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A NOVEL MULTI-OBJECTIVE DISCRETE PARTICLE SWARM OPTIMIZATION WITH ELITIST PERTURBATION FOR RECONFIGURATION OF SHIP POWER SYSTEM

Lingjie Zhang[1*]
Jianbo Sun[1]
Chen Guo[2]
[1] Marine Engineering College, Dalian Maritime University, China
[2] Information Science and Technology College, Dalian Maritime University, China
* corresponding author

ABSTRACT

A novel multi-objective discrete particle swarm optimization with elitist perturbation strategy (EPSMODPSO) is proposed and applied to solve the reconfiguration problem of shipboard power system(SPS). The new algorithm uses the velocity to decide each particle to move one step toward positive or negative direction to update the position. An elitist perturbation strategy is proposed to improve the local search ability of the algorithm. Reconfiguration model of SPS is established with multiple objectives, and an inherent homogeneity index is adopted as the auxiliary estimating index. Test results of examples show that the proposed EPSMODPSO performs excellent in terms of diversity and convergence of the obtained Pareto optimal front. It is competent to solve network reconfiguration of shipboard power system and other multi-objective discrete optimization problems.

Keywords: Shipboard power system, Reconfiguration, Multi-objective, Discrete PSO, Elitist perturbation

INTRODUCTION

Reconfiguration of an electrical network in ship power system(SPS) refers to the ability of ship power system to redirect power by closing or opening the breakers related to the loads in the event of a component failure, fault or generator loss, its main task is to maximize the survivability, security and reliability of ships[1]. The generation capacity and ship scale keep enlarging in space with the application of high power density integrated generating system, DC medium voltage transmission, zonal distribution system, power conversion device, and the high power electric propulsion system, which makes it more and more difficult to reconfigure the SPS effectively[2].

Reconfiguration of SPS is a typical discrete, nonlinear, NP complete combinatorial optimization problem with multiple objectives and multiple constraints[3]. The traditional methods based on how to reduce the network loss of the land power system do not work well on the ship[4]. Hence, additional objectives, such as load balance, transmission, and stability margins have been considered when dealing with the reconfiguration of SPS. While in solving this kind of multi-objective reconfiguration problems, the main approach adopted in traditional methods is: firstly, converting the multi-objective optimization problems(MOP) to the single objective optimization problems (SOPs) through a certain weight vector which reflects the priority between the objectives, then, utilizing the computational intelligence algorithms to optimize the SOPs[5]. Up to now, lots of single objective optimization algorithms(SOAs) are proposed and applied to reconfigure the SPS, including genetic algorithms, particle swarm optimization(PSO), differential evolution, ant colony optimization, hybrid approach and some other heuristic algorithms[6-12].

However, the reconfiguration solutions obtained by the SOAs could not always satisfy the requirements under the uncertain circumstances. On one hand, due to the different nature of each objective, it is difficult to make quantitative analysis when converting the MOPs to SOPs. On the other hand, the distribution of the coefficients in the weight vector between the objectives relies mainly on subjective experience and lack theoretical support[13]. Since the MOPs always contain conflicting objectives, there is no single optimal solution but a set of Pareto optimal solutions as a result[14]. Fortunately, multi-objective optimization algorithms(MOAs) based on Pareto dominance are proposed by researchers to solve the MOPs. Among them, the multi-objective particle swarm optimization(MOPSO), which has a fast convergence speed and simple structure, seems to be one of the most potential method[15]. The challenge remained in MOPSO is how to effectively and efficiently achieve a better balance between convergence and diversity of the swarm[16]. More research works need to be done to handle the multi-objective reconfiguration problem of SPS.

