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Social Evolutionary Programming Algorithm on Unit Commitment in Wind Power Integrated System

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Abstract: Social Evolutionary Programming algorithm based on a Social Cognitive Model is proposed in this paper. The uphill and downhill spinning reserves are introduced to cope with the power imbalances caused by wind fluctuation on the premise of full utilization of wind energy. The proposed algorithm has an advantage in the convergent stability and computational efficiency. Since climbing rates constraints have impacts on both start-up & shutdown schedules of generating units and the economic dispatch based on a fixed schedule, two different ways are put forward to calculate UC problem containing climbing rates constraints. Simulation results of a 10-unit system show that such a Social Evolutionary Programming algorithm can effectively cope with the change of reserve requirement due to the grid-connection of wind farm, and meet the multiple requirements of UC and dispatching.

1. INTRODUCTION

The growing power consumption inevitably reduced the storage of fossil fuels. Wind power has gained more and more popularity around the world due to its excellent features of no energy consumption and no pollution emissions. However, wind energy is intermittent and random volatility affected by natural factors. Although scholars have already done a lot of wind forecasting research work, it is still difficult to obtain accurate wind speed and wind power prediction results. When the scale of wind power increased above a certain proportion, its uncertainty is bound a risk to the power system dispatching operation. To research the unit commitment (UC) and economic dispatch(ED) problem including wind farms and consider various time interaction between sections can effectively reflect the operation requirements of the system, and therefore has a very important value.

In recent years, genetic algorithms (GA) and other intelligent algorithms have been applied to the study of UC. Since the initial population of genetic algorithm is randomly generated, most of the resulting individuals do not meet the minimum up/down time constraints and become infeasible. Further, in the process of crossover and mutation, since genetic factors operate random, the individuals are also usually infeasible. In allusion to these shortcomings of GA, social evolution programming (SEP) algorithm is introduced. This algorithm replaced individuals in the traditional GA with cognitive agents, which imitated human decision-making behaviours to obtain the feasible solutions. It also replaced the mechanism of crossover and mutation with the mechanism of “paradigm study and update”. Therefore it had an advantage in the convergent stability and the computational efficiency.

To a UC model including wind farms, in order to ensure reliability of the system, appropriate measures need to be taken to deal with intermittent and stochastic volatility of wind. Currently there are two main ways. The first way is to optimize wind power output and take into account the randomness of the wind. The second way is to optimize conventional thermal power only according to a given wind power prediction curve, leaving enough spare to deal with possible fluctuations of wind power. Since the state supports for full utilization of renewable energy generation, besides, wind power output after optimization is difficult to achieve in practical real-time control system, the second approach is adopted in this paper to process UC and ED containing wind farms. Furthermore, in the process of generating the individuals, the minimum up/down time constraints and the spinning reserve constraints are considered in cognitive regulation to ensure that each individual corresponding to the start-up & shutdown schedules is a feasible solution which will be calculated by interior point method. When considering the dynamic economic dispatch, different ways are put forward to deal with ramping rates constraints, and compares the different outcome. Finally a 10-unit system proves that the algorithm is practical and has good convergence stability.

2. MODEL OF UC

2.1 Objective Function

Since the construction and maintenance cost of thermal power plants and wind farm need to be recovered after a long run, so under normal circumstances, for the short-term ED problem, only the operational costs of thermal power plants is considered which include fuel costs and start-up costs. For wind farms, since they operate without consuming fuel, their fuel cost is zero. In summary, the expression for the total cost of electricity is as in

$$\min f = \sum_{t=1}^{t=T}\sum_{i=1}^{i=N}[U_{it}C_{it} + U_{it}\left(1-U_{i,t-1}\right)S_i] \tag{1}$$

Where, f is the total generation cost; N is the total number of generating units; T is the total number of periods; U_{it} represents the status of unit i at time t; $U_{it}=1$ means the unit is running and $U_{it}=0$ means the unit is down.

C_{it} represents the generation cost of unit i at time t, generally expressed with a quadratic function.

$$C_{it} = a_i + b_i P_{it} + c_i P_{it}^2 \tag{2}$$

Where, a_i, b_i and c_i are fuel cost coefficients of unit i; p_{it} is the actual output of unit i at time t.

