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SECURITY CONSTRAINED HYDROTHERMAL UNIT COMMITMENT FOR DIFFERENT HYDROLOGICAL SCENARIOS USING GENETIC ALGORITHM

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A b s t r a c t: The main objective of the Security Constrained Hydrothermal Unit Commitment (SCHTUC) is the optimal committing of the hydro and thermal units, i.e. to minimize the total cost (which are very non-linear and non-convex) of thermal plants while satisfying the many hydrothermal constraints. Such constraints, together with the nonlinear non-convex and mixed-integer objective function, make the search space extremely complex. The time of operation of the units is considered to be 24 h. To achieve this objective, a Genetic Algorithm (GA) with two new constraint handling repair mechanisms was applied. The proposed algorithm will be applied to the hydrothermal system, under different hydrological conditions, to prove i.e., confirmation of the initial hypothesis, which indicates that the total operating costs depend significantly on the hydrological conditions, i.e., the available volume of water and the inflows in the reservoirs of the hydropower plants. The proposed algorithm was applied on IEEE 30 bus system, but also tested on a benchmark system, and confirmed by comparison with other hybrid techniques such as PSO–GWO and DA-PSO. The efficiency of the proposed algorithm is established by comparing it to these two hybrid algorithms.

Key words: security constrained hydrothermal unit commitment; genetic algorithm; heat rate repair mechanism; constraint handling repair mechanism

ПРИМЕНА НА ГЕНЕТСКИ АЛГОРИТАМ ЗА ОПТИМАЛНО АНГАЖИРАЊЕ АГРЕГАТИ ВО СИСТЕМ СОСТАВЕН ОД ХИДРОЕЛЕКТРАНИ И ТЕРМОЕЛЕКТРАНИ СО УВАЖУВАЊЕ НА СИГУРНОСНИТЕ ОГРАНИЧУВАЊА ПРИ РАЗЛИЧНИ ХИДРОЛОШКИ СЦЕНАРИЈА

А п с т р а к т: Главната цел на оптималното ангажирање агрегати во сложен систем составен од хидро- и термоединици, со уважување на сигурносните ограничувања (Security Constrained Hydrothermal Unit Commitment – SCHTUC), е оптимален избор на хидро- и термоединиците, т.е. минимизација на вкупните трошоци (кои се изразито нелинеарни и неконвексни) на термоединиците, при истовремено задоволување на многу ограничувања. Ваквите ограничувања, заедно со нелинеарната неконвексната и мешано-целобројна критериумска функција, го прават пребарувачкиот простор исклучително сложен. Оперативното време, т.е. оптимизациониот период на хидро- и термоединиците, е 24 часа. За да се постигне оваа цел, односно да се реши овој оптимизационен проблем, применет е генетски алгоритам (GA) со два нови механизма за справување со ограничувањата. Предложениот алгоритам е применет на систем од хидро- и термоединици, при различни хидролошки услови, за да се докаже односно потврди почетната хипотеза, која укажува на тоа дека вкупните трошоци за работа значително зависат од хидролошките услови, т.е. од расположливиот волумен вода и дотоците во акумулациите на хидроединиците. Предложениот алгоритам е применет на IEEE 30 bus system, но и тестиран на референтен тест-систем, а следствено и потврден преку споредба со други хибридни метахеуристички методи, како што се PSO – GWO и DA-PSO. Ефикасноста и перформансите на предложениот алгоритам се верифицирани преку споредба со овие две хибридни техники.

Клучни зборови: ангажирање агрегати во хидро-термо систем со уважени сигурносни ограничувања; генетски алгоритам; repair mechanism базиран на параметарот heat rate; repair mechanism за справување со ограничувањата

1. INTRODUCTION

1.1. Motivation

Hydrothermal Unit Commitment (HTUC) is a crucial task in the economic operation of a power system. A good generation schedule of the committed units reduces the production cost, increases the system reliability, and maximises the energy capability of reservoirs by utilizing the limited water resource. The primary objective of the HTUC is to find the optimal combination of committed hydro and thermal units so as to minimize the fuel cost of thermal units. The problem requires that a given amount of water be used in such a way so as to achieve this objective, which is usually much more complex than the scheduling of all thermal system. This is because if water available is used up in the present interval there will not be any water for the next interval increasing this way the future operation costs. Electrically coupled hydro units themselves are difficult to coordinate with the thermal generation system to obtain minimum total system cost subject to various equality and inequality constraints. The SCHTUC is a non-linear programming problem involving non-linear objective function and a mixture of linear and non-linear constraints.

However, the solution of the UC or HTUC problem is not a guarantee that the produced, i.e. the generated power will successfully flow through the transmission lines to the final consumers. The Security Constrained Hydrothermal Unit Commitment (SCHTUC) considers more constraints than the standard HTUC or UC, such as the spinning reserve constraint, transmission line constraint and ramp rate constraint.

1.2. Literature review

Earlier papers have investigated the scheduling problem based on classical optimization techniques such as Lagrange relaxation [1], branch and bound search method [2], multistage Bender's decomposition method [3, 4], stochastic programming [5], mixed-integer linear programming [6, 7, 8] and hybrid decomposition strategy [9]. In these papers, only a quadratic objective function was considered.

Classical optimization methods, which can be direct or gradient, are characterized by multiple drawbacks in solving complex optimization problems. Gradient methods converge rapidly but are inefficient and inapplicable in problems characterized by non-convex and discontinuous objective functions, such as the SCHTUC problem. The main disadvantages of both groups of classical optimization methods are: the convergence of the optimal solution depends on the initial solution; stuck in local optimum; are not effective in problems that have discrete variables in addition to real variables.

Recent research has increasingly applied metaheuristic algorithms, as in [10] and [11]. But in them and many others a classical UC of an all thermal power system is solved. In the papers [12, 13, 14, 15] respectively a GA, invasive weed optimization algorithm, PSO-MILP, and adaptive general variable neighborhood search are applied to solve the classical UC, but only on a thermal system, considering a quadratic objective function, as well as much simpler constraints..

1.3. Contributions

When it comes to HTUC or SCHTUC, the optimization problem becomes significantly more complex, having in mind to solve hydrothermal economic dispatch, while satisfying the system, thermal and hydro constraints.

For the above reasons, it is clear that classical optimization methods cannot be successfully applied to the SCHTUC optimization problem. Therefore, methods are needed that will overcome the shortcomings of classical methods. One of them is the GA. GA gives a global optimum, because it works with a population, i.e. a group of solutions, compared to gradient methods, which works with a single solution and gives a local optimum.

