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Adaptive Genetic Algorithm for Hydro-thermal Unit Commitment Considering the Security Constraints

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Abstract— **This paper proposes a new approach with two efficient metaheuristic algorithms, in combination with quadratic programming, to solve the nonlinear optimization problem Unit Commitment in a complex hydro-thermal power system i.e. Hydrothermal Unit Commitment (HTUC). The main goal is to minimize the total costs (which are a very non-linear and non-convex problem), while satisfying the many hydro-thermal constraints. Such constraints, together with the nonlinear non-convex and mixed-integer objective function, make the search space extremely complex. To solve such a complicated system, the paper proposes a hybridization of a developed binary-coded genetic algorithm (in which quadratic programming is integrated), with a particle swarm optimization (PSO) algorithm. PSO is applied to the final economic load dispatch (ELD), based on the optimal binary combination obtained from the genetic algorithm. A new approach has been proposed through the application of a repair mechanism, which is based on a priority list, in order to maintain the diversity of the population and prevent premature convergence. The entire algorithm was developed and tested in MATLAB and then applied to the IEEE 30 BUS test system. The experimental results show better performance of the proposed algorithm compared to the recently published algorithms, in terms of convergence, constraint handling, as well as better solution quality.**

Keywords-Unit Commitment; Genetic Algorithm; Heat Rate Repair Mechanism; Constraint handling Repair Mechanism;

I. INTRODUCTION

Unit Commitment (UC) [1], is one of the most important tasks in the operation and planning of centralized power systems. Many papers have also introduced the property of uncertainty [2-4], transmission line constraint [5], and various energy sources [2, 3, 4, 6]. UC problem is becoming more complex, and therefore for its solution requires a well developed algorithm. This is especially true in dealing with constraints and convergence, given that these constraints, control and state variables are are in a very strong correlation. On other hand, simultaneous satisfaction of all the constraints is very difficult. Recently, various metaheuristic methods such as genetic algorithm (GA) [7-12], differential evolution (DE) [13-15], particle swarm optimization (PSO) [16-19], gravitational search algorithm (GSA) [2], are increasingly used by researchers, in order to solve many nonlinear optimization problems in power systems.

Unit Commitment in a hydro-thermal system, i.e. Hydro-thermal Unit Commitment (HTUC), is an extension of the UC problem, so it as such does not only take into account the commitment of thermal units, but also the commitment of hydropower units and their complex constraints. To achieve efficient and approximately optimal solutions to the HTUC problem, many traditional methods have been proposed, such as Lagrange relaxation [20], branch and bound search method [21], multistage benders decomposition method [22, 23], stochastic programming [24] and hybrid decomposition strategy [25].

A. *Scientific contribution*

The main advantages of classical optimization methods, such as the Lagrange relaxation method, are its simplicity and fast convergence. But on the other hand, Lagrange relaxation is characterized by significant shortcomings, such as local optimum, the problem with the complex mathematical model due to the large dimensionality of the optimization problem, inability to apply discontinuous objective functions due to his gradient nature, but also the large calculation time that increases significantly with the dimensionality of the problem. The same resulted in other classical algorithms, in which penalty functions were applied. This is due to the fact that due to the large correlation between the constraints, i.e. the complexity of the problem (not the dimensionality), the application of only a penalty factor is not sufficient to push the solutions within the feasible area. In other words, due to the large penalty factor, the fitness function of almost every (infeasible) solution gets a big value, so the algorithm cannot converge even after hundreds of iterations.

GA and PSO give a global optimum, because they work with a population, i.e. a group of solutions, compared to gradient methods such as Lagrange relaxation, which works with a single solution and gives a local optimum.

For this reason in this research the GA/PSO is used where two algorithms (i.e., GA and PSO) are merged together to design a more efficient algorithm to solve HTUC problem.

This paper proposes a new approach to the HTUC problem, which simultaneously considers the main thermal and hydroelectric constraints and system constraints (compared to the other proposed methods), in order to obtain a real and physically acceptable solution.