Based on the above analysis, this paper presents a novel multi-objective discrete particle swarm optimization with elitist perturbation strategy(EPSMODPSO) to solve the multi-objective reconfiguration problem of SPS. While in establishing the mathematical model of SPS, the power system homogeneity index is adopted as an auxiliary evaluation of the obtained Pareto optimal solutions. To achieve the conversion between the multiple discrete states(0,1,2), the particle's velocity value is utilized as the probability to determine the particle to move one step in the positive or negative direction. An elitist perturbation strategy(EPS), in which several dimensions are selected to be perturbed, is also proposed to help the algorithm to improve its local searching ability and jumping out ability. In the external archive updating process, the crowding distance of the obtained Pareto optimal solutions in objective space are calculated to keep the archive a good diversity.

RECONFIGURATION MATHEMATICAL MODEL OF SPS

RELATED WORK

Generally, a multi-objective optimization problem can be described as follow:

$$\min F(x) = [f_1(x), f_2(x), \cdots,]f_m(x) \quad (1)$$

where $x=(x_1,x_2,...,x_m)$ is a n-dimensional vector bounded in the decision space Ω, m is the number of objective functions and the mapping function F: $\Omega \to R^m$ defines m objective functions bounded in the objective space R^m. The objectives may contradict each other, thus the best trade-offs among the objectives can be defined in terms of Pareto optimality.

Definition 1. (Pareto dominance): a decision vector x is said to dominate another decision vector y (noted as $x \succ y$) if and only if $\{\forall i \in \{1,2,\cdots m\}: f_i(x) \le f_i(y)\} \wedge \{\exists i \in \{1,2,\cdots m\}: f_i(x) < f_i(y)\}$.

Definition 2. (Pareto optimal): a solution x is said to be Pareto optimal if and only if $\neg\exists y \in \Omega : y \succ x$.

Definition 3. (Pareto optimal set, PS): The set of PS is defined as: $PS=\{x \in \Omega \mid \neg\exists y \in \Omega : y \succ x\}$.

Definition 4. (Pareto front, PF): The PF is defined as: $PF=\{F(x) \mid x \in PS\}$.

THE RECONFIGURATION FORMULATION

Modern SPS usually consists of several generators and lots of loads, and interconnected by buses and breakers into a ring or network structure. The critical loads are supplied with two power circuit: the normal circuit and the standby circuit. Some critical are directly connected to the main buses to guarantee the power supply priority.

Objective 1: minimize the load loss of SPS

SPS requires the maximum restoration of loads with a certain priority after network reconfiguration, the loads are divided into 3 grades by priority. The objective function to minimize the load loss is defined as follow:

$$\min f_1 = \lambda_1 \sum_{i=1}^{N_1}(1-x_i)L_{g1i} + \lambda_2 \sum_{j=1}^{N_2}(1-x_j)L_{g2j} + \lambda_3 \sum_{k=1}^{N_3}(1-x_k)L_{g3k} \quad (2)$$

Where f_1 is the total loss of loads; N_1, N_2 and N_3 are the total numbers of each grade loads, the toward number of loads is $N_L = N_1 + N_2 + N_3$; L_{g1i}, L_{g2j} and L_{g3k} are the 3 grade loads; λ_1, λ_2 and λ_3 are the weight coefficients which indicate the priority of each grade loads; x_i, x_j and x_k are the Boolean power state of the loads.

Objective 2: minimize the switching operation cost

The switching operation cost(SOC) is an important index to measure the rapidity of the fault recovery solutions, and SPS requires the total operation times of switches as fewer as possible. The objective function to minimize the SOC is described as follow:

$$\min f_2 = \theta_1 S_1 + \theta_2 S_2 \quad (3)$$

Where θ_1 and θ_2 are the weight coefficients of automatic switches and manual switches; S_1 and S_2 are the total numbers of each kind of switches.

It is necessary to mention that, the switching of the generator is determined by the energy management system according to the actual situation of the ship, and it takes a long time to put the generator into work. While in the emergency conditions, all the generators are required to be operated in parallel to protect the power supply. Hence, the switching operation of the generators will not be considered in this study.