In this paper, a hybrid approach is proposed through the application of a repair mechanism. First, for SCHTUC in binary GA (in which ELD is calculated by quadratic programming (QP)), a new repair mechanism is applied based on the priority list according to the Heat Rate parameter, which repairs the binary chromosome, in order to satisfy the classical condition for UC. Furthermore, when calculating the final ELD with a newly developed real-coded GA, a newly proposed constraint handling repair mechanism has been implemented, for consideration of the constraints that are most difficult to satisfy. The main contributions of this paper are:

- A compact formulation for SCHTUC, including new allocation of the spinning reserve.
- New procedure for gradual consideration of constraints, in order to reduce the calculation time, especially the binary GA.
- New repair mechanism for repairing binary chromosomes, in order to increase the diversity of the population, which results in finding a global optimum, i.e. lower total costs.
- New constraint handling repair mechanism for simultaneous satisfaction of all constraints, especially power balance and ramp rate constraint. This allows for a significantly more physically realistic solution.
- Presentation and analysis of the sensitivity, i.e. the relative change of the total costs, depending on the available volume and inflows, i.e. at different types of years. This analysis will indicate a greater commitment to the optimal use of

water in the reservoirs of hydro units, especially during dry years.

2. HYDROLOGICAL SCENARIOS OF HYDRO UNITS

In terms of energy, hydropower plants are characterized by possible production, which is usually expressed as the average annual production in GWh and obtained as the arithmetic means of possible annual production in the observed long series of years for which data on inflows are available (Figure 1). The term "possible production" means the maximum production that could be achieved by using the largest amount of available water under the most favorable conditions, taking into account the size of the construction of each of the hydropower plants [16, 17].

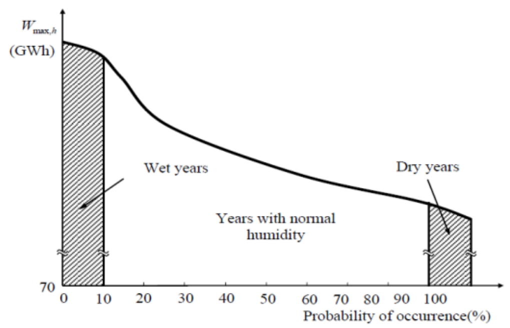

Fig. 1. Production duration curve of hydro unit

Hydro units can use the water stored in their reservoir for production, thus reducing the engagement of thermal units while reducing total fuel costs and emission costs. The limit of possible production of each hydro unit is given by the size of its reservoir, the installed flow, and in some cases the reservoir inflow. The Figure 2 shows a decision scheme for committing hydro units [18, 19].

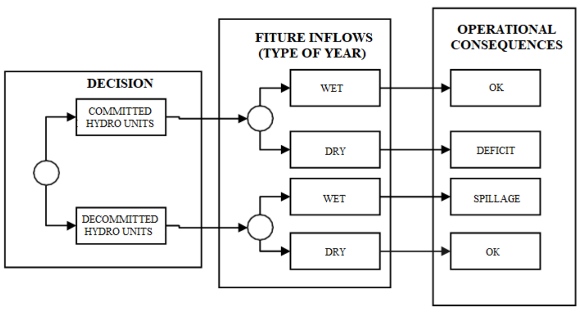

Fig. 2. Decision scheme for committing hydro units

According to Pereira's model, the current cost curve (CCC) is obtained as the curve of committed thermal units in interval *j* while the future cost curve (FCC) represents the production cost of thermal units in interval *j+1*, i.e. after the observed period [18].

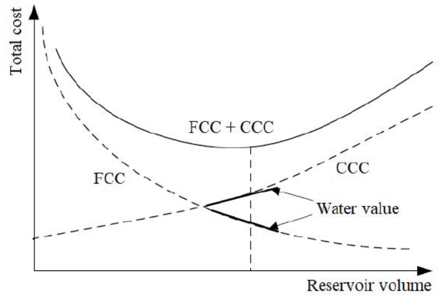

Fig. 3. Diagram of current and future operating costs

As the total available volume decreases, so is less energy available for production from hydro units, accordingly, to satisfy the consumption, it is necessary to increase the production of thermal units, which causes an increase in the current cost curve (CCC) and increases the water value (Figure 3). On the other hand, when hydro unit production at interval *j* is lower, more water volume is left in the reservoir for the future interval (*j* + 1) which means that the future cost curve (FCC) is going down. The curve of future costs is obtained by simulating the operation of the observed system in the future, where different states of the reservoir at interval *j* are taken as different scenarios. From them, the amount of operation of hydro units is then calculated, and as a consequence of achieving the energy balance of production and consumption, the production of thermal units is calculated, i.e. the future cost.

This mean that the described problem, due to a large number of variables that are not deterministically determined but only their limits, is stochastic and several hydrological scenarios must be developed to determine the dependence and sensitivity of total costs [18, 19, 20].

3. PROBLEM FORMULATION

3.1. Objective function

This paper analyzes a power system of *NT* thermal units and *NH* hydro units. The SCHTUC problem is solved with a time resolution of 1 hour, i.e. at 24 intervals. Here, the objective function of the SCHTUC problem is expressed as the minimization of the sum of the fuel costs *FT*, and the start-up costs *FS* of the committed thermal units [26, 27].

3.1.1. *Fuel cost*

The fuel cost function of the thermal plant *t*, can be expressed by a non-convex function, by considering the *valve point* effect, so a significantly more physically realistic model is obtained:

$$F_{t,j} = a_t + b_t \cdot P_{GTt,j} + c_t \cdot P_{GTt,j}^2 + \left| d_t \sin\left(e_t\left(P_{GTt}^{\min} - P_{GTt,j}\right)\right)\right|$$
$$\forall t \in NT;\ j \in J \quad (1)$$

where a_t, b_t, c_t, d_t, e_t are constant coefficients, and $P_{GTt}^{\min}$ is the technical minimum of the thermal power plant *t*.

3.1.2. *Start-up cost*

The start-up cost is the cost of committing the decommitted thermal unit, and it depends on the duration when the thermal unit was out of operation, according to:

$$FS_{t,j} = \begin{cases} HSC_t \text{ if } MDT_t \le T_{t,off}^{j} \le \left(MDT_t + CSH_t\right) \\ CSC_t \text{ if } T_{t,off}^{j} > \left(MDT_t + CSH_t\right) \end{cases}$$
$$\forall t \in NT;\ j \in J \quad (2)$$

where HSC_t is Hold Start Cost thermal unit *t*; CSC_t is Cold Start Cost of thermal unit *t*; MDT_t is Minimum Down-Time of thermal unit *t*; $T_{t,off}^{j}$ is a number of hours when the thermal unit *t* was decommitted up to the interval *j*; CSH_t is Cold Start Hours of thermal unit *t*.

3.1.3. *Total cost*

According to what has been previously mentioned, the total objective function will be:

$$\min F = \sum_{j=1}^{J}\sum_{t=1}^{NT}\left[F_{t,j} \cdot j + FS_{t,j}\left(1-u_{t,j-1}\right)\right]\cdot u_{t,j}$$
$$\forall t \in NT;\ j \in J; u \in \{0,1\} \quad (3)$$

where *u* is the commitment state of thermal unit *t* or hydro unit *h* at interval *j* (0 for decommitted unit or 1 for a committed unit).