S_i represents the start-up cost of unit i.

$$S_i = \begin{cases} S_{hi} : \tau_i^{off} \le (-X_{it}) \le \tau_i^{off} + H_{csi} \\ S_{ci} : (-X_{it}) \ge \tau_i^{off} + H_{csi} \end{cases} \tag{3}$$

Where, S_{hi} is the hot start cost of unit i; S_{ci} is the cold start-up cost of unit i; τ_i^{off} is the minimum downtime of unit i; H_{csi} is the cold start time of unit i; X_{it} is the number of period that unit i has been continuous running (positive value) or down (negative value).

2.2 Constraints

UC problem containing wind farms must satisfy the following constraints in the optimization process.

1) Power balance of system

$$\sum_{i=1}^{i=N} U_{it}P_{it} + P_{wt} = D_t, (t = 1, 2, \ldots, T) \tag{4}$$

Where, P_{wt} is the predictive active power output of the wind farm at time t; D_t is the total system load at time t.

2) Minimum up/down time constraint of generating units

Once the unit is running/shutdown there is a minimum time before it can be stopped/started.

$$X_{it} \ge \tau_i^{on} \tag{5}$$

$$(-X_{it}) \ge \tau_i^{off} \tag{6}$$

Where, τ_i^{on} is the minimum uptime of unit i.

3) Minimum and maximum outputs of units

A unit can be dispatched within a certain limit.

$$P_i^{\min} \le P_{it} \le P_i^{\max} \tag{7}$$

Where, $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum outputs of unit i.

4) Ramping rates of generating units

$$\begin{cases} P_{\mathrm{it}} - P_{i,t-1} \le P_i^{up}, P_{it} > P_{i,t-1} \\ P_{i,t-1} - P_{i,t} \le P_i^{down}, P_{it} < P_{i,t-1} \end{cases} \tag{8}$$

Where, P_i^{up} and P_i^{down} are the maximum uphill and downhill power of unit i.

5) Spinning reserve capacity of system

To prevent the load and wind power fluctuations, adequate spinning reserve must be provided.

The uphill spinning reserve constraint is:

$$S_t^{up} = \sum_{i=1}^{i=N} S_{it}^{up} \ge R_t \times D_t + P_{wt} \times W_{up} \tag{9}$$

$$S_{it}^{up} = \min(P_{it}^{\max} - P_{it}, U_{it}P_i^{up}) \tag{10}$$

$$P_{it}^{\max} = \min(P_i^{\max}, P_{i,t-1} + P_i^{up}) \tag{11}$$

Where, S_t^{up} is the uphill spinning reserve capacity the system can provide at time t; S_{it}^{up} is the uphill spinning reserve capacity unit i can provide at time t; R_t is the proportion of load reserve capacity; W_{up} is the proportion uphill spinning reserve of wind power; $P_{it}^{\max}$ is the maximum output of unit i can reach at time t.

The downhill spinning reserve constraint is:

$$S_t^{down} = \sum_{i=1}^{i=N} S_{it}^{down} \ge P_{wt} \times W_{down} \tag{12}$$

$$S_{it}^{down} = \min(P_{it} - P_{it}^{\min}, U_{\mathrm{it}}P_i^{down}) \tag{13}$$

$$P_{it}^{\min} = \min(P_i^{\min}, P_{i,t-1} - P_i^{down}) \tag{14}$$

Where, S_t^{down} is the downhill spinning reserve capacity the system can provide at time t; S_{it}^{down} is the downhill spinning reserve capacity unit i can provide at time t; W_{down} is the proportion downhill spinning reserve of wind power; $P_{it}^{\min}$ is the minimum output of unit *i* can reach at time *t*.

3. APPLICATION OF SEP ON UC PROBLEM

3.1 Introduction of SEP

SEP algorithm and GA algorithm are both based on population evolution and survival of the fittest, but the two optimization mechanisms have essential differences. GA is based on such a series operation on the encoding as selection, crossover and mutation. SEP replaces chromosomes in GA with cognitive subjects, and its optimization mechanism is based on a series of intelligent cognitive behaviour, that is the establishment and transformation of paradigm and cognitive subjects inheriting from paradigms.