CONSTRAINTS

Constraint 1: switching constraint

For the loads can be restored, there is only one closure between the normal power supply path and the alternative path. Then, the constraint is defined as:

$$z_{i\alpha} + z_{i\beta} = 1 \quad (4)$$

Where $i = 1,2,...,\Omega$, Ω is the number of transfer switches; $z_{i\alpha}$ and $z_{i\beta}$ are the Boolean state of the normal switch and the alternative switch.

Constraint 2: branch capacity constraint.

The load of each branch cannot exceed its permission capacity.

$$y_i S_{C_i} \le C_i \quad (5)$$

Where $i = 1,2,..., N_f$ is the index number of the branches, N_f is the number of the branches; S_{C_i} is the needed capacity of branch i after reconfiguration; y_i is the Boolean state of each branch; C_i is the rated capacity.

THE AUXILIARY EVALUATION INDEX

Since the optimization result of MOP is a set of Pareto optimal solutions, an auxiliary evaluation index of the obtained Pareto solutions is needed to help the decision makers to choose the appropriate solutions. The power system homogeneity is an effective approach to evaluate the ability of the power system to deal with all kinds of uncertain factors[17]. The larger the index value, the better the reliability and economy of the system. Assume that the load rate of the power line as $\boldsymbol{L} = [L_1, L_2,..., L_{NL}]$, and the load rate L_i of branch i is defined as :

$$L_i = P_i / P_{i,\max} \quad (6)$$

Where P_i is the working power of breach i, and $P_{i,\max}$ are the maximum capacity.

Then the power system state homogeneity H is defined as:

$$H = 1 - std(\boldsymbol{L}) \quad (7)$$

Where std is the standard deviation function.

EPSMODPSO

The basic MOPSO algorithm has a simple structure and a fast convergence speed, it is easy to realize through programming. However,due to the sensitivity to the initial value and the weak local search ability, the diversity of the population is poor and it is easy to fall into local extremum when dealing with complex MOPs. Therefore, this paper improves the algorithm, and proposes a novel multi-objective discrete particle swarm optimization with elitist perturbation strategy(EPSMODPSO).

MODPSO

Traditional PSO uses the personal best (*pBest*) along with the global best (*gBest*) or local best (*lBest*) to guide the member particles search in the decision space. However, global PSO may be unable to locate the Pareto front because there is no single optimal solution could be selected as *gBest* or *lBest* which optimizing all objective functions simultaneously. Thus, we utilize the local best (*lBest*) to guide the member particles. The *lBest* is randomly selected from the external archive in each iteration, it is a effective approach to keep the swarm a good diversity. The iteration function is described as follow:

$$v_{id}(t+1) = \omega v_{id}(t) + c_1 r_1 (pBest_{id} - x_{id}(t)) + c_2 r_2 (lBest_{id} - x_{id}(t)) \quad (8)$$

$$x_{id}(t+1) = x_{id}(t) + sign(v_{id}(t+1)) \quad if\ rand < sigm(v_{id}(t+1)) \quad (9)$$

Where $i = 1,2,..., S$, S is the number of particles; $d = 1,2,..., D$, D is the maximum dimension of the decision space; ω, c_1 and c_2 are the coefficients; r_1 and r_2 are two random numbers within [1,0]; v and x are the velocity vector and position vector; $sigm(v) = abs(2/(1+\exp(-vt/T_{\max})) - 1)$, $abs()$ is the absolute value function; t is iteration steps; $sign()$ is the sign function.

ELITIST PERTURBATION STRATEGY

The elitist particles are employed to guide the group members approaching to the Pareto optimal front. When the objective functions are complex, there may be many local optimal solutions in the solution space. These solutions are easy to lead the population to fall into the local traps, and make the algorithm enter the stagnation condition. What's more, when the optimal area of the MOP is relatively smooth, it is difficult for the population to improve the search accuracy without additional search strategy. Based on the above situation, an elitist perturbation strategy is proposed to increase the local search ability of the population.