3.2. *Constraints*

3.2.1. *Power balance constraint*

The power balance constraint, applied in the developed mathematical model is:

$$\sum_{t=1}^{NT} u_{t,j} P_{GTt,j} + \sum_{h=1}^{NH} u_{h,j} P_{GHh,j} = P_{P,j} + P_{L,j} \quad (4)$$

in which the transmission losses are calculated according to Crohn's formula, i.e.,:

$$P_L\left(j\right) = \sum_{i=1}^{NG}\sum_{j=1}^{NG} P_{Gi} B_{ij} P_{Gj} + \sum_{j=1}^{NG} B_{i0} P_{Gj} + B_{00}$$
$$\forall i \in NG;\ j \in NG; NG = NT + NH \quad (5)$$

3,2,2, *Generator constraint*

The output power of each unit should not be higher than the technical maximum, or not less than the technical minimum, i.e.:

$$u_{t,j} P_{GTt}^{\min} \le P_{GTt,j} \le u_{t,j} P_{GTt}^{\max}$$
$$u_{h,j} P_{GHh}^{\min} \le P_{GHh,j} \le u_{h,j} P_{GHh}^{\max} \quad (6)$$

3.2.3. *Spinning reserve constraint*

From the aspect of preserving the safety of the system from unforeseen load variations, it is necessary to provide an appropriate level of spinning reserve in the system:

$$\sum_{t=1}^{NT} u_{t,j} P_{GTt}^{SR} \ge R_T$$
$$\sum_{h=1}^{NH} u_{h,j} P_{GHh}^{SR} \ge R_H \quad (7)$$

where $P_{GT,t}^{SR}$ and $P_{GH,h}^{SR}$ are available spinning reserve of thermal unit *t* or hydro unit *h*; R_r is totall required spinning reserve of thermal units; R_H is totall required spinning reserve of hydro units. In this paper, it is selected $R_T = 0.75R$ and $R_H = 0.25R$.

The required spinning reserve is calculated according to the empirical formula of ENTSO (UCTE), i.e. [23, 24]:

$$R = \sqrt{a \cdot P_{P\max} + b^2} - b; \quad (8)$$

∈

3.2.4. *Minimum up/down time constraint*

The mathematical formulation of the given constraint is as follows:

$$u_{t,j} = \begin{cases} 1,\ if\ 1 \le T_{t,j-1}^{on} \le MUT_t \\ 0,\ if\ 1 \le T_{t,j-1}^{off} \le MDT_t \\ 0\ or\ 1,\ otherwise \end{cases} \quad (9)$$

where MUT_t is minimum uptime of t^{th} unit; MDT_t is minimum downtime of t^{th} unit; $T_{t,j-1}^{on}$ is consecutive hours of committed state of t^{th} unit going into j^{th} hour; $T_{t,j-1}^{off}$ is consecutive hours of decommitted state of t^{th} unit going into j^{th} hour.

3.2.5. *Ramp rate constraint*

The active generated power of units cannot be decreased or increased instantaneously:

$$\begin{aligned} P_{GTt,j} &= \max\left(P_{GTt}^{\min},\left(P_{GTt,j}-DRT_t\right)\right)\\ P_{GHh,j} &= \max\left(P_{GHh}^{\min},\left(P_{GHh,j}-DRH_h\right)\right)\\ P_{GTt,j} &= \min\left(P_{GTt}^{\max},\left(P_{GTt,j}+URT_t\right)\right)\\ P_{GHh,j} &= \min\left(P_{GHh}^{\max},\left(P_{GHh,j}+URH_h\right)\right) \end{aligned} \quad (10)$$

where URT_t, DRT_t, URH_h, and DRH_h, are the allowable increasing and decreasing rates of thermal unit t or hydro unit h.

3.2.6. *Transmission line constraint*

The active power of the transmission line, during the whole optimization period, must not be greater than the maximum limit:

$$\left|P_{GR,g}\right| \le P_{GR,g}^{\max},\ g=1,\ldots,G \quad (11)$$

where G is the total number of transmission lines in the system. The active power of the transmission line can be obtained from the active power of the generators, by applying the **H** matrix, by applying the DC model, i.e. DC power flow.

3.2.7. *Water availability constraint*

The total water discharge, during the whole period, must not exceed that which is available:

$$\sum_{j=1}^{J} Q_{th,j}\cdot T_j \le V_{h,k} \quad (12)$$

where T_j is the duration of interval j, Q_{th} is the water discharge i.e. input-output curve of the hydropower plant and is represented by a quadratic function:

$$Q_{th}\left(P_{GH,h}\right)=\alpha_h+\beta_h\cdot P_{GHh}+\gamma_h\cdot P_{GHh}^2 \quad (13)$$

where $P_{GH,h}$ is output power of hydro unit h; α_h, β_h and γ_h are constant coefficients of the input-output curve.

3.2.8. *Available production constraint*

$$\sum_{i=1}^{NT+NH} P_{Gi,j}\cdot T_j = W_{\max,i} \quad (14)$$

where $W_{\max,i}$ is the total available energy of generator i for the entire optimization period. The maximum possible production of hydropower plants is defined according to the available (initial) volume V_k and the total discharge time T_{dis}, i.e.

$$Q_{\max,h}=Q_{ins,h}=f\left(\alpha_h,\beta_h,\gamma_h,P_{GH,h}^{\max}\right)\ \left(\mathrm{m^3/h}\right) \quad (15)$$

$$T_{dis,h}=\frac{V_{k,h}}{Q_{\max,h}}\ (\mathrm{h}) \quad (16)$$

$$HR_t=\frac{F_t\left(P_{GT,t}^{\max}\right)}{P_{GT,t}^{\max}}\ (\text{€/MW}) \quad (17)$$

3.2.9. *Water dynamic balance constraint*

$$V_{h,j}=V_{h,(j-1)}+I_{h,j}-Q_{th,j}-S_{h,j} \quad (18)$$

where $V_{h,j}$ is storage volume of hydroplant h at interval j; $I_{h,j}$ is the inflow of hydro reservoir h at time interval j; $S_{h,j}$ is the water spillage of hydroplant h at time interval j. In this paper, water spillage is neglected.

4. GENETIC ALGORITHM

In the proposed Genetic Algorithm (GA) for solving the SCHTUC problem, a quadratic programming algorithm (QP) has been implemented, whose task is economic load dispatch (ELD), i.e. fitness function calculation.

In order to increase the robustness of the algorithm, the quadratic criterion function is calculated with the QP and only the main constraints are considered, as power balance constraint, ramp-rate constraint, available production constraint, spinning reserve constraint, and transmission line constraint. The other constraints, together with the non-convex objective function, are taken into account in the final economic load dispatch (for the optimal binary chromosome), which is solved with the newly proposed real-coded genetic algorithm and an appropriate repair mechanism. The initial population for the main ELD is modeled based on the solution obtained from QP.