Furthermore, a hybrid approach is proposed through the application of a repair mechanism, in addition to a penalty function. First, in the genetic procedure for HTUC in binary AGA (in which ELD is calculated by quadratic programming (QP)), a 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 PSO algorithm, a newly proposed constraint handling repair mechanism has been implemented to deal with the constraints that are most difficult to satisfy.

II. PROBLEM FORMULATION

In a power system with hydropower plants and thermal power plants, the list of optimally committed thermal power plants and the coordinated plan of hydrothermal production can significantly reduce total production costs of thermal power plants. This paper deals with the power system of *NT* thermal power plants and *NH* hydro power plants. The HTUC problem is solved with a time resolution of 1 hour, i.e. at 24 intervals. Generally, hydropower plants are allocated as much output power as possible, and thermal power plants are allocated the power of the required spinning reserve, or they are decommitted when the hydropower plants can meet the system load *PP*, including the system losses *PL*. Here, the objective function of the short-term HTUC problem is expressed as the minimization of the sum of the Fuel costs F_t, and the Start-up costs *FS* of the committed thermal power plants, as shown in the following expression: [26, 27]:

$$\min F = \sum_{j=1}^{J}\sum_{t=1}^{NT}\left[F_{t,j}\left(P_{GT,t,j}\right)\cdot T_j + FS_{t,j}\left(1-u_{t,j-1}\right)\right]\cdot u_{t,j}\ , \quad (1)$$

where, *NT* is the number of thermal power plants, *J* is the number of time intervals, $u_{t,j}$ is the status (1 means in commited and 0 decommitted) of the thermal power plant *t* in the interval *j*, $P_{GT,t,j}$ is the output power of the thermal power plant *t* in the interval *j*, $FS_{t,j}$ is the Start-up cost for committing the decommitted thermal power plant *t*, at interval j. The fuel cost function of the thermal plant *t*, can be expressed by a quadratic function:

$$F_t\left(P_{GT,t}\right) = a_t + b_t\cdot P_{GT,t} + c_t\cdot P_{GT,t}^2\ , \quad (2)$$

where a_t, b_t and c_t are cost curve coefficients. By considering the *valve point* effect, a significantly more physically realistic model is obtained, but the fuel cost function becomes a non-convex, i.e.:

$$F_t\left(P_{GT,t}\right) = a_t + b_t\cdot P_{GT,t} + c_t\cdot P_{GT,t}^2 + \left|d_t \sin\left(e_t\left(P_{GT,t}^{\min} - P_{GT,t}\right)\right)\right|, \quad (3)$$

where d_t, e_t are constant coefficients, and $P_{GT,t}^{\min}$ is the technical minimum (lower bound) of the thermal power plant *t*.

The start-up cost is the cost for committing the decommitted power plant, and it depends on the time when the power plant was out of operation, as shown by the following expression:

$$FS_{t,j} = \begin{cases} HSC_t \ \text{ако}\ MDT_t \le T_{t,off}^{j} \le \left(MDT_t + CSH_t\right) \\ CSC_t \ \text{ако}\ T_{t,off}^{j} > \left(MDT_t + CSH_t\right) \end{cases}, \quad (4)$$

where, HSC_t is Hot Start Cost of thermal power plant *t*, CSC_t is Cold Start Cost , MDT_t is Minimum Down-Time of thermal power plant *t*, $T_{t,off}^{j}$ is the number of hours when the thermal power plant *t* was out of operation (decommitted) until the interval *j*, CSH_t is Cold Start Hours of thermal power plant *t*. Given that the paper analyzes short-term HTUC (for the needs of short-term hydro-thermal coordination), it will be taken into account that all thermal power plants (during the entire optimization period of 24 hours) are kept in hot state, i.e. banking. This means that the total Start-up costs will be calculated according to the Hot Start Cost HSC_t , and the MDT_t, MUT_t parameters will be neglected.

