Smart grid planning method based on multi-objective particle swarm optimisation algorithm

Jianguang Zhang

State Grid Shaoxing Power Supply Company,
Shaoxing, Zhejiang, 312000, China
Email: jianguangzhan@163.com

Abstract: Smart grid refers to a modern electric energy supply system to tackle a lot of problems in grid management, such as, resource shortage, environment pollution and so on. In this paper, we propose a novel smart grid planning method using multi-objective particle swarm optimisation algorithm. The goal of smart grid plan is to calculate the minimum investment and annual operating costs, when we obtain the planning level of load distribution, substation capacity and power supply area to satisfy the load requirement and optimised substation location. Afterwards, we propose a multi-objective particle swarm optimisation algorithm which integrates the estimation of distribution algorithm. Furthermore, the propose approach divides the particle population into a lot of sub-populations and then build probability models for each population. Finally, experimental results demonstrate that the proposed method can effectively arrange new substation, which is able to make up for deficiencies of current existing substations.

Keywords: smart grid planning; multi-objective optimisation; particle swarm optimisation; estimation of distribution algorithm.

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Biographical notes: Jianguang Zhang received his MS in Power System Automation from the Zhejiang University in 1992. He is currently a Senior Engineer in the State Grid Shaoxing Power Supply Company Shaoxing. His research interests include diagnosis and analysis of power system and power grid operation situation

1 Introduction

Energy and environment are the major problems which have attracted attention of all countries in the world today (Zheng and DeMarco, 2016). Electric energy, as an indispensable two energy source in daily life, is easy to transport and very safe. The power grid is the link between the power supply terminal and the power terminal (Zahurul et al., 2016). Besides the traditional functions such as power transmission, smart grid is also the carrier of the optimal allocation of resources. Smart grid deeply integrates information technology and communication technology and it can be applied to all aspects of power business to achieve a high degree of automation, information and interaction (Xing wt a., 2016; Wang et al., 2016). Furthermore, smart grid is an important method of the development trend of modern power grid. In order to solve the energy and environmental challenges, all countries should promote energy-saving emission reduction and clean energy development (Ravadanegh et al., 2016). Smart grid has been an important driver force in the new round of energy revolution.

Different from conventional power grids, smart grid should be paid more attention on power gird planning, operation and management (Qiu et al., 2016; Nezamoddini and Wang, 2016; Han and Yan, 2016). The total process of electric energy generation, transmission and consumption are needed to be more efficient, economical and secure in modern society. At the same time, smart grid also provides better controllability and experiences for users (Ul Hassan et al., 2015).

Smart grid represents the main trend of power grid development in the future. However, currently, the development of smart grid in the future has not yet formed a unified mode. In recent years, there are many developed countries, which have carried out a lot of research and practice in the study of smart grid, such as development objectives, policies and measures and evaluation approaches (Nejadfard-Jahromi et al., 2015; Huang and Wang, 2015). At present, it is necessary to strengthen power grid construction and complete power grid interconnection (D'Elia et al., 2015). At the same, we also should strengthen the active distribution network construction and effort to promote the level of intelligent power grid. The aim of smart grid construction is to satisfy the comprehensive intelligent development requirements of the main network and the distribution network (Torres and Castro, 2014; Rueda et al., 2013).

The paper is organised as follows. In the next section, we introduce the related works about theory and application of multi-objective particle swarm optimisation (PSO). In Section 3, we explain the problem of smart grid planning. Afterwards, we discuss how to plan smart grid using the multi-objective PSO algorithm. Experiments are conducted in Section 5. Finally, this paper is concluded in Section 6.

2 Related works

In this section, we review related works of theory and application about multi-objective PSO, which has been widely used in many areas and has achieved good performance.

Zheng et al. (2017) proposed a population recombination strategy with a new mutation strategy to strengthen the ability to jump out of local optimum. In this work, population recombination strategy exploits the information of the best variable found so far to build the new population.

Zhang et al. (2017) proposed the first study of multi-objective PSO for cost-based feature selection problems. The main idea of this paper is to build a Pareto front of non-dominated solutions, that is, feature subsets, to satisfy different needs of decision-makers in real-world applications.