4.1. *Initialization*

Given the complexity of the problem, i.e. many constraints that are strongly correlated with the decision variables, the initialization is not implemented randomly, i.e. by standard uniform distribution, but generating a binary population of N_{pop} chromosomes, with dimension $\left(NT+NH\right)\cdot J$ of decision variable vector, which satisfy the standard condition for UC:

$$\sum_{i=1}^{NT+NH} u_{i,j}\cdot P_{Gi}^{\min} \le P_{P,j} \le \sum_{i=1}^{NT+NH} u_{i,j}\cdot P_{Gi}^{\max},\quad j=1,2,\ldots,J \quad (19)$$

4.2. *Fitness function evaluation*

4.2.1. *Fitness function evaluation and constraint handling for binary GA*

Immediately after the first initialization, a check for the satisfaction of the condition (19) follows. Therefore, ELD is performed by QP and only on feasible solutions, i.e. chromosomes, and the infeasible are given a high value of the objective function and the procedure continues for the next chromosome. Given the change in genes that result from selection and mutation operators, it is possible that many chromosomes do not meet the condition (19). Therefore, such a standard procedure can be a serious constraint on the diversity of the population, as many chromosomes will be discarded, which may lead to premature convergence of the algorithm or stuck in a local optimum.

In this paper, a new approach is proposed, with the implementation of a priority list repair mechanism, which is formed at the beginning of the algorithm, based on the principle of the economics of thermal power plants [25, 26]:

$$HR_t = \frac{F_t\left(P_{GT,t}^{\max}\right)}{P_{GT,t}^{\max}} \ \left(€/\mathrm{MW}\right) \tag{20}$$

where the *HR* parameter is called *Heat Rate*. The thermal unit with the lowest *HR* is at the top of the priority list. In short, the proposed repair mechanism checks the chromosome for condition (19) fulfillment at each interval. If $P_{P,j} > \sum_{i=1}^{NT+NH} u_{i,j} \cdot P_{Gi}^{\max}$, the thermal unit with the highest priority is committed. If it is already committed, the algorithm commits the next one and so on until the one with the lowest priority or until the condition (19) is met. Otherwise, if $\sum_{i=1}^{NT+NH} u_{i,j} \cdot P_{Gi}^{\min} > P_{P,j}$, the algorithm decommits the thermal unit with the lowest priority, and for the others, the analogous procedure defined above applies.

Immediately after this repair mechanism, QP is activated for the needs of ELD.

After calculating the ELD, i.e., the objective function with QP, for the further genetic process, the fitness function is also calculated, i.e.:

$$fitness = \frac{1}{1 + f\left(x_1, x_2, \ldots, x_{(NT+NH)J}\right)} \tag{21}$$

4.2.2. *Fitness function evaluation and constraint handling for real GA*

The final ELD with considering all defined constraints is solved using the newly proposed real GA, based on superiority of feasible individuals on infeasible ones [27, 28]. The main feature of the proposed method is that it makes a clear distinction between feasible and infeasible solutions, and the fitness function is calculated without the use of a penalty factor, as follows:

$$F(x) = \begin{cases} f(x) & \text{if } \mathbf{x} \text{ is feasible} \\ f_{\max} + \left[\sum_{j=1}^{J} \left\langle g_j(\mathbf{x}) \right\rangle + \sum_{k=1}^{K} \left| h_k(\mathbf{x}) \right| \right] & \text{if } \mathbf{x} \text{ is infeasible} \end{cases} \tag{22}$$

where f_{max} is the value of the objective function of the worst feasible solution i.e. chromosome in the population. An important feature of this method is that infeasible solutions do not require a calculation of the objective function, but only the value of the violated constraints.

4.3. *Selection*

If one chromosome is dominant over the others, it means that the other chromosomes have a very small chance of being selected. This can lead to premature convergence in GA. By applying linear rank selection, the problem that occurs with roulette selection is avoided. In ranking selection, the chromosomes from the best to the worst are sorted first, based on the fitness function. Each chromosome is then assigned a rank from 1 (worst) to N_{pop} (best). The rest of the procedure is identical to the roulette selection. To prevent premature convergence, the fitness function is linearly scaled. The linear relationship between the original fitness function and the scaled fitness function is given by the expression:

$$\begin{aligned} f_s &= a_s f + b_s, \\ a_s &= (sp - 1)\, f_{av} / \left(f_{\max} - f_{\min}\right), \\ b_s &= (1 - a_s)\, f_{av}, \end{aligned} \tag{23}$$

where *sp* is a selection pressure parameter and has a value between 1.2 and 2, f_s is scaled fitness of the chromosome, f is original fitness of the chromosome, f_{av} is average fitness of the entire population, f_{max} and f_{min} are the largest and lowest value of the fitness function in the current population, a_s and b_s are scaling coefficients [22, 29, 30].

4.4. *Crossover*

4,4,1, *Crossover for binary GA*

In binary-coded GA for SCHTUC problem, at first 20 generations uniform crossover was applied, for better exploration of GA, and then two-point crossover.

At uniform crossover, each gene from both parents, in the new chromosomes, i.e. children would be selected with a probability of 0.5.

At a two-point crossover, two intersection points in the chromosomes are randomly generated, and genes between those two points are exchanged between the two parents.

4.4.1. *Crossover for real GA*

For the newly proposed real-coded genetic algorithm, Simulated Binary Crossover (SBX) was applied. The application of SBX to two parent chromosomes is done in three steps. First, *u* parameter is randomly selected so that it is valid u $u \in [0,1)$. Then, the parameter β_q, is calculated as follows:

$$\beta_q = \begin{cases} (2u)^{\frac{1}{\eta_c+1}} & if \ \ u \le 0.5 \\ \left(\dfrac{1}{2(1-u)}\right)^{\frac{1}{\eta_c+1}} & if \ \ 0.5<u<1 \end{cases} \tag{24}$$

where η_c is the distribution index that controls the distribution of the solution. Most often, this parameter has a value [1 – 10].