The role of selection and crossover in GA is to copy the best individual gene fragment, which is trying to inherit the excellent information from the previous generation groups. The corresponding optimization mechanisms in SEP are cognitive subjects' paradigm learning process. All paradigms are some of the excellent subjects. In the process of paradigm learning, a new cognitive subject selects a series of paradigms and imitates them after intelligent analysis, the fundamental purpose of which is inheritance of good information. The fundamental purpose of both mechanisms is consistent, but they still have intrinsic differences:

1) The genes in GA are spread generation to generation while a paradigm in SEP is independent of the groups, which will always exist until a better paradigm replaces it. So dissemination of the excellent information in SEP is continuous and stable.

2) Individual genes inherit only from two individuals of previous generation groups in GA, while cognitive subjects in SEP can inherit multiple or all the good paradigms. Dissemination of information in SEP is beyond the limit of "space (two individuals)" and "time (generations)".

3) To a new individual in GA, inheritance of excellent information is passive, and it is just a random reorganization of genes from parents, which is likely to dissatisfy incompatible constraints. Cognitive subjects in SEP are different. They are motivated to choose, rather than passive accept. After analysis and inference, cognitive subjects will make reasonable choices.

3.2 Steps of SEP to Solve UC Problem

UC is a mixed integer combinatorial optimization problem containing both integer variable *U* (U_{it}, *i = 1,2, ⋯, N, t = 1,2, ⋯, T*) and continuous variable *P* (P_{it}, *i = 1,2, ⋯, N, t = 1,2, ⋯, T*). Correspondingly, it can be decomposed into two sub-problems.

Determining integer variable *U*: On the premise of the constraints (5), (6), (9) and (12), determine the operating status of each unit in the scheduling periods to obtain a feasible start-up & shutdown schedule. This is UC sub-problem.

Calculating continuous variable *P*: After getting the variable *U*, distribute economically the total system load among all operating generating units at each time and determine the power of each unit to achieve the minimum total cost. This is ED sub-problem.

For ED sub-problem, the interior point method is used to achieve economic distribution among generating units, so the first sub-question which is to determine a feasible schedule is need to be solved by SEP. First, define the relevant variables:

1) K_D, $K_D(t,i) = X_{it}$, recording the number of periods unit *i* has been continuously running (positive value) or down (negative value) to date at time *t*.

2) K_J , $K_J(t,i) = \{1, 0, -1\}$, $K_J(t,i) = 1$ means that the shutdown unit can be started at time *t*; $K_J(t,i) = -1$ means that the unit in operation can stop at time *t*; $K_J(t,i) = 0$ means the current status of the unit can not be changed, that is, it must maintain the original status of running or shutdown. K_J is determined by the same dimensional arrays K_{J1} and K_{J2}.

3) K_R, $K_R(t,i) = U_{it}$, recording the status unit *i* at time *t*, $K_R(t,i) = 1$ means unit *i* is in operation; $K_R(t,i) = 0$ means unit *i* is down.

4) G , total number of generations.

5) *size*, population size.

6) *M*, total number of paradigms.

Cognitive subjects make decisions in two ways, one is self-awareness, and the other is paradigm learning. Generally, cognitive subjects of the past *H-th* generations get feasible solutions though self-awareness, later they primarily inherit paradigms. In addition, some of the cognitive subjects are also able to break the impact of the existing paradigms. Define mutation probability threshold τ and generate a random number by uniformly distributed random number generator, if the number is less than τ , cognitive subjects of this generation get solutions though self-awareness, else through paradigm learning. The flow chat of SEP is shown in Fig.1.

