optimization (Fig. 9(c)).

5.2. Case study 2

This section addresses the problem of the Stochastic- SO-STHTSS (S-SO-STHTSS) using the HHO algorithm. As mentioned earlier, the paper analyzes the imapct of uncertaitnies associated with energy price, ancillary service price, WP and PV with and without SH and PHS units by considering factors such as VLC and POZs on profit maximization of energy GENCOs. In summary, Fig. 10 shows that hawks search different areas for prey. If the algorithm is in the exploration stage, then the prey escaping energy will be $|E_F| \geq 1$, and when the algorithm is in operation, it will be $|E_F| < 1$. The Escaping Energy-iteration diagram shows the E_F behavior during three runs and 500 iterations in Fig. 10.

Therefore, according to Table 2, the expected profit and total generated electrical power from the stochastic solution of the short-term SO-STHTSS problem in the presence of WP/PV/SH/PHS units are 5843083.07$ and 184800.29 MW, respectively, which are calculated within 72 s.

Fig. 11 shows the changes in the total generation power of HT, WP, PV, SH, and PHS units and energy prices in a short period (24 hours). However, most thermal units participate in energy generation besides the rest of power plants by increasing energy prices in the market.

Fig. 12 shows the imapct of changes of energy price on the profit of GENCOs.

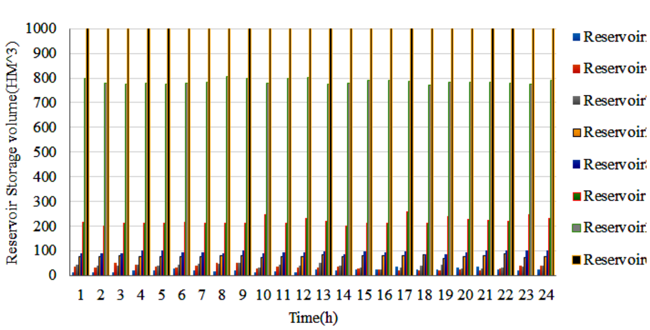
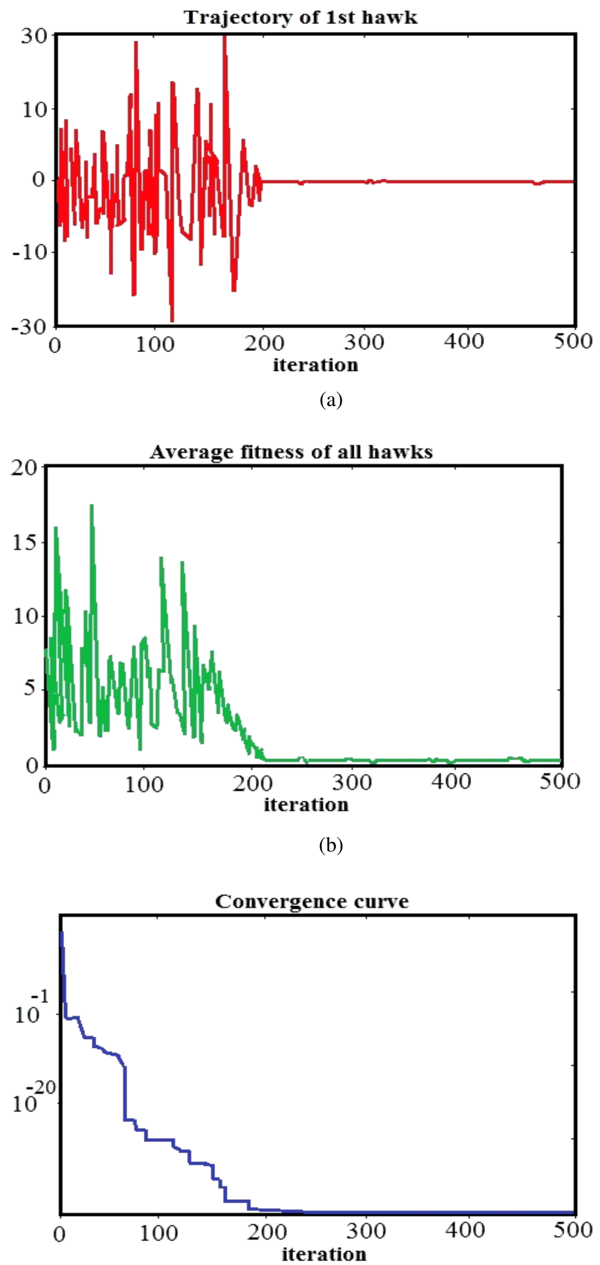