Finally, in the third step, the two new chromosomes are calculated as shown:

$$\begin{aligned} ch_1 &= 0.5\left[\left(1+\beta_q\right)p_1 + \left(1-\beta_q\right)p_2\right], \\ ch_2 &= 0.5\left[\left(1-\beta_q\right)p_1 + \left(1+\beta_q\right)p_2\right]. \end{aligned} \tag{25}$$

4.5. *Mutation*

4.5.1. *Mutation for binary GA*

In order not to impair the quality of the chromosome, especially if it is in the last generations, when the algorithm should converge to the global optimum, a non-uniform mutation for binary-coded GA is applied in this paper [27]. In the case of a non-uniform mutation, the mutated gene depends on the domain of change, the random number generated *rand* [0,1], the current generation *gen*, the maximum number of generations *maxgen*, and its lower limit $x^{(l)}$ or upper limit $x^{(u)}$, according to the following expression:

$$x_k^{'} = \begin{cases} x_k + \left(x^{(u)} - x_k\right) \cdot \left(1 - r^{\left(1-\frac{gen}{\max gen}\right)^{\mu}}\right), & rand \le 0.5 \\ x_k - \left(x_k - x^{(l)}\right) \cdot \left(1 - r^{\left(1-\frac{gen}{\max gen}\right)^{\mu}}\right), & rand > 0.5 \end{cases} \tag{26}$$

where *r* is a uniformly distributed random number [0,1], μ is a systemic parameter called the non-uniform mutation coefficient and has a value of 5 or 2.

4.5.2. *Mutation for real GA*

For the newly proposed real-coded genetic algorithm, Polynomial Mutation (PLM) was applied. The application of the polynomial mutation operator is also performed in three steps. First, the parameter *r* is selected so that $r \in [0,1]$. Then, the parameter $\bar{\delta}$ is calculated according to the following expression:

$$\bar{\delta} = \begin{cases} (2r)^{\frac{1}{(\eta_m+1)}} - 1 & if \ \ r < 0.5 \\ 1 - \left[2(1-r)\right]^{\frac{1}{(\eta_m+1)}} & if \ \ r \ge 0.5 \end{cases} \tag{27}$$

where η_m is the distribution index that controls the deviation of the new mutated chromosome *ch'* relative to the chromosome *ch*. The value of this parameter is usually selected from the range 10 – 100. In the last, i.e. in the third step, the new mutated chromosome is calculated in relation to the chromosome *ch* (obtained from the crossover operator), according to the following expression:

$$ch' = ch + \left(x^{(u)} - x^{(l)}\right)\bar{\delta}. \tag{28}$$

4.6. *Elitism strategy*

The best solutions, i.e. chromosomes are stored for the next generation so that they are not lost during the genetic process. In this paper, a new strategy is proposed by forming a group of parent's chromosomes and children's chromosomes. All of these chromosomes are ranked according to their fitness function in descending order. Half of the solutions with the best fitness function from the combined population are saved for the further genetic process, which will be performed in the next generations.

4.7. *Block diagram and repair mechanism*

Considering that it is SCHTUC, the main goal is that possible steadier production by thermal units, and maximum use of the available reservoir volume of hydro units. Therefore, in the newly proposed constraint handling repair mechanism, the power outputs of the hydro units are first corrected. Furthermore, there is a correction of the ramp rate constraint, and finally correction of the power balance constraint. The newly proposed repair mechanism is given in Figures 4 and 5.

for $i = 1: NH$
for $j = 1: J$
if $P_{GH}(i,j) \neq 0$
if $P_{GH}(i,j) \leq \max\left(P_{GH}^{\min}(i), \left(P_{GH}(i,j) - DRH(i)\right)\right)$
$P_{GH}(i,j) = \max\left(P_{GH}^{\min}(i), \left(P_{GH}(i,j) - DRH(i)\right)\right);$
elseif $P_{GH}(i,j) \geq \min\left(P_{GH}^{\max}(i), \left(P_{GH}(i,j) + URH(i)\right)\right)$
$P_{GH}(i,j) = \min\left(P_{GH}^{\max}(i), \left(P_{GH}(i,j) + URH(i)\right)\right);$
end
end
end
end
for $j = 1: J$
$WH(j) = \sum_{i=1}^{NH} P_{GH}(i,j);$
$P_{PT}(j) = P_P(j) + P_L(j) - WH(j);$
end
$P_L(j) = \sum_{m=1}^{NT+NH} \sum_{n=1}^{NT+NH} P_{G,m}(j) \cdot B_{mn} \cdot P_{G,n}(j);$
for $j = 1: J$
$\Delta P_{PT}(j) = \sum_{t=1}^{NT} P_{GT}(t,j) - P_{PT}(j) - P_L(j)$
while $\left|\Delta P_{PT}(j) > 10^{-6}\right|$
$\Delta P_{PT,sr}(j) = \Delta P_{PT}(j) / NT;$
for $t = 1: NT$
if $P_{GT}(t,j) \neq 0$
$P_{GT}(t,j) = P_{GT}(t,j) - \Delta P_{PT,sr}(j);$
if $P_{GT}(t,j) \leq \max\left(P_{GT}^{\min}(t), \left(P_{GT}(t,j) - DRT(t)\right)\right)$
$P_{GT}(t,j) = \max\left(P_{GT}^{\min}(t), \left(P_{GT}(t,j) - DRT(t)\right)\right);$
elseif $P_{GT}(t,j) \geq \min\left(P_{GT}^{\max}(t), \left(P_{GT}(t,j) + URT(t)\right)\right)$
$P_{GT}(t,j) = \min\left(P_{GT}^{\max}(t), \left(P_{GT}(t,j) + URT(t)\right)\right);$
end
end
$\Delta P_{PT}(j) = \sum_{t=1}^{NT} P_{GT}(t,j) - P_{PT}(j) - P_L(j);$
end
end
end

Fig. 4. Pseudocode of the constraint handling repair mechanism

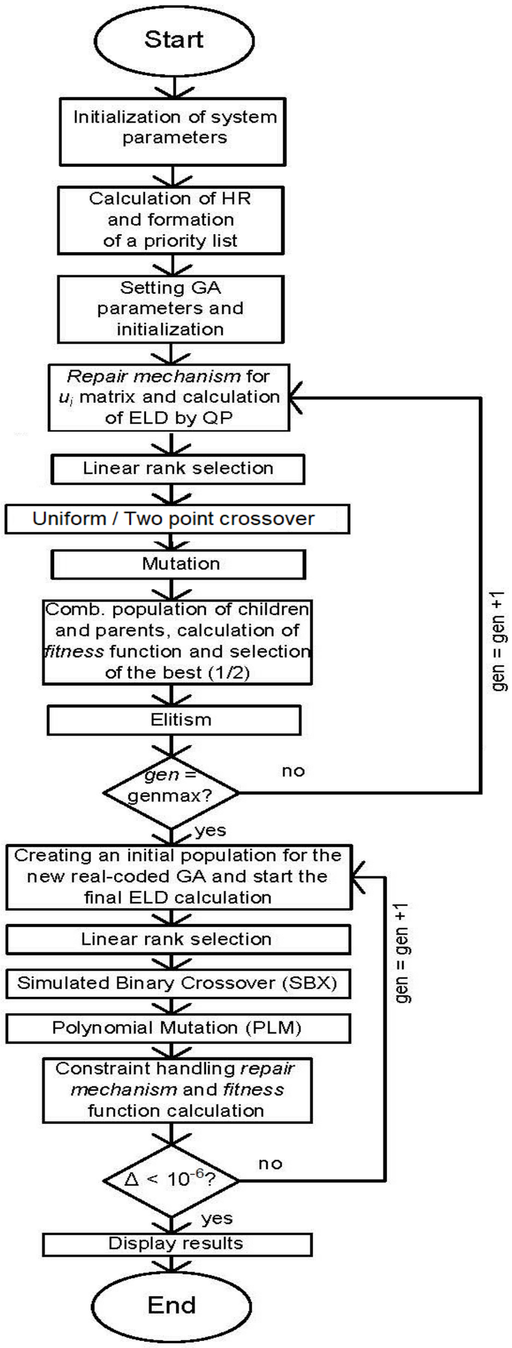

Fig. 5. Block diagram of the proposed algorithm

As shown in Table 1, newly proposed GA has obviously achieved the best results compared with other approaches. The maximum and minimum improvements of the variation in solution quality by proposed GA compared to the classical GA approach are 0,279%. According to the results, it should be mentioned that the proposed GA can be applied to large-scale optimization problems.