A. Power balance constraint

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

$$\sum_{t=1}^{NT} P_{GT,t}\left(j\right) + \sum_{h=1}^{NH} P_{GH,h}\left(j\right) = P_P\left(j\right) + P_L\left(j\right), \quad (5)$$

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

$$P_L\left(j\right) = \sum_{i=1}^{NG}\sum_{j=1}^{NG} P_{Gi} B_{ij} P_{Gj}\ . \quad (6)$$

B. Generator constraint

The output power of each unit should not be higher than the upper bound, or not less than the lower bound, i.e.:

$$\begin{aligned} P_{GT,t}^{\min} &\le P_{GT,t} \le P_{GT,t}^{\max} \\ P_{GH,h}^{\min} &\le P_{GH,h} \le P_{GH,h}^{\max} \end{aligned} \quad (7)$$

C. Total water discharge constraint

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

$$\sum_{j=1}^{J} Q_{th}\left(j\right)\cdot T_j \leq V_{h,k}\,, \tag{8}$$

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

$$Q_{th}\left(P_{GH,h}\right)=\alpha_h+\beta_h\cdot P_{GH,h}+\gamma_h\cdot P_{GH,h}^2 \tag{9}$$

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.

D. Transmission line constraint

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

$$\left|P_{GR,g}\right| \leq P_{GR,g}^{\max},\ g=1,\ldots,G\,, \tag{10}$$

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 (composed of G rows and NT + NH columns), which gives the dependence of the power of the lines on the power of the generators, i.e. $\mathbf{P_{GR}}=\mathbf{H}\cdot\mathbf{P_G}$, and is obtained by power flow calculation, by applying the DC model, i.e. DC power flow.

E. Spinning reserve constraint

The available spinning reserve is the difference between the maximum capacity of all synchronized units, and the system load [2]:

$$\begin{gathered}\sum_{i=1}^{NT+NH} u_{ij}P_{Gi,\max} \geq \left(P_P\left(j\right)+P_L\left(j\right)+R\right),\\ 1<j<24h,\ u_{ij}=\left[0,1\right].\end{gathered} \tag{11}$$

In the mathematical model, and consequently in the developed algorithm in MATLAB, the required spinning reserve is calculated according to the empirical formula of ENTSO, ie. [6, 7]:

$$R=\sqrt{a\cdot P_{P,\max}+b^2}-b;\ a=10MW;\ b=150MW\,, \tag{12}$$

in which a and b represent empirical constants, $P_{P,max}$ is the system's peak load during the optimization period.

F. Ramp Rate constraint

$$\begin{aligned}&P_{Gi}\left(j\right)-P_{Gi}\left(j-1\right)\leq UR_i,\ \text{if the power increases}\\ &P_{Gi}\left(j-1\right)-P_{Gi}\left(j\right)\leq DR_i,\ \text{if the power decreases.}\end{aligned} \tag{13}$$

G. Available production constraint

$$\sum_{i=1}^{NT+NH} P_{G,i,j}\cdot T_j = W_{\max,i}\,, \tag{14}$$

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_{pr}, i.e:

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

$$T_{pr,h}=\frac{V_{k,h}}{Q_{\max,h}}\ \left[h\right], \tag{16}$$

$$W_{\max,h}=P_{GH,h}^{\max}\cdot T_{pr,h}\left[MWh\right]. \tag{17}$$

III. GENETIC ALGORITHM

In the proposed Adaptive Genetic Algorithm (AGA) to solve the HTUC 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 the main constraints are considered, i.e. the key to the course of the calculation (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 Particle Swarm Optimization (PSO) algorithm and an appropriate repair mechanism. The initial population for the main ELD is modeled based on the solution obtained from QP.