Fig. 18. The water contents of reservoir storage for case study 3



(a)

(b)

(c)

Fig. 19. Qualitative analysis results for case study 3

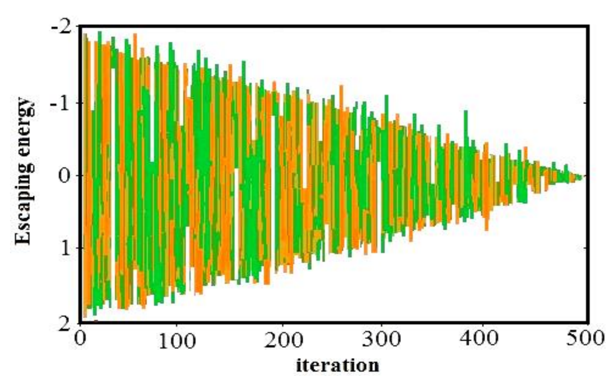


Fig. 20. The behavior of EF during three runs and 500 iterations for case 4

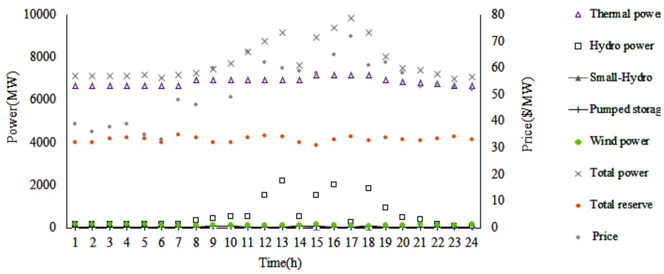


Fig. 21. Results of total generation power (HT-WP-PV-SH-PHS) and price for case study 4

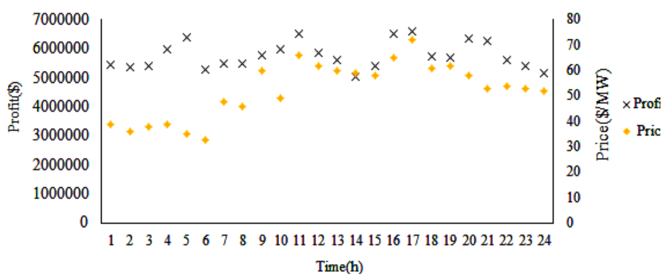


Fig. 22. Hourly energy price and expected profit of GENCOs for case study 4

Fig. 13 illustrates the hourly water contents of reservoir storage.
In summary, Fig. 14 show the results include three well-known metrics: the trajectory of the first hawk, average fitness of population, and convergence behavior. The search history diagram reveals the history of those positions visited by artificial hawks during iterations. The map of the trajectory of the first hawk monitors how the first variable of the first hawk varies during the steps of the process (Fig. 14(a)). The average fitness of hawks monitors how the average fitness of whole population varies during the process of optimization (Fig. 14(b)). The convergence metric also reveals how the fitness value (best solution) varies during the optimization (Fig. 14(c)).

5.3. Case study 3

The Stochastic- SO-STHTSS (S-SO-STHTSS) problem is solved here using the HHO-A. In the suggested model, only the best scenario out of 500 scenarios generated by LMCS and RWM will remain. The result in Fig. 15 shows that if $|E_F|\geq 1$, HHO will search different areas to find the prey's location, so the algorithm is in the exploration phase, and when $|E_F|<1$, the algorithm is in the exploitation phase. In general, PV, HT, WP, and PHS units produce a total of 181961.27 MW of electrical power. Therefore, as per Table 3, the expected benefit from stochastic solving the short-term SO-STHTSS problem in the presence of WP/PV/SH/PHS units will be 5424418.01$ with a calculation time of 63 s.