On other hand, for a better comparison of the proposed GA, a classical GA is also applied to this benchmark system. This means that in classical GA, the priority list repair mechanism, constraint handling repair mechanism, and linear fitness scaling, are not included. The population size and maximum iteration count are 100 and 500, respectively. The spinning reserve is set to 10% of the total load demand.

The best, average, and worst total generation costs have been yielded with a proposed GA. The bold results show the superiority of a proposed GA over other well-known methods, i.e. Genetic Algorithm (GA), Dragonfly Algorithm – Particle Swarm Optimization (DA-PSO) [31], and Particle Swarm Optimization – Grey Wolf Optimization (PSO – GWO) [11] in Table 1.

Table 1

Comparison of results for benchmark system

	Best €)	Average (€)	Worst (€)	Variation (%)
DA-PSO [31]	13292.28	–	–	–
PSO-GWO [11]	13600.00	–	–	–
Classical GA	13223.99	13285.00	13346.01	0.459
Proposed GA	13152.27	13177.,78	13201.51	0.180

– means that it is not reported in the referred literature

5. RESULTS

5.1. IEEE 30 Bus System

The performance of the proposed formulation and methodology has been evaluated using the IEEE 30 bus system. This system consists of 30 buses, 6 generators (of which the generators in buses 11 and 13 represent the hydro units), and 41 transmission lines [19 – 23]. In addition, 75% of the spinning reserve is covered by thermal units, and the remaining 25% is covered by hydro units. Figure 6 shows the daily load diagram of the system, and Figure 7 shows its single-pole scheme. 50 independent trials are conducted to compare the solution quality of newly proposed GA with other optimization methods. The parameters of transmission lines and buses are taken from [22, 23].

The proposed methodology is tested in Windows 10 system by MATLAB R2020a and implemented on an Intel Core i7-9750H CPU@2.60GHZ with 16GB RAM personal notebook computer. The parameters are set through trial and error. The main fined parameters are shown as the following: population – 200, elite number – 5. One of the stopping criteria is the deviation of the fitness value of the individual chromosome from the average fitness value of the entire population. This criterion may be of benefit for faster convergence, but can cause a stopping algorithm close to the global optimum, but not in the global optimum. Because of this, the stopping criterion in this paper is the maximum number of generations, i.e. 500.

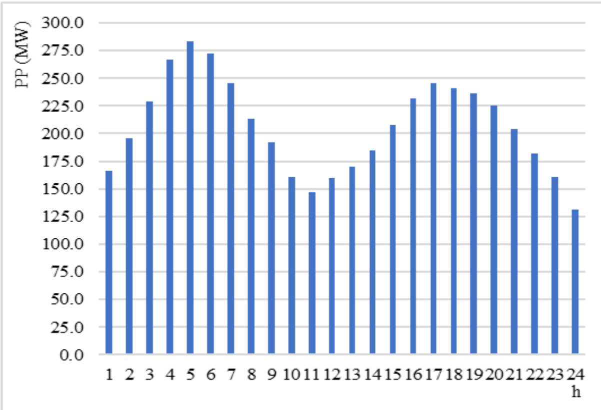

Fig. 6. Daily load diagram

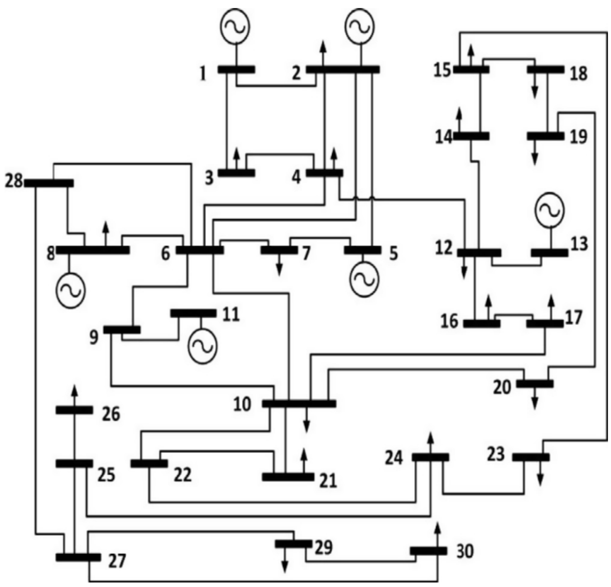

Fig. 7. IEEE 30 bus system

This paper will present the results for four hydrological scenarios. The first scenario is basic, i.e., a year with normal humidity, for which, in addition to the total costs, the optimal schedule will be shown. The second scenario refers to a wet year, in which the total available volume in the reservoirs and natural inflow will be increased by 25%. The third scenario is a dry year scenario, in which the total available volume in the reservoirs and natural inflow will be reduced by 25%. Finally, the fourth scenario is an extremely dry year scenario, in which the total available volume in the reservoirs and natural inflow will be reduced by 50%.

Table 2 shows the parameters of thermal units and Table 3 shows the parameters of hydro units, while Table 4 shows natural inflow (for basic scenario) in the reservoirs of hydro units. Furthermore, Table 5 shows optimal solution i.e. optimal scheduling (for basic scenario) for IEEE 30 bus system, using proposed algorithm, and Table 6 shows total costs and it's relative change for all defined scenarios.