Since the elitist particles are already the optimal solutions obtained by the current population, the current population can no longer provide more effective search information for the elitist particles. Firstly, generate a random integer c, let $\boldsymbol{E} = \{E_1, E_2,..., E_c\}$, where $E_1, E_2,..., E_c$ are randomly selected from $[1,2,..., D]$. Then, for each selected dimension of one elitist particle, perturb as follow:

$$lBest^{esp}_{E_k} = lBest_{E_k} + \left(\max\left(\boldsymbol{X}_{E_k}\right) - \min\left(\boldsymbol{X}_{E_k}\right)\right) \cdot N\left(\mu, \sigma^2\right) \quad (10)$$

Where $k = 1,2,\ldots,c$; $N(\mu, \sigma^2)$ is a random number of normal distribution with a mean value $\mu = 0$, standard deviation σ is calculated as :

$$\sigma = R_{\max} - (R_{\max} - R_{\min}) \cdot t / T_{\max} \tag{11}$$

Where t is the current iteration step, $T_{\max}$ is the maximum step; $R_{\max} = 1$ and $R_{\min} = 0.1$ are the maximum and minimum disturbance limit.

The random integer number c is generate as follow:

$$c = ceil\left(Rand \cdot \left(1 + 3 \cdot t / T_{\max}\right)\right) \tag{12}$$

Where *ceil*() is a ceiling function, and $Rand$ is a random number within [0,1].

ARCHIVE UPDATE

While in updating the external archive, the Pareto dominance relationship between the obtained optimal solutions and the archive solutions are checked firstly, then the non-dominanced solutions will be save into the archive. Since the number of the Pareto optimal solutions of a MOP could be very large, which will rapidly increase the computational time, it is necessary to limit the size of the archive. When the number of the obtained Pareto optimal solutions exceed the limit size, the European distance in objective space between the solutions will be calculated, and the most crowding solutions will be deleted until the number of the optimal solutions meets the requirement.

THE COMPLETE FRAMEWORK

As shown in Figure 1 is the complete framework of the proposed EPSMODPSO. In EPSMODPSO, a population is generated and initialized at first, then, the algorithm goes into the iterative process. When the iteration of the algorithm ends, output the optimal solutions in the archive.

EPSMODPSO

Randomly generate a swarm with N particles ;
Initial the position $\boldsymbol{x} = \{x_1, x_2, \ldots, x_N\}$,and the velocity $\boldsymbol{v} = \{v_1, v_2, \ldots, v_N\}$;
Calculate the objective function $F(\boldsymbol{x})$ with equation 2~5 ;
Initial the archive with position vector $\boldsymbol{x}$;
For t=1 to $T_{\max}$
    For i = 1 to N
        $lBest_i$ = randomly select an elitist solution from the archive ;
        Update v_i and x_i with equation 8,9 ;
        Calculate objective function $F(x_i)$ with equation 2~5 ;
        Perform the EPS strategy on $lBest_i$ with equation 10~12 ;
    End for ;
    Update the archive with all the generated positions ;
End for
Output the archive solutions;
Calculate the auxiliary index H of obtained solutions with equation 6,7 ;

Fig. 1. The complete framework of EPSMODPSO

RECONFIGURATION OF SPS BASED ON EPSMODPSO

Considering a classical model of SPS as shown in Figure 2, and the related topological parameters are present in Table1. The generators are connected through the main buses, parts of critical loads with high priority are directly powered by the main buses, and the remaining loads are powered through the regional buses. In figure 2, symbol G represents the generators, LC is the connecting line between the main buses. The critical loads are powered with two supply lines, the solid lines represent the normal power supply lines, and the dotted lines represent the alternative lines. "•" is the endpoint of a device or a breach, "↓" represents the load L, "◘" represents the circuit breaker CB. ABT is the automatic breaker transfer, and MBT is the manual breaker transfer.