A. Initialization

Given the complexity of the problem, ie. many constraints that are strongly correlated with the control variables, the initialization is not implemented randomly, ie. by standard uniform distribution, but generating a population of N_{pop} chromosomes (a random combination of 0 and 1), with control variables number $\left(NT+NH\right)\cdot J$, which satisfy the standard condition for UC:

$$\sum_{i=1}^{NT+NH} u_{i,j}\cdot P_{G,i}^{\min} \leq P_{P,j} \leq \sum_{i=1}^{NT+NH} u_{i,j}\cdot P_{G,i}^{\max},\quad j=1,2,\ldots \tag{18}$$

B. Fitness function evaluation

Immediately after the first initialization, a check for fulfillment of the condition (18) follows. Therefore, ELD is performed with 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 (18). Therefore, such a standard methodology 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 optim.

In this paper, a new approach is proposed, with the implementation of a *repair mechanism* based on the priority list method (which is formed at the beginning of the algorithm), based on the principle of economics of thermal power plants [30, 31]:

$$HR_t = \frac{F_t\left(P_{GT,t}^{\max}\right)}{P_{GT,t}^{\max}} \ \left[€/MW\right], \tag{19}$$

where the *HR* parameter is called *Heat Rate*. The thermal power plant with the lowest HR is at the top of the priority list. In short, the proposed repair mechanism checks the chromosome for condition (18) fulfillment at each interval. If $P_{P,j} > \sum_{i=1}^{NT+NH} u_{i,j} \cdot P_{G,i}^{\max}$, the power plant 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 (18) is met. Otherwise, if $\sum_{i=1}^{NT+NH} u_{i,j} \cdot P_{G,i}^{\min} > P_{P,j}$, the algorithm decommits the thermal power plant with the lowest priority, and for the others the analogous procedure defined above applies. Hydroelectric power plants are not subject to correction of this repair mechanism, as their operating costs can be neglected. 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.:

$$fitness = \frac{1}{1 + f\left(x_1, x_2, \ldots, x_{(NT+NH)J}\right)}. \tag{20}$$

C. 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:

$$\begin{gathered} f_s = a_s f + b_s, \\ a_s = \left(sp - 1\right) f_{av} / \left(f_{\max} - f_{\min}\right), \\ b_s = \left(1 - a_s\right) f_{av}, \end{gathered} \tag{21}$$

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 [32, 33, 27].

D. Crossover

For this optimization problem, first uniform crossover was applied, for the purpose of better exploration of AGA, 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 two-point crossover, two intersection points in the chromosomes are randomly generated, and genes between those two points are exchanged between the two parents.

E. Mutation

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 [35]. 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 l_b or upper limit u_b, according to the following expression:

$$x_k^{'} = \begin{cases} x_k + \left(ub - x_k\right) \cdot \left(1 - r^{\left(1 - \frac{gen}{\max gen}\right)^{\mu}}\right), & rand \le 0.5 \\ x_k - \left(x_k - lb\right) \cdot \left(1 - r^{\left(1 - \frac{gen}{\max gen}\right)^{\mu}}\right), & rand > 0.5 \end{cases} \tag{22}$$

where r is an 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.

F. Elitism strategy

The best solutions ie. chromosomes are stored for the next generation so that they are not lost during the genetic process. In this paper, a strategy is proposed by forming a group of parents chromosomes and children 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.

G. *Particle Swarm Optimization*

The final ELD with considering all defined constraints, is solved using the *particleswarm* function in MATLAB [37]. A unconstrained problem has been solved, in which, in addition to the penalty function, a newly developed constraint handling *repair mechanism* has been implemented, to deal with the constraints, which satisfaction is most difficult. The initial population of the PSO algorithm is created from the ELD solution P_{G00} of the optimal binary combination, previously obtained with QP, as follows:

$$\begin{aligned} P_{G0,m}^{a} &= \left(1-z_t\right)\cdot P_{G00,m} \\ P_{G0,m}^{b} &= \left(1+z_t\right)\cdot P_{G00,m} \\ P_{n,m} &= P_{G0,m}^{a} + rand\cdot\left(P_{G0,m}^{b}-P_{G0,m}^{a}\right), \\ n &= 1,\ldots,N_{pop}, \\ m &= 1,\ldots,N_{\text{var}} = \left(NT+NH\right)\cdot J. \end{aligned} \tag{23}$$