The total costs of the thermal power plants are 10605,79 €. The total water discharge during the entire optimization period is $V_{1,spent} = 5,762 \cdot 10^3 m^3$ and $V_{2,spent} = 10,965 \cdot 10^3 m^3$, respectively for hydro unit 1 and hydro unit 2, thus satisfying the hydroelectric constraint

Table 2

Data for thermal units

	a_t (€/h)	b_t (€/MW)	c_t (€/MW^2)	d_t	e_t	$P_{GT,t}^{min}$ (MW)	$P_{GT,t}^{max}$ (MW)	UR_t (MW)	DR_t (MW)	HSC_t (€)	MUT_t (h)	MDT_t (h)
PGT1	0	2	0.00375	18	0.037	50	200	65	85	70	1	1
PGT2	0	1.75	0.01750	16	0.038	20	80	12	22	74	2	2
PGT3	0	1	0.06250	14	0.040	15	50	12	15	50	1	1
PGT4	0	3.25	0.00834	12	0.045	10	35	8	16	110	1	2

Table 3

Data for hydro units

	α_h (m^3/h)	β_h (m^3/MWh)	γ_h (m^3/MW^{2}h)	$P_{GH,h}^{min}$ (MW)	$P_{GH,h}^{max}$ (MW)	UR_h (MW)	DR_h (MW)	$Vh_{,k}$ (10^3 m^3)
PGH1	56.067	8.665	0.0061	10	30	8	16	5.863
PGH2	26.505	17.33	0.01	12	40	8	16	11.326

Table 4

Natural inflows in reservoirs 1 and 2 (m^3/h)

$P_{GH,1}$	*j*	1	2	3	4	5	6	7	8	9	10	11	12
	$I_h(j)$	100	90	80	70	60	70	80	90	100	110	120	100
	J	13	14	15	16	17	18	19	20	21	22	23	24
	$I_h(j)$	110	120	110	100	90	80	70	60	70	80	90	100
$P_{GH,2}$	*J*	1	2	3	4	5	6	7	8	9	10	11	12
	$I_h(j)$	80	80	90	90	80	70	60	70	80	90	90	80
	J	13	14	15	16	17	18	19	20	21	22	23	24
	$I_h(j)$	80	90	90	80	70	60	70	80	90	90	80	80

Table 5

Optimal scheduling for IEEE 30 bus system using proposed GA (for basic scenario)

Interval	P_{GT1} (MW)	P_{GT2} (MW)	P_{GT3} (MW)	P_{GT4} (MW)	P_{GH1} (MW)	P_{GH2} (MW)	P_L (MW)	Q_1 (m^3/h)	Q_2 (m^3/h)
1	79.10	24.10	15.01	10.01	19.62	20.37	2.22	228.45	383.59
2	102.34	29.12	15.05	10.05	20.12	22.81	3.49	232.91	426.98
3	126.03	34.26	15.69	10.14	21.66	26.36	5.15	246.59	490.35
4	152.81	40.17	17.51	10.36	23.91	29.64	7.40	266.73	548.94
5	162.38	42.29	18.17	10.45	25.75	32.73	8.37	283.21	604.48
6	154.18	40.47	17.60	10.37	25.02	31.95	7.60	276.68	590.45
7	137.06	36.75	16.51	10.31	23.28	28.14	6.05	261.06	522.10
8	115.74	32.04	15.13	10.12	19.83	24.52	4.37	230.30	457.45
9	99.83	28.59	15.07	10.07	19.66	22.11	3.33	228.81	414.64
10	72.98	22.72	15.00	10.00	20.45	21.82	1.97	235.82	409.48
11	65.79	21.18	15.00	10.00	16.91	19.73	1.62	204.38	372.33
12	85.71	25.47	0.00	10.00	20.22	21.23	2.63	233.76	398.87
13	82.03	24.66	15.00	10.00	20.21	20.46	2.36	233.72	385.26
14	93.51	27.18	15.00	10.00	20.01	22.28	2.98	231.88	417.56
15	111.65	31.14	15.09	10.09	20.05	24.08	4.10	232.25	449.66
16	128.54	34.89	15.95	10.25	21.42	26.29	5.33	244.43	488.96
17	137.58	36.85	16.52	10.29	22.74	28.11	6.08	256.23	521.46
18	133.89	36.04	16.28	10.26	22.56	27.76	5.78	254.67	515.34
19	130.92	35.34	16.03	10.19	22.13	26.92	5.53	250.81	500.32
20	123.63	33.79	15.61	10.20	21.05	25.68	4.96	241.16	478.19
21	109.14	30.58	15.07	10.07	19.70	23.36	3.92	229.18	436.80
22	91.97	26.84	15.00	10.00	20.21	20.85	2.87	233.71	392.12
23	73.91	22.91	15.00	10.00	19.13	22.06	2.01	224.08	413.65
24	62.22	20.37	15.00	0.00	16.59	18.26	1.43	201.46	346.31

Furthermore, from Figures 8, 9 and 10, it can be seen that during a wet year, the optimal output power of the hydro units is higher and the optimal output power of the thermal unit is lower, resulting in lower total costs. This is a consequence of the larger available volume in the reservoirs and the larger inflows.

Contrary to what has been said before, in dry and extremely dry years, the optimal output power of the hydro units is lower, due to the reduced inflows and the smaller available volume. This results in higher and more variable optimal output power of the thermal units, which results in higher or significantly higher total costs.

Therefore, as in Table 6, it can be seen that the hydrological conditions significantly affect the total costs of thermal units, especially in extremely dry years, in which the relative increase in total costs is as much as 16.87%, or even 2452.33 euros, which on an annual basis is a huge amount that should not be neglected. Therefore, the initial hypothesis is confirmed that the total operating costs depend significantly on the hydrological conditions, i.e. on the available volume and inflows in the reservoirs of the hydro units. This confirmed hypothesis must be taken into account, especially in dry and extremely dry years, in which measures should be taken for optimal use of the available volume of hydro units, throughout the year.