The reconfiguration of SPS is a discrete switching problem with multiple objectives, while in the use of EPSMODPSO to solve this problem, it is necessary to discrete the variables of the switches in the SPS model. According to the characteristics of SPS, in this paper, the encoding states of 0,1,2 are utilized for the transfer switches, 0,1 coding for the other switches. 0 represents the loss of power or unloading, 1 represents the loads are powered by the normal lines, 2 represents the loads are powered by the alternative lines. Each dimension of a particle represents a switch, the number of dimensions depends on the total number of switches.

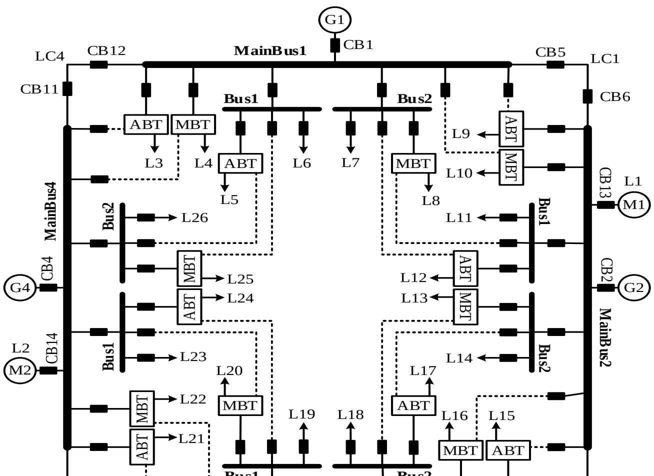

Fig. 2. A classical shipboard power system

Tab. 1. Parameters of elements

Number	Rated power	Priority	Number	Rated power	Priority
L_1	5.0	2	L_{18}	0.022	3
L_2	5.0	2	L_{19}	0.075	3
L_3	0.168	1	L_{20}	0.086	2
L_4	0.208	2	L_{21}	0.135	1
L_5	0.067	1	L_{22}	0.217	2
L_6	0.061	3	L_{23}	0.027	3
L_7	0.052	3	L_{24}	0.069	1

Number	Rated power	Priority	Number	Rated power	Priority
L_8	0.063	2	L_{25}	0.023	2
L_9	0.163	1	L_{26}	0.031	3
L_{10}	0.163	2	G_1	1	–
L_{11}	0.062	3	G_2	6	–
L_{12}	0.030	1	G_3	1	–
L_{13}	0.081	2	G_4	6	–
L_{14}	0.021	3	LC_1	3	–
L_{15}	0.123	1	LC_2	3	–
L_{16}	0.225	2	LC_3	3	–
L_{17}	0.077	1	LC_4	3	–

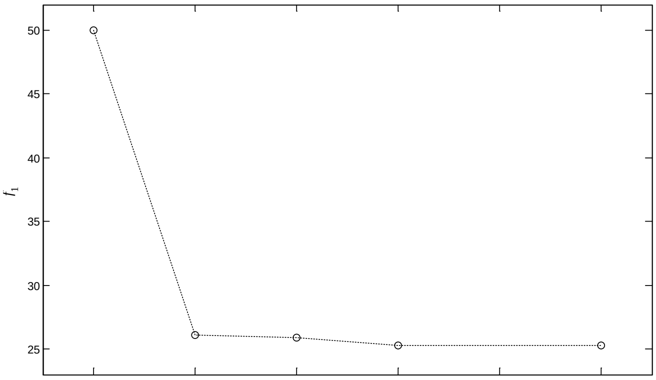

Fig. 3. Pareto fronts of fault example 1

SIMULATION STUDIES

The settings of the controlling parameters for EPSMODPSO are summarized as : the particle number $N = 200$, the maximum iteration $T_{\max} = 100$, the weight coefficient ω linearly decrease from 0.9 to 0.4 with the iterative steps, coefficients $c_1 = c_2 = 2$. The priority weight coefficients of the loads $\lambda_1 = 1000$, $\lambda_2 = 5$, $\lambda_1 = 1000$. The weight coefficients of the switches θ_1 and θ_2 are all set as 1 in this test. The initial operation state of SPS is : generator G1,G3,G4 are paralyzed through the main buses, generator G2 is out of service. The MainBus2 are powered though the connecting switches CB7 and CB9. The connecting switches CB2,CB5 and CB13 are broke off, and the other switches are all closed. All the loads are powered through the normal breach lines.

