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Spider Monkey Optimization for Optimal Operational Planning of Energy Plants

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***Abstract*—This paper proposes a spider monkey optimization (SMO) based method for optimal operational planning of energy plants (OOPEPs). The effectiveness of the proposed spider monkey optimization (SMO) based method is verified by comparing with the differential evolutionary particle swarm optimization (DEEPSO), brain storm optimization (BSO), modified BSO (MBSO), and multi-population MBSO (MP-MBSO) based methods. The results are verified by the statistical tests.**

***Keywords*—Optimal operational planning of energy plants, mixed integer non-linear programming problem, spider monkey optimization, cooperative metaheuristics**

I. Introduction

In recent years, Building/Factory Energy Management System (BEMS/FEMS) have drawn attention. BEMS and FEMS are utilized in large-scale office buildings, commercial facilities, and factories. One of the purposes of BEMS and FEMS is to optimize the operation of energy plants in a facility based on the energy consumption of the target facility. The realization of optimal operation of the energy plant in a facility contributes to a reduction of purchased energy costs and has a significant management impact. Therefore, research has been conducted on optimal energy plant operational planning for BEMS and FEMS [1]-[4].

In the OOPEP, it is required to simultaneously consider both linear and nonlinear equipment characteristics, binary variables for start-stop status, and continuous variables for input/output quantities for each piece of equipment in the energy plant. Thus, the problem is formulated as a mixed-integer nonlinear programming problem.

This paper proposes a SMO based method for the OOPEPs. SMO is one of the methods that dynamically changes the number of groups according to the search situation. The effectiveness of the proposed method was confirmed by comparing it with DEEPSO, BSO, MBSO, and MP-MBSO based methods. The results are verified using the Kruskal-Wallis test and the Mann-Whitney U tests with holm correction.

II. A Problem Formulation of The OOPEPs

A. A Target Energy Plant Model

The target energy plant model in this paper which is a benchmark proposed by the Institute of Electrical Engineers of Japan (IEEJ) as a model of energy plants installed in large commercial facilities and factories is shown in Fig.1 [5].

B. Decision Variables

(a) Gas turbine generators (GTGs): start-stop status($y_{gk}^{i} \in \{0,1\}$: $i = 1, \ldots, T, k = 1, \ldots, N_g$), natural gas input quantities (x_{gk}^{i}: $i = 1, \ldots, T, k = 1, \ldots, N_g$).

(b) Turbo Refrigerators (TRs): start-stop status ($y_{tk}^{i} \in \{0,1\}$: $i = 1, \ldots, T, k = 1, \ldots, N_t$), heat output quantities (x_{tk}^{i}: $i = 1, \ldots, T, k = 1, \ldots, N_t$).

(c) Steam Refrigerators (SRs): start-stop status ($y_{sk}^{i} \in \{0,1\}$: $i = 1, \ldots, T, k = 1, \ldots, N_s$), heat output quantities (x_{sk}^{i}: $i = 1, \ldots, T, k = 1, \ldots, N_s$).d

T is the 24 hours of the day ($T = 24$), N_g is the number of GTGs, N_t is the number of TRs, N_s is the number of SRs. When the binary variable y^i is 0, the equipment is stopped, and when y^i is 1, the equipment is in operation.

C. Objective Function

The objective function is to minimize sum of the costs (purchased electric power and purchased natural gas) required to operate the energy plant 24 hours a day.

D. Constraints

1) Supply and demand constraints: The quantity of each energy supply, such as electricity, steam energy, and thermal energy, must be equal to the quantity of each energy consumed at each time of day.

2) Facility constraints: The mechanical characteristics and operational limits of each piece of equipment that composes the energy plant are presented by benchmark problem.

3) Operational constraints: Each equipment has a minimum continuous operation time and continuous shutdown time.

III. OOPEPs Using Spider Monkey Optimization

A. A Round-up Function [6]

OOPEPs require simultaneous consideration of both binary and continuous variables. In this paper, by applying a round-up function, the binary variables can be treated as

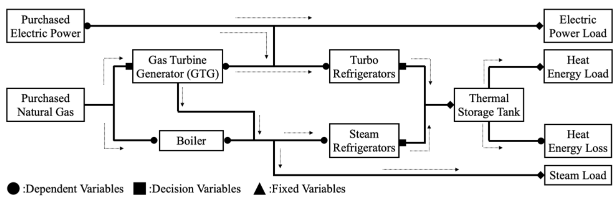

Fig.1. A target energy plant model.

continuous variables. Using the function, it is expected that a search for the shutdown status of each piece of equipment will be sufficiently performed.