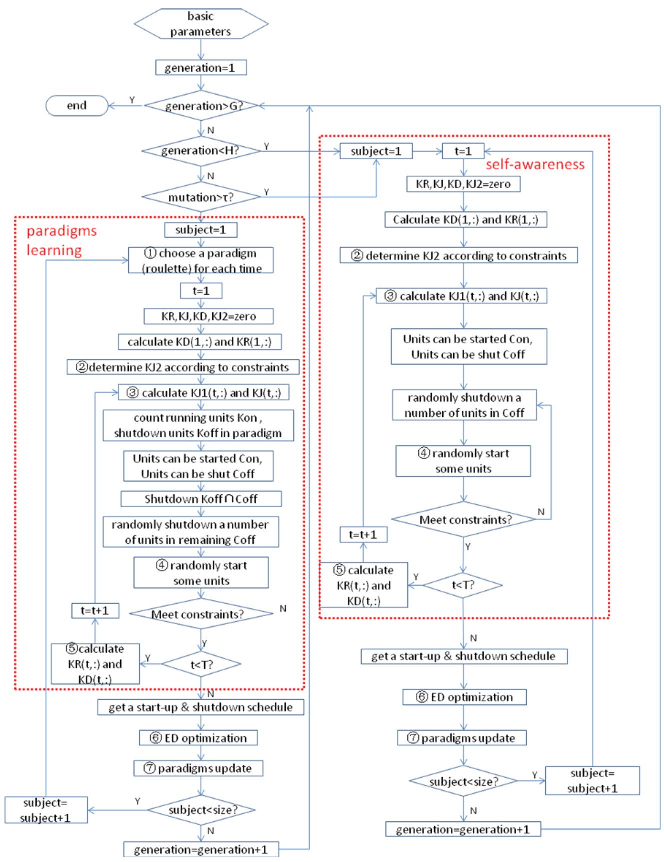

Fig.1. Flow chart of SEP to solve UC

Next, it's just to make clear, with some emphasis, about the numeral identifies in Fig.1.

1) Each period, the cognitive subject selects a paradigm in accordance with roulette method. In order to strengthen the local search ability of SEP, p_1 is artificial appropriately increased which is the probability the best paradigm being inherited. Meanwhile, to prevent the convergence of entire social groups to the best paradigm, which reduces the ability of global optimization, p_1 should be decreased in terms of attenuation coefficient μ by generation.

2) If *num* (*num = 1,2, ..., n*; *n* is determined by the total unit numbers) generating units simultaneously be stopped at time *t*, then all or part of the num generating units can not be started in a period of time following *t*, resulting the power balance and spinning reserve constraints dissatisfied, so the *num* generating units can not simultaneously be stopped at time *t*. We can randomly started several generating units from the *num* generating units, then the value of K_{J2} of all started generating units at time *t* is assigned zero, and corresponding K_R is 1. The rest values of K_{J2} are 1.

3) K_{J1} impacts generating units only from the point of the minimum up/down time constraints. Apparently K_{J1} is determined by K_D.

$$K_{J1}(t,i)=\begin{cases}1 & K_D(t,i)\le -\tau_i^{off}\\ -1 & K_D(t,i)\ge \tau_i^{on}\\ 0 & -\tau_i^{off}<K_D(t,i)<\tau_i^{on}\end{cases} \tag{1}$$

For unit *i*, $i\in\{i\,|\,K_{J1}(t,i)=-1\}$, we should also consider K_{J2}. K_J is ultimately determined by K_{J1} and K_{J2}.

$$K_J(t,i)=K_{J1}(t,i)\times K_{J2}(t,i) \tag{2}$$

4) Randomly select a number of generating units to start but not just from C_{on}. The shutdown generating units in the previous step can also be started in this step. This will increase the randomness of the algorithm to help avoid the local optimum. First randomly select one unit to start, if it can not meet the power balance and spinning reserve constraints, and then randomly selected two, in ascending order. Random selection also follows the principle of starting fewer generating units as far as possible.

5) If *t*<*T*, $K_D(t+1,i)$ is determined by $K_R(t,i)$.

$$K_D(t+1,i)=\begin{cases}K_D(t,i)+1 & K_R(t,i)=1,\ K_D(t,i)>0;\\ 1 & K_R(t,i)=1,\ K_D(t,i)<0;\\ -1 & K_R(t,i)=0,\ K_D(t,i)>0;\\ K_D(t,i)-1 & K_R(t,i)=0,\ K_D(t,i)<0;\end{cases} \tag{3}$$

6) ED is solved by interior point method.

7) A paradigm is the record of a good feasible solution. Sort the M paradigms in accordance with their objective function values from low to high order. After a cognitive subject gets a new feasible solution, if its objective function value is less than that of a paradigm, then the feasible solution will be inserted to the increasing *M* paradigms as a new paradigm and the last paradigm will be deleted. So the paradigms are always dynamic updating throughout this evolution.