FAULT EXAMPLE 1

Fault description: contacting line LL3 occurs a short-circuit fault, switch CB9, CB10 and CB3 are broke off for protection, generator G3 quits operation, the loads of MainBus2 and MainBus3 lose the power.

Tab. 2. Reconfiguration results of fault example 1

No.	Reconfiguration solutions	f_1	f_2	H(%)
1	G1,G4 run in parallel; close switch CB5, MainBus2 is restored via the interconnection switches; unload L2	50	2	86.20
2	G1,G4 run in parallel; close switch CB5, MainBus2 is restored via the interconnection switches; unload L4,L7	26.092	3	88.67
3	G1,G4 run in parallel; close switch CB5, MainBus2 is restored via the interconnection switches; unload L6,L10,L23	25.903	4	92.19
4	G1,G4 run in parallel; close switch CB5, MainBus2 is restored via the interconnection switches; unload L6,L7,L11,L19	25.250	5	90.82
5	G1,G4 run in parallel; close switch CB5, MainBus2 is restored via the interconnection switches; unload L6,L7,L11,L14,L18,L26	25.249	7	90.99

The reconfiguration results of Fault Example 1 using EPSMODPSO are presented in Table 2, and the Pareto optimal front in Figure 3. Analyzing on the Fault Example 1, it can be seen that, the loads of MainBus2 and MainBus3 can only be restored by closing the switch CB5. However, in this situation, the capacity of the running generators is G1+G4=7, while the total loads are 7.249. Therefore, in the reconfiguration solution 1, after the closure of CB5, the load L2 is also cut off to ensure the power supply for the SPS. Solution 1 holds the least operation costs of function f_2 , but the largest load loss of function f_1. Solution 5 holds the least loads loss of function f_1, but the operation cost is the largest in all the solutions at the same time, because it need to cut off 6 loads of grade 3 in priority, including L6,L7and the others. Solution 2~4 are the trade-offs, while solution 3 holds the highest auxiliary index value *H*, which indicates that the load ratio of the connecting lines is more well-distributed.

FAULT EXAMPLE 2

Fault description: MainBus2 occurs a short-circuit fault, the connecting switch CB7 is broke off for protection, MainBus2 loses the power.

Tab. 3. Reconfiguration results of fault example 2

No.	Reconfiguration solutions	f_1	f_2	H(%)
1	Transfer L9 to the standby power lines; Unload L10,L11,L12,L13,L14	56.303	1	95.90
2	Transfer L9,L12to the standby power lines; Unload L10,L11,L13,L14	26.303	2	95.19
3	Transfer L9,L10,L12 to the standby power lines; Unload L11,L13,L14	25.488	3	95.56
4	Transfer L9,L10,L12,L13 to the standby power lines; Unload L11,L14	25.083	4	96.99