B. Spider Moneky Optimization

SMO is a dynamic multi-population based multi-point search evolutionary computation method proposed by J. C. Bansal et al. in 2014 [7]. The method was proposed to simulate the fission-fusion social structure of spider monkeys. They usually form large groups, and depending on the situation, such as foraging, large one group is divided into several smaller groups led by a particular spider monkey to feed.

C. OOPEPs using Spider Monkey Optimization

The overview of algorithm of the proposed SMO based method applied to OOPEPs is following.

Step.1 Initialize each individual (SMs) using the round-up function. $iter = 1$.

Step.2 Update each individual using Local Leaders (LLs) and Global Leader (GL). After converting the decision variable values into the input/output values and operating status of each equipment based on the round-up function, the objective function values of each individual are calculated.

Step.3 Update LLs and GL based on the updated population.

Step.4 Random search and reconstruct the population based on the update cycle of LLs and GL.

Step.5 Update LLs and GL. If $iter$ reaches its maximum, output the best solution so far and exit. If $iter$ is not reached, $iter = iter + 1$, go to Step 2.

IV. Simulations

Effectiveness of the proposed method is verified by applying the DEEPSO based method [2], the BSO based method [3], the MBSO based method [4], the MP-MBSO based method [4] and the proposed SMO based method to the energy plant model shown in Figure 1.

A. Simulation Conditions

The energy plant of the model consists of one GTG, one TR, two SRs, and one boiler. The parameters for the methods are shown below.

1) Common parameters:the maximum number of evalutions: $320{,}000$ (The value is determined so that the evaluation number of all methods are the same.), *the number of trials:* 100.

2) The round-up function's parameters:
$\alpha: -0.5, \beta: -0.05, \gamma: 1.05$

3) The proposed SMO based method's parameters: The maximum number of N_g*: 5, the number of individuals SMs:* 40*, probability threshold* pr: 0.8*, the maximum number of LLC*: 1*, the maximum number of GLC*: 5

B. Simulation Results

Table I shows the minimum, the maximum, average, and standard deviation values of the objective function values by the proposed SMO based method, and the conventional methods and the p-value of the Kruskal-Wallis test. Each value in Table I represents the value when the average value by DEEPSO based method is set to 100 as the benchmark. These simulation results indicate that the proposed SMO based method is the best in all values. The results of the Kruskal-Wallis test verified to be a significant difference at 5% significance level.

Moreover, to reveal significant differences among the methods, the Mann-Whitney U tests with holm correction are conducted as a post hoc test, and the results are shown in Table II. In Table II, the p-values between the proposed method and other conventional methods are not exceeded 0.05 significant level. Therefore, it is verified that the proposed SMO based method is superior to the conventional DEEPSO, BSO, MBSO, MP-MBSO based methods.

V. Conclusions

This paper proposes the spider monkey optimization based method for the OOPEPs. It was confirmed by simulation using a plant model that the proposed method can stably obtain better quality solutions compared to the conventional methods. Moreover, effectiveness of the proposed method is verified by the statistical tests.

As future works, applications of the improved spider monkey optimization methods and other advanced evolutionary computation methods to the OOPEPs will be investigated.

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TABLE I. The Compariton of the Minimum, the Maximum, Average, and Standard Deviation Values of the Objective Function Values by the Proposed SMO based method and the Conventional DEEPSO, BSO, MBSO, MP-MBSO based Methods.

	MIN.	MAX.	AVE.	STD.	p-value
DEEPSO[2]	98.42	102.63	100.00	100.00	**4.67E-111**
BSO[3]	98.20	99.71	98.74	23.93	
MBSO[4]	98.12	101.95	99.93	85.17	
MP-MBSO[4]	97.36	97.75	97.47	6.31	
SMO	**97.23**	**97.41**	**97.29**	**3.04**	

TABLE II. p-values of the Mann-Whiteney U test with Holm correction between Each two methods..

	DEEPSO	BSO	MBSO	MP-MBSO	SMO
DEEPSO[2]	-	1.14E-20	9.85E-01	2.56E-33	2.56E-33
BSO[3]	S	-	4.72E-20	2.56E-33	2.56E-33
MBSO[4]	NS	S	-	2.56E-33	2.56E-33
MP-MBSO[4]	S	S	S	-	2.56E-33
SMO	**S**	**S**	**S**	**S**	-

*S: Significant (the p-value is not exceeded 0.05 significant level.)
NS: Non-Significant (the p-value is exceeded 0.05 significant level.)