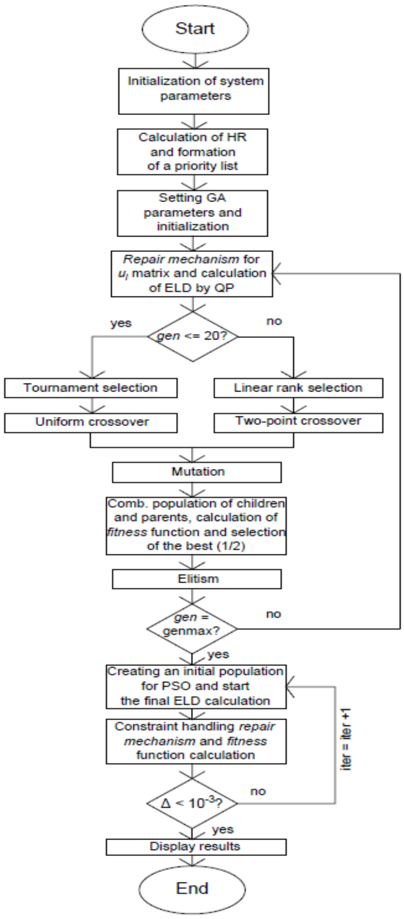

Figure 1. Block diagram of the newly proposed AGA

Considering that it is HTUC, the main goal is that possible steadier production by thermal power plants, and maximum use of the available volume of hydropower plants. Therefore, in the newly proposed constraint handling *repair mechanism*, the power outputs of the hydropower plants 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 Figure 2.

```
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 $\left|\Delta P_{PT}(j) > 10^{-3}\right|$
  $\Delta P_{PT,sr}(j) = \Delta P_{PT}(j)/NT;$
  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
```

Figure 2. Pseudo code of the newly proposed constraint handling repair mechanism

IV. IEEE 30 BUS SYSTEM

The proposed AGA, developed in MATLAB, is applied to the IEEE 30 BUS SYSTEM. This system consists of 30 buses, 6 generators (of which the generators in buses 11 and 13 represent the hydropower plants) and 41 transmission lines [34, 38 - 41]. The spinning reserve of the system per hour is calculated according to the empirical formula of UCTE. In addition, 75% of the spinning reserve is covered by thermal power plants, and the remaining 25% is covered by hydropower plants. Figure 3 shows the daily load diagram of the system, and Figure 4 shows its single-pole scheme. The proposed approach with AGA is applied with 30 independent simulations.

Table 1 shows the parameters of thermal power plants, and Table 2 shows the parameters of hydro power plants. The parameters of transmission lines and nodes are taken from [40,41].

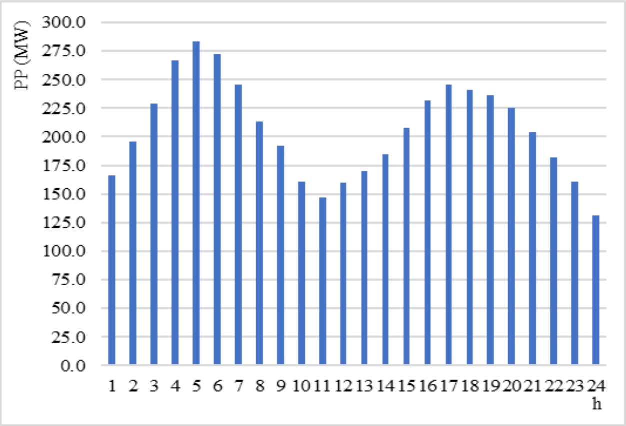

Figure 3. Daily load diagram

The parameters of AGA are: population - 200, elite number - 2. 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 stopping algorithm close to the global optimum, but not in the global optimum. Because of this, stopping criterion in this paper is the maximum number of generations, which is 500.