4. CASE STUDIES

In this paper, 10-unit system is analyzed as an example. The parameters of generators are as in Table 1.

Table 1. Data for the 10-unit system

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
P_i^{max} (MW)	455	455	130	130	162
P_i^{min} (MW)	150	150	20	20	25
a_i (\$/h)	1000	970	700	680	450
b_i (\$/MWh)	16.19	17.26	16.60	16.50	19.70

c_i (\$/MW^{2}h)	0.0005	0.0003	0.002	0.0021	0.00398
τ_i^{on} (h)	8	8	5	5	6
τ_i^{off} (h)	8	8	5	5	6
S_{hi} (\$)	4500	5000	550	560	900
S_{ci} (\$)	9000	10000	1100	1120	1800
H_{csi} (h)	5	5	4	4	4
	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
$P_i^{\max}$ (MW)	80	85	55	55	55
$P_i^{\min}$ (MW)	20	25	10	10	10
a_i (\$/h)	370	480	660	665	670
b_i (\$/MWh)	22.26	27.74	25.92	27.27	27.79
c_i (\$/MW^{2}h)	0.0071	0.0008	0.0041	0.0022	0.00173
τ_i^{on} (h)	3	3	1	1	1
τ_i^{off} (h)	3	3	1	1	1
S_{hi} (\$)	170	260	30	30	30
S_{ci} (\$)	340	520	60	60	60
H_{csi} (h)	2	2	0	0	0

The wind farm is composed of 100 generating units, capacity of which is 1500kW. 24 hours of load and wind forecasting power are shown in Table 2. Basic parameters of SEP are shown in Table 3:

Table 2. 24-hour load and wind forecasting power

Time (h)	Load (MW)	Wind (MW)	Time (h)	Load (MW)	Wind (MW)
1	700	72	13	1400	72
2	750	106	14	1300	116
3	850	113	15	1200	77
4	950	103	16	1050	64
5	1000	139	17	1000	106
6	1100	116	18	1100	142
7	1150	122	19	1200	116
8	1200	88	20	1400	124
9	1300	53	21	1300	135
10	1400	41	22	1100	122
11	1450	55	23	900	92
12	1500	53	24	800	57

Table 3. Basic parameters of SEP

Parameter	G	$size$	H	M	p_1
Value	200	20	10	15	0.5
Parameter	μ	τ	W_{up}	W_{down}	R_t
Value	1.5	0.95	20%	20%	10%

If climbing power constraints are not considered, the convergence curves are shown in Fig.2 and Fig.3. After about 40 iterations, the objective function value begins to decrease very slowly, which indicates that the algorithm can quickly search for the optimal solution or suboptimal solution. After the wind farm connected to the grid, the system minimum generation cost reduced from \$ 566260 to \$ 517,360.

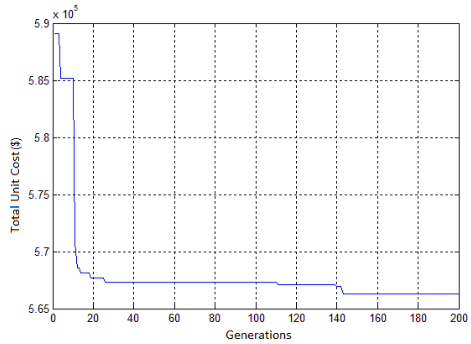

Fig.2 Convergence curve before the wind farm connected

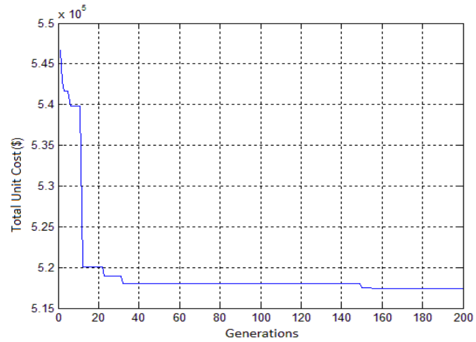

Fig.3. Convergence curve including the wind farm

Assume these ten generating units have uphill climbing constraints P_i^{up} and downhill climbing constraint P_i^{down}, and $P_i^{up} = P_i^{down} = 50MW$. Two methods are used to consider climbing power constraints. The first one is to calculate hourly. That is first to calculate ED of the first hour, then limit the following power output based on the formal output accoding to climbing constaints. The second method is to treat 24-hour output power of 10 generating units as a whole to calculate. Results of two methods are shown in Table 4.