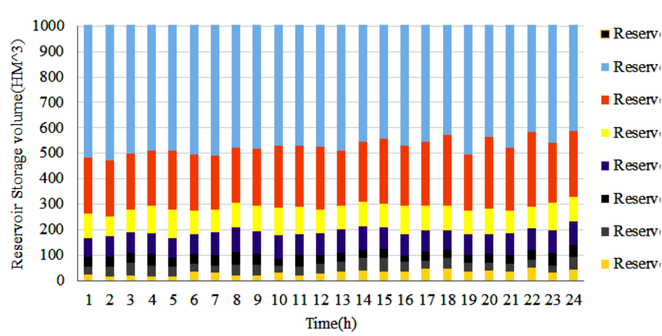


Fig. 23. The water contents of reservoir storage for case study 4

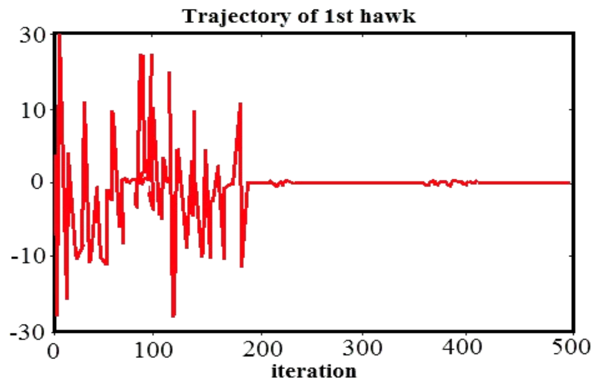
Fig. 16 shows the relationship between changes in energy prices and total power output by HT, WP, PV, SH, and PHS units over a period of 24 hours. However, with rising energy prices, most thermal(G) units tend to continue to participate in energy generation alongside other power plants.
Fig. 17 shows the impact of changes of energy price on the profit of GENCOs.
Fig. 18 illustrates the hourly water contents of reservoir storage.
In summary, Fig. 19 show the results include three well-known metrics: the trajectory of the first hawk, average fitness of population, and convergence behavior. The search history diagram reveals the history of those positions visited by artificial hawks during iterations. The map of the trajectory of the first hawk monitors how the first variable of the first hawk varies during the steps of the process (Fig. 19(a)). The average fitness of hawks monitors how the average fitness of whole population varies during the process of optimization (Fig. 19(b)). The convergence metric also reveals how the fitness value (best solution) varies during the optimization (Fig. 19(c)).

5.4. Case study 4

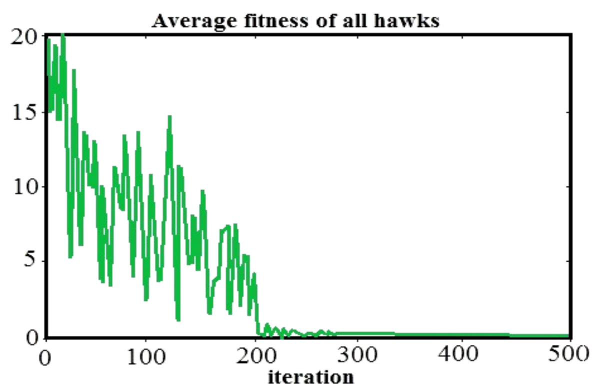
The Stochastic SO-STHTSS (S-SO-STHTSS) problem solution using the HHO algorithm is presented. The aim is to investigate the impacts of uncertainties associated with energy price, spinning reserve storage price, etc. WP and PV with and without SH and PHS units by taking into account the effect of the VLC factor on GENCOs profit maximization. In the suggested model of the S-SO-STHTSS problem for WP/PV/SH/PHS units, only the best scenario out of 500 scenarios produced by LMCS and RWM will remain. The result in Fig. 20 shows that if $|E_F|\geq 1$, the HHO will search different areas to find the position of the prey, so the algorithm is in the exploration phase, and when $|E_F|<1$, the algorithm is in the exploitation phase. The escaping energy-iteration curve shows E_F behavior during three runs and 500 iterations in Fig. 20.
In general, PV, HT, WP, and PHS units produce a total of 184864.4 MW of electrical power. Therefore, according to Table 4, the expected benefit from randomly solving the S-SO-STHTSS with WP/PV/SH/PHS units will be $ 5845853.17 with a calculation time of 59 s.
Fig. 21 shows the changes in the total power generation of HT, WP, PV, SH, and PHS units and energy prices in a short period of 24 hours. However, most thermal units participate in energy generation besides the rest of power plants by increasing energy prices in the market.
Fig. 22 shows the imapct of variations of energy price on the profit of GENCOs.
Fig. 23 illustrates the hourly water contents of reservoir storage.
In summary, Fig. 24 show the results include three well-known metrics: the trajectory of the first hawk, average fitness of population, and convergence behavior. The search history diagram reveals the history of those positions visited by artificial hawks during iterations. The map of the trajectory of the first hawk monitors how the first variable of the first hawk varies during the steps of the process (Fig 24(a)). The average fitness of hawks monitors how the average fitness of whole population varies during the process of optimization (Fig 24(b)). The convergence metric also reveals how the fitness value (best solution) varies during the optimization (Fig. 24(c)).