The total costs of the thermal power plants are € 10048.36, while the total production during the entire optimization period is 5054.90 MWh. The total water discharge during the entire optimization period is, $V_{1,pot} = 5,663 \cdot 10^3 m^3$ and $V_{2,pot} = 10,965 \cdot 10^3 m^3$ respectively for HEC1 and HEC2, thus satisfying the hydroelectric constraint.

Table 3 shows the optimal power outputs of thermal power plants and hydropower plants, as well as the optimal discharges through the turbines, for the entire optimization period.

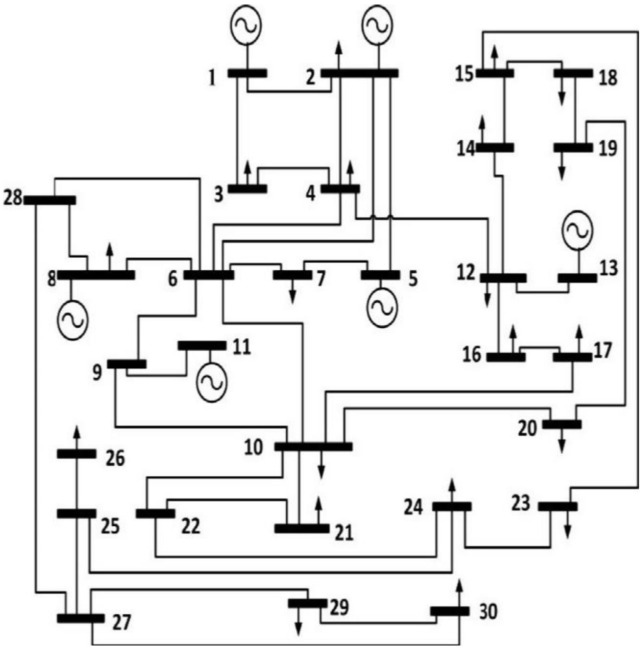

Figure 4. IEEE 30 BUS SYSTEM

Figures 5 and 6 respectively show the optimal hourly power generation of thermal plants and hydro power plants. Table 4 shows the u_i matrix, i.e. the optimal binary combination of committed units.

TABLE I. DATA FOR THERMAL UNITS

	a_t (€/h)	b_t (€/MW)	c_t (€/MW^2)	d_t	e_t	$P_{GT}^{\min}$ (MW)	$P_{GT}^{\max}$ (MW)	UR (MW)	DR (MW)	HSC_t (€)
P_{GT1}	0	2	0,00375	18	0,037	50	200	65	85	70
P_{GT2}	0	1,75	0,01750	16	0,038	20	80	12	22	74
P_{GT3}	0	1	0,06250	14	0,040	15	50	12	15	50
P_{GT4}	0	3,25	0,00834	12	0,045	10	35	8	16	110

TABLE II. DATA FOR HYDRO UNITS

	α_h (m^3/h)	β_h (m^3/MWh)	γ_h (m^3/MW^{2}h)	$P_{GH}^{\min}$ (MW)	$P_{GH}^{\max}$ (MW)	UR (MW)	DR (MW)	$V_{h,k}$ (10^3 m^3)
PGH1	56,067	8,665	0,0061	10	30	8	16	5,663
PGH2	26,505	17,33	0,01	12	40	8	16	11,326