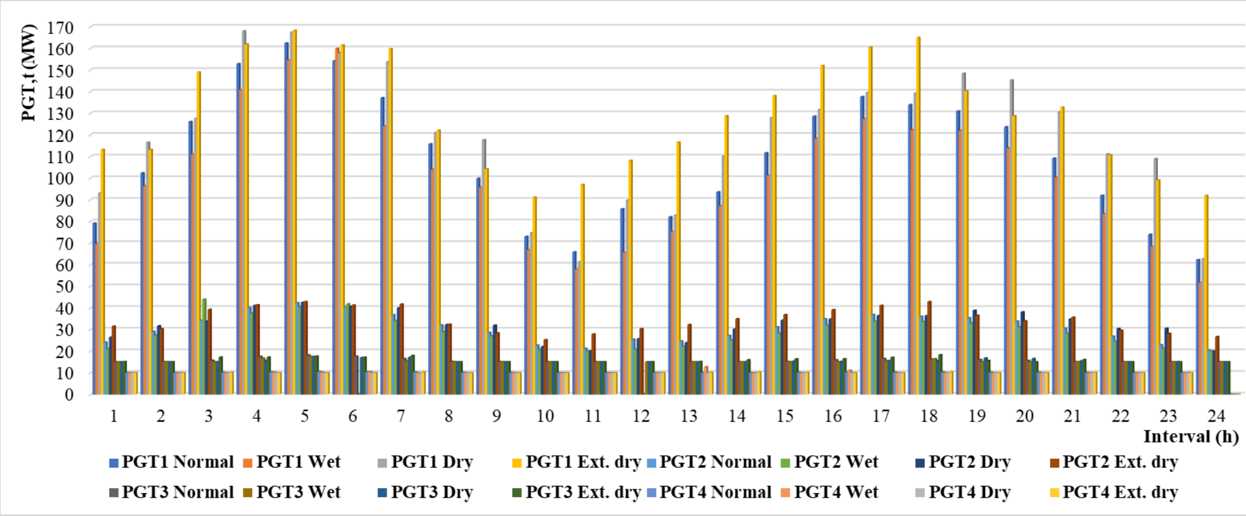

Fig. 8. Optimal hourly power generation of thermal units

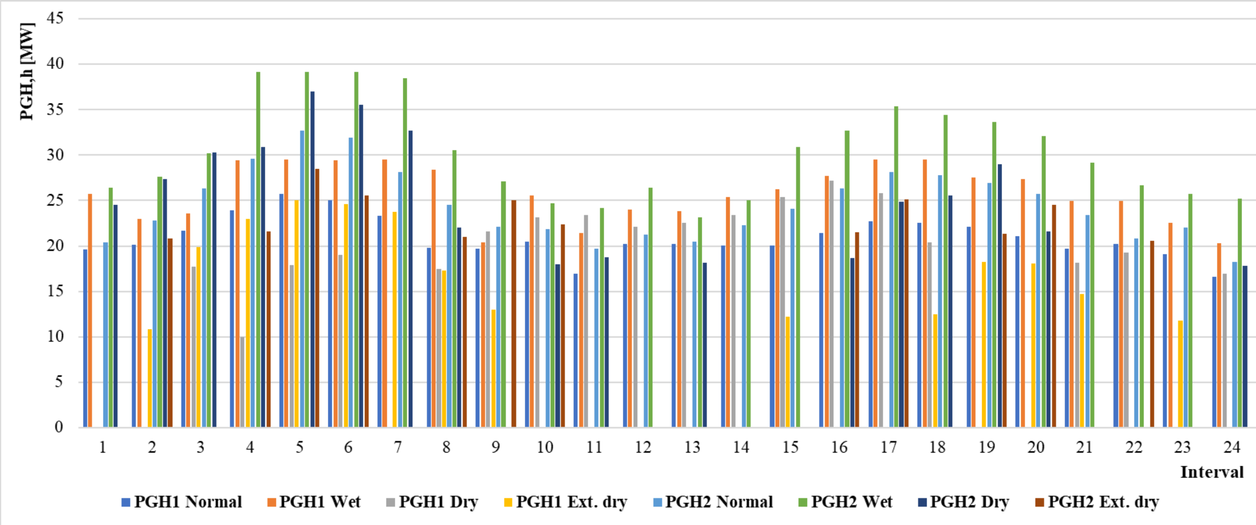

Fig. 9. Optimal hourly power generation of hydro units

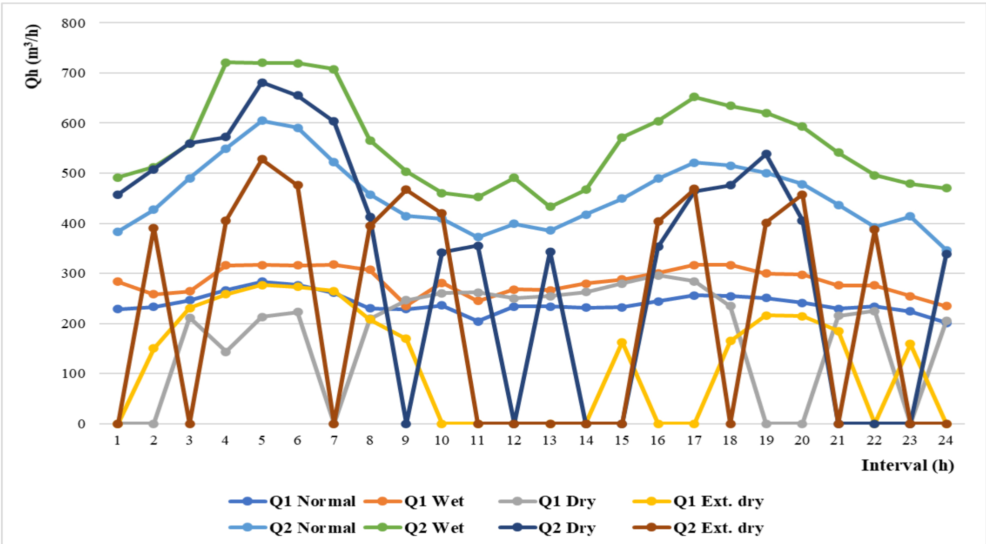

Fig. 10. Optimal hourly discharges of hydro units

Table 6

Total costs and their relative change for different hydrological scenarios

Scenario (type of year)	F (€)	Rel. change (%)
Normal	10099.19	/
Wet	9350.09	–7.42
Dry	10900.46	7.93
Ext. dry	11802.42	16.87

5.2. Analysis of the obtained results

Firstly, from the obtained results, the parameter *HR* respectively for the thermal units 1, 2, 3, and 4 is 2.74, 3.12, 4.01, and 3.53 €/MW. This means that the priority list of thermal units according to *HR*, is 1, 2, 4, 3. In other words, thermal unit 1 is at the top of the priority list, i.e. most economical, and the thermal unit 3 most expensive. From the graph in Figure 8 it can be seen (for all scenarios) that the thermal unit 1, i.e. P_{GT1} (which actually has the lowest HR) is characterized by the largest and most variable output power, i.e., with the largest production, so together with the hydro units, it covers both the base and the peak part of the load diagram. On the other hand, thermal unit 3, i.e. P_{GT3}, which is actually the most expensive (with the highest HR), works almost to its technical minimum. In addition, thermal unit 4, i.e. P_{GT4}, which has the second highest-heat rate, in interval 24 is even out of operation i.e., decommitted.

6. CONCLUSION

The hydrothermal unit commitment, especially with security constraints, i.e. SCHTUC, is an important task in power system operation and planning. In this paper, a GA-based metaheuristic approach has been proposed and successfully applied to solve SCHTUC problem. To evaluate the performance of the proposed algorithm, it has been applied on IEEE 30 bus system that consists of two hydro units and four thermal units, and results are presented. The effect of valve-point and water dynamic balance are also considered. The results obtained by the proposed method have been compared with other evolutionary algorithms like DA-PSO and GWO-PSO. It is found that a newly proposed GA can produce better results in terms of considering the key hydrothermal constraints, which is necessary to obtain a physically acceptable solution.

Furthermore, can be concluded that the proposed algorithm provides an optimal and efficient solution to the SCHTUC optimization problem, i.e. it can serve as a basis for its further upgrading and application in both operational planning and academic research, in order to obtain an economical and reliable power system operation.

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