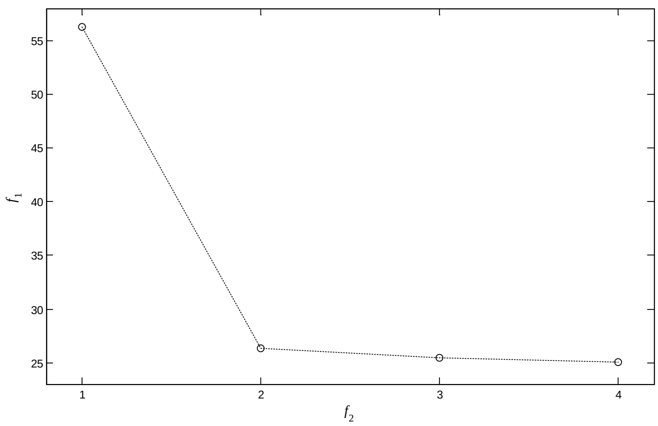

Fig. 4. Pareto fronts of fault example 2

Solve the multi-objective fault reconfiguration problem using EPSMODPSO, the obtained Pareto optimal solutions are presented in Table 3, and the Pareto optimal front is shown in Figure 4. Through Fault Example 2, it is clear to see that, there is no way to restore the MainBus2, thus, the loads of MainBus2 have to transfer to the alternative power lines. Therefore, in solution 1, the largest load L9 with grade 1 in priority is transferred to its standby power line. Solution 1 holds the least operation cost of all the solutions. In solution 4, 4 loads including L9,L10 and the others are transferred to the standby power lines, and the L11,L14 are cut off because there is no alternative line to restore. Solution 4 holds the least loss of loads, but the largest operation cost and auxiliary index value *H* at the same time. Solution 2 and 3 are two trade-offs.

DISCUSSION

From the test results it can be seen that the proposed EPSMODPSO is very excellent in terms of searching accuracy, diversity and convergence, which makes the EPSMODPSO possible to satisfy the demands of MOPs. The EPS strategy adopted to increase the local search ability and jumping out ability of the swarm is very helpful. In the discrete decision space, the traditional perturbation strategies which select only one dimension are not always effective to help the algorithms to jumping out the local traps. Taking two dimensional discrete decision space as an example, assume that "01" is the current discrete binary state, while the global optimal state is "10". If state "00"and "11" are not accepted as an Pareto optimal state, then, the single dimensional perturbation can never transfer from state "01" to state "10" within one step. Therefore, the proposed EPS employed an inter c to select several dimensions to perform the perturbation operation at the same time, which could increase the possibility to jump out the local traps. To achieve the conversion between the multiple discrete states(0,1,2), the particle's velocity value is utilized as the probability to determine the particle to move one step in the positive or negative direction. This strategy simplified the coding of the discrete variables, and help the algorithm to realize the encode of switches with multiple state(0,1,2). The test results indicate that the proposed EPSMODPSO is competent to solve the reconfiguration problem of SPS and obtain a Pareto optimal front with good diversity. It is necessary to mention that, since the EPSMODPSO exhibited superior performance in the experimental results reported in the previous subsections, our future study will further enhance the performance of EPSMODPSO, and extend it for tackling MOPs with more objectives. Moreover, the future research direction can also be pursued on the present study to investigate the performance improvement with parallel computation technology.

CONCLUSION

This paper presents a novel multi-objective discrete particle swarm optimization with elitist perturbation strategy(EPSMODPSO) to solve the multi-objective reconfiguration problem of SPS. To achieve the conversion between the multiple discrete states(0,1,2) of the switches, the particle's velocity value is utilized as the probability to determine the particle to move one step in the positive or negative direction. The proposed elitist perturbation strategy(EPS) in which several dimensions are selected to be perturbed, has been proved to be able to improve the local searching ability and jumping out ability of the particle swarm. While in establishing the mathematical model of SPS, the power system state homogeneity is adopted as an auxiliary evaluation of the obtained Pareto optimal solutions to help the decision makers choose the appropriate solutions. In the external archive updating process, the crowding distance of the obtained Pareto optimal solutions in objective space are calculated to keep the archive a good diversity. Test results of examples show that the proposed EPSMODPSO performs excellent in terms of reliability, efficiency and convergence. It is competent to solve network reconfiguration of shipboard power system and other multi-objective discrete optimization problems.

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CONTACT WITH THE AUTHORS

Lingjie Zhang

Marine Engineering College
Dalian Maritime University
Dalian 116026
China