6. Comparative Analysis

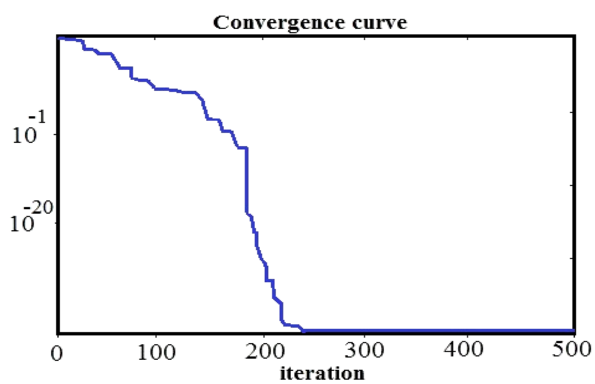
Here, we will compare and briefly review the References [2], [9], [10], [31], [32], [33], [34], [36]. In general, the structure of these References is in such a way that some of these refer to solving the problem of coordination and scheduling of generation units based on profit and others based on costs. Therefore, in[2], MIP was adopted to solve the problem. For case 2 of this paper, the amount of profit obtained from the random variables is



(a)



(b)



(c)

Fig. 24. Qualitative analysis results for case study 4

938340.178$. The MIP has been used to solve the problem [9]. Moreover, it only refers to the objective function of cost from an independent system operator's (ISO's) perspective. To solve the problem, Reference [10] adopts the MIP. Of the three case studies, only the third case reported a profit of 5980401.18$. It also refers to computer tools used to investigate the adoption of Res (H-T-WP-PV-SH-PHS) . To determine the efficiency of a power system, Reference [31] refers to an optimization model that combines a compressed air energy storage system (CAES) with H-T, WP, and PV units. Reference [32] provides a complete description of the technical, economic, and optimization of PHS power plants combined with WP and PV units. Reference [33] refers to the method of optimizing multi-objective functions to minimize costs and the use of transmission channels in a power system that combines wind-thermal-PV units and energy storage with solar energy and an electric heater. Reference [34] mentions the use of the optimization solution method for profit maximization of energy GENCOs for a power system that combines CAES and wind and thermal units in simultaneous energy and storage markets. Reference [36] uses a proposed optimization method to solve the problem of coordination of the HS-wind system for day-ahead energy and spinning reserve markets by considering the pollution rate and maximizing the profit. According to the summary of the cases mentioned in the References [31], [32], [33], [34], [36] and comparing them with the present study, some of their features can be summarized as shown in Table 5. However, in this study, according to the acceptable results, the use of the HHO algorithm, which is one of the population-based optimization techniques, is proposed to solve various problems in the field of stochastic scheduling, short-term coordination, and effective participation of GENCOs to maximize profits and, if necessary, reduce pollution and various costs (in terms of multi-objective functions) of power plants.

7. Conclusions

It has already been mentioned that the main strategy is to decide on the simultaneous participation of conventional, non-conventional power plants, different methods, and the harris hawk optimization algorithm to achieve the maximum profit expected by GENCOs. Therefore, this paper referred to solving a stochastic single-objective problem using short-term self-scheduling for an integrated power system that is a combination of HT, WP, PV, and PSH units. To solve the problem, the paper has used the optimization method based on the HHO. Importantly, to increase the computational speed, the nonlinear MIP problem was transformed into a linear MIP problem using linear approximation. It is worth noting that to achieve a more realistic structure and subsequent more accurate problem-solving results, a key parameter called the efficiency curve, which is specific to hydro units, is considered. In general, the profit in case 1, i.e. in S-HTSS with WP/PV/SH/PHS units, is influenced by VLC and POZ factors, is equal to 5421648.01$. The second case study profit without POZ and VLC factors is 5843083.07$. Nonetheless, the profit of the third case study, which refers to S-HTSS with WP/PV/SH/PHS units and is influenced by the VLC factor, is equal to 5424418.01$. In the fourth case study, the profit without the VLC factor is equal to 5845853.11$. By examining factors such as POZs, VLCs as well as considering types of uncertainty and predicting errors such as the price of SR and NSR energy, and PV and wind power, in this study, it was shown to what extent the expressed factors can achieve the maximum profit of power plant units to be effective. Another point, as shown, is how energy GENCOs can achieve their maximum profit, by what methods, and by considering what important factors. In this way, GENCOs can easily analyze the factors mentioned or even other factors and make the necessary scheduling plans and correct decisions to achieve their goals (including profit maximization). Finally, the method of achieving the expected maximum profit (by introducing the use of the HHO-A (algorithm)) was discussed and desirable results were found.

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