Table 4. Generation cost of two methods

Without climbing constraints	Considering climbing constraints	
	First method	Second method
\$517360	\$543816.5	\$538497.4

Since the second method overall optimizes 24-hour unit output, it is able to search a better solution. The resulting start-up & shutdown schedules of these two methods are as in Table 5 and Table 6.

Table 5. Resulting schedule of the first method

Units	1	2	3	4	5	6	7	8	9	10
1h	1	1	0	0	1	0	0	0	0	0
2h	1	1	1	1	1	0	0	0	0	0
3h	1	1	1	1	1	0	0	0	0	0
4h	1	1	1	1	1	0	0	0	0	0
5h	1	1	1	1	1	1	0	0	0	0
6h	1	1	1	1	1	1	1	1	0	1
7h	1	1	1	1	1	1	1	0	0	1
8h	1	1	1	1	1	0	1	0	0	1

9h	1	1	1	1	1	0	1	0	0	1
10h	1	1	1	1	1	1	1	0	1	1
11h	1	1	1	1	1	1	1	1	1	1
12h	1	1	1	1	1	1	1	1	1	1
13h	1	1	1	1	1	1	1	1	1	1
14h	1	1	1	1	1	1	1	1	0	0
15h	1	1	1	1	1	1	1	0	0	0
16h	1	1	1	1	1	1	0	0	0	0
17h	1	1	1	0	1	1	0	0	0	0
18h	1	1	1	0	0	1	1	0	0	0
19h	1	1	1	1	0	1	1	0	0	0
20h	1	1	1	1	1	1	1	0	0	0
21h	1	1	1	1	1	1	1	0	0	0
22h	1	1	1	1	1	1	0	0	0	0
23h	1	1	1	1	1	0	0	0	0	0
24h	1	1	1	0	1	0	0	0	0	0

Table 6. Resulting schedule of the second method

Units	1	2	3	4	5	6	7	8	9	10
1h	1	1	1	1	0	0	0	0	0	0
2h	1	1	1	1	0	0	0	0	0	0
3h	1	1	1	1	0	0	0	0	0	0
4h	1	1	1	1	0	0	0	0	0	0
5h	1	1	1	1	0	0	0	0	0	0
6h	1	1	1	0	0	1	0	1	0	0
7h	1	1	1	0	1	1	1	0	0	0
8h	1	1	1	0	1	1	1	0	0	0
9h	1	1	1	0	1	1	1	0	1	0
10h	1	1	1	1	1	1	1	1	1	0
11h	1	1	1	1	1	1	1	1	1	1
12h	1	1	1	1	1	1	1	1	1	1
13h	1	1	1	1	1	1	1	1	1	1
14h	1	1	1	1	1	0	1	1	0	1
15h	1	1	1	1	1	0	1	0	0	1
16h	1	1	1	1	1	0	1	0	0	1
17h	1	1	1	1	1	0	0	0	0	0
18h	1	1	1	1	1	0	0	0	0	0
19h	1	1	1	1	1	1	0	0	0	0
20h	1	1	1	1	1	1	1	0	0	0
21h	1	1	1	1	1	1	1	0	0	0
22h	1	1	1	0	1	1	1	0	0	0
23h	1	1	1	0	1	0	1	0	0	0
24h	1	1	0	0	1	0	0	0	0	0

5. CONCLUSIONS

SEP and interior point method are combined in this paper to calculate the UC and ED problem including a wind farm and come to the following conclusions.

1) For the volatility and randomness of wind power, the model introduced the uphill and downhill spinning reserve constraints, which achieved minimal generation cost under the premise of safe and stable operation and maximizing the wind power.

2) In the process to determine a start-up & shutdown schedule, spinning reserve and minimum up/down time constraints are considered, to ensure each of the schedules is a feasible solution, thus greatly improving the convergence stability and search efficiency.

3) Comparison of two methods considering climbing power constraints indicates that 24-hour overall optimization can find a better solution, the resulting schedule and more cost can be saved under the premise of ensuring power system reliability.

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