TABLE III. HTUC SOLUTION FOR IEEE 30 BUS SYSTEM WITH AGA

Hour	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	78,83	24,04	15,01	10,01	19,87	20,45	2,2	230,65	385,02
2	102,34	29,11	15,05	10,05	20,12	22,82	3,5	232,85	427,12
3	125,97	34,24	15,69	10,14	21,66	26,45	5,1	246,59	491,88
4	152,25	40,05	17,47	10,36	24,12	30,11	7,4	268,64	557,46
5	162,28	42,27	18,16	10,45	25,63	32,97	8,4	282,15	608,82
6	154,43	40,53	17,62	10,37	24,94	31,73	7,6	275,95	586,43
7	136,85	36,71	16,50	10,31	23,27	28,40	6,0	261,03	526,76
8	115,62	32,01	15,12	10,12	19,96	24,53	4,4	231,42	457,61
9	99,97	28,62	15,07	10,07	19,67	21,94	3,3	228,84	411,52
10	73,10	22,75	15,00	10,00	20,47	21,66	2,0	235,97	406,60
11	65,27	21,07	15,00	10,00	16,98	20,29	1,6	204,95	382,24
12	85,91	25,52	0,00	10,00	20,25	20,96	2,6	234,01	394,20
13	82,25	24,71	15,00	10,00	20,02	20,39	2,4	231,98	384,00
14	94,09	27,31	15,00	10,00	19,57	22,03	3,0	228,01	413,16
15	111,76	31,16	15,09	10,09	19,90	24,10	4,1	230,93	449,94
16	128,71	34,92	15,96	10,25	21,42	26,07	5,3	244,48	485,11
17	137,59	36,85	16,53	10,29	22,63	28,20	6,1	255,29	523,19
18	133,72	36,00	16,26	10,26	22,59	27,94	5,8	254,95	518,47
19	130,86	35,33	16,03	10,19	22,09	27,03	5,5	250,43	502,28
20	123,62	33,79	15,61	10,20	20,92	25,82	5,0	240,05	480,66
21	109,28	30,61	15,07	10,07	19,57	23,34	3,9	227,94	436,35
22	92,14	26,87	15,00	10,00	20,16	20,70	2,9	233,23	389,50
23	73,93	22,91	15,00	10,00	19,48	21,68	2,7	227,16	406,91
24	62,19	20,36	15,00	0,00	16,96	17,92	2,1	204,78	340,25

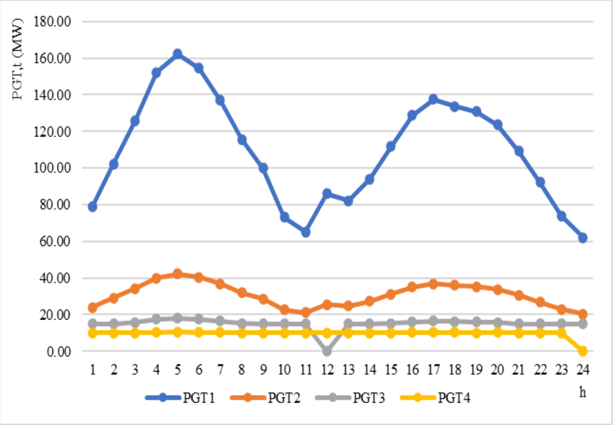

Figure 5. Optimal hourly power generation of thermal units

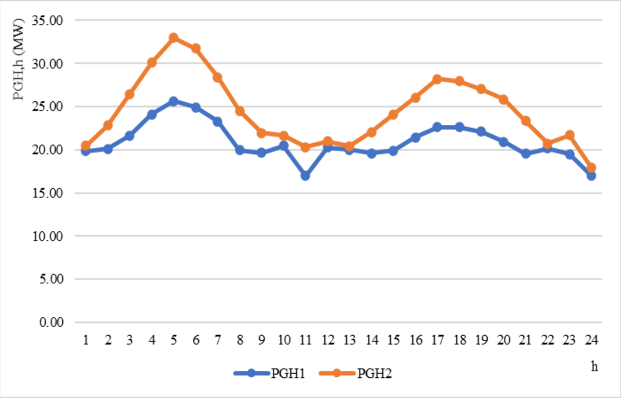

Figure 6. Optimal hourly power generation of hydro units

TABLE IV. UNIT COMMITMENT TABLE FOR IEEE 30 BUS SYSTEM

hour	PGT1	PGT2	PGT3	PGT4	PGH1	PGH2
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	1	1	1	1	1
8	1	1	1	1	1	1
9	1	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1
12	1	1	0	1	1	1
13	1	1	1	1	1	1
14	1	1	1	1	1	1
15	1	1	1	1	1	1
16	1	1	1	1	1	1
17	1	1	1	1	1	1
18	1	1	1	1	1	1
19	1	1	1	1	1	1
20	1	1	1	1	1	1
21	1	1	1	1	1	1
22	1	1	1	1	1	1
23	1	1	1	1	1	1
24	1	1	1	0	1	1

A. Analysis of the obtained results

As it was pointed out, the total costs are € 10048.36, compared to [38] and [39], where they amount to € 13292.28 and € 13517.00. Although in these two references it is a classic UC (for a system which consists only thermal power plants), if we take into account that in this paper a non-convex criterion function is considered, but also the transmission line constraint (DC optimal power flow), and on the other hand there is a big difference in total costs, so it can be concluded that the newly proposed AGA gives better results compared to the algorithms proposed in [38] and [39].

This is based on the fact that the transmission line constraint has a big impact on operating costs as it affects the power flow. This means that if the active power of one of the transmission lines, at some interval, is equal to its maximum capacity, then the power produced by a hydro unit or thermal unit (whether it is the most economical thermal unit) will be redirected to another transmission line, or distributed across multiple transmission lines, which will result in larger transmission losses, i.e. operating costs. In the worst case, this constraint limits production from the "optimal" hydro or thermal unit, and forces production from another thermal unit, which maybe has a higher HR, which significantly affects the total operating costs.

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 5 it can be seen that the thermal unit 1 (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, the thermal unit 3, which is actually the most expensive (with the highest HR), works with its technical minimum and in the interval 12 is even out of operation i.e. decommitted.

As for the hydro units, the total water discharge is $V_{1,pot} = 5,663 \cdot 10^3 m^3$ and $V_{2,pot} = 10,965 \cdot 10^3 m^3$, while the available volume is $V_{1,k} = 5,663 \cdot 10^3 m^3$ and $V_{2,k} = 11,326 \cdot 10^3 m^3$. This indicates the fact that the hydro units have almost completely used their available volume, in order to obtain smaller and more even production of thermal units, i.e. lower operating costs.

From the above it can be concluded that the proposed algorithm provides an optimal and efficient solution to the HTUC 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.

Therefore, it can be concluded that the newly proposed AGA successfully tackles the optimization problem HTUC, which is characterized by high dimensionality and complexity, given the many constraints, which are inevitable to be considered in order to obtain a real and physically acceptable solution, which is especially important for reducing the economic losses during the power system operation.

V. CONCLUSION

This paper proposes a new AGA with a modified constraints handling approach, through a *repair mechanism*, as well as a newly proposed *repair mechanism* for ELD (for gene correction of infeasible solutions according to UC condition), for solving the HTUC optimization problem with considering security constraints.

The newly proposed AGA is able to maintain good genetic code, through the newly proposed *repair mechanisms* and linear rank selection, which can effectively overcome the main disadvantage of GA, i.e. premature convergence. Although the GA search algorithm generally provides a globally optimal solution, there is still some possibility of premature convergence, i.e. GA being stuck in a local optim. In order to overcome such shortcomings of GA, AGA was developed by applying a new *repair mechanism* in the genetic procedure to obtain the optimal binary combination, as well as a new constraint handling *repair mechanism* in solving the main ELD with PSO.

The HTUC optimization problem is gaining momentum in the scientific field "Power System Optimization", and on the other hand a real and physically acceptable solution is needed for the most economical operation possible. Taking this into account it should be noted that this requires the creation of more complex mathematical model, considering more constraints. Because the correlation of constraints is very strong, a hybrid approach is needed to consider and satisfy them. Therefore, it is necessary to develop an appropriate repair mechanism, which is different for each optimization problem, according to the "No free lunch" theorem. In addition, in order to avoid large calculation time and getting stuck in a local optimum, this paper proposes a step-by-step procedure for considering the constraints.

According to that, through step-by-step considering of the constraints, constraint handling repair mechanism, as well as the modified approach to creating the initial population of the main ELD, the HTUC results (applied to the IEEE 30 BUS SYSTEM) obtained in this paper demonstrate the effectiveness of AGA.

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