Wei and Tia (2017) presented an adaptive mutation PSO (AMPSO) to implement multi-objective optimisation design method via scale-based product platform theory model. The Pareto-optimal solution is achieved with AMPSO and the fuzzy statistics algorithm is designed to obtain the optimal solution of multi-objective optimisation issue.

Verma and Kaushal (2017) proposed a non-dominance sort based hybrid particle swarm optimisation (HPSO) algorithm to solve the workflow scheduling issue with multiple conflicting objective functions on IaaS clouds. In particular, the proposed method is belonged to a hybrid of Deadline constrained Heterogeneous Earliest Finish Time algorithm.

Sheikholeslami and Navimipour (2017) designed three conflicting objectives, that is, maximising revenue for users and providers as well as seeking the optimal solution at a specific time. The authors utilise a multi-objective PSO with crowding distance to handle the problem. On the other hand, fuzzy set theory is also used to specify the best compromise solution.

Saxena and Mishra (2017) proposed a modified multi-objective PSO, in which new leader choosing scheme and personal best (pbest) replacement scheme is given. Main innovations of this paper lie in that useful information is utilised through choosing the most appropriate leader from the archive which has minimum distance from the region.

Nagano et al. (2017) proposed a new GPU-accelerated per-pixel inverse rendering optimisation algorithm with PSO. The proposed method can effectively estimate the per-pixel scene attributes-including reflectance properties-of a 3D model and is very rapid to run in situ visualisation of the optimisation with the real-time mode.

Apart from the above works, multi-objective PSO has also been used in other areas, such as flexible process planning problem (Miljkovic and Petrovic, 2017), path planning approach for mobile robots (Mac et al., 2017), dynamic multi-objective optimisation (Liu et al., 2017), six-phase copper rotor induction motor (Lin and Hwang, 2017), complex network clustering (Li et al., 2017) economic environmental hydrothermal energy system scheduling (Feng et al., 2017), bi-objective inventory routing problem (Dabiri et al., 2017), hybrid teaching learning (Cheng et al., 2017), multi-objective and many-objective large-scale optimisation (Cao et al., 2017) and hybrid micro-grid system (Azaza and Wallin, 2017).

3 Problem statement

In this paper, we aim to determine how to make sure the substation location. Substation location determination problem can be described as follows.

When we know that the planning level of load distribution, substation capacity and power supply area, how to obtain the minimum investment and annual operating costs (including the cost of investment and operation cost of investment and operation, the substation line) to meet the load requirement and optimised substation location. The proposed algorithm is described as follows.

$$MinCost = Cost_S + Cost_L \tag{1}$$

where $Cost_s$ refers to the cost of a newly built substation and $Cost_L$ denotes Loss cost of the line cost in a newly built substation.

$$Cost_S = \frac{q_0 (1+q_0)^{T_S}}{(1+q_0)^{T_S} - 1} f(S) + \mu(S) \tag{2}$$

$$Cost_L = \frac{q_0 (1+q_0)^{T_L}}{(1+q_0)^{T_L} - 1} \sum_{j \in J} \alpha(W_j) d_j + \sum_{j \in J} \beta_j (W_j)^2 d_j \tag{3}$$

where the parameters in equations (1) and (2) are listed as follows:

q_0 discount rate

T_s depreciation period of newly built substation

S capacity of newly built substation

$f(S)$ investment cost of newly built substation

$\mu(S)$ operation cost of newly built substation

T_L depreciation period of low voltage side line of newly built substation

j the j load point supplied by the newly built substation

J a set of load points supplied by a new substation

W_j the active load value of the j load point

d_j the line length between the newly built substation and the J load point

β_j conversion coefficient of line loss, which relies on the current electricity price.

4 The proposed algorithm

PSO is able to simulate the knowledge evolvement of a social organism, in which each individual is represented as an infinitesimal particle in a n dimension space.

The position vector and velocity vector of the i^{th} particle are described as follows:

$$X_i(t) = \left(X_{i1}(t), X_{i2}(t), \cdots, X_{in}(t)\right) \tag{4}$$

$$V_i(t) = \left(V_{i1}(t), V_{i2}(t), \cdots, V_{in}(t)\right) \tag{5}$$

Afterwards, particles move in terms of the following formula:

$$V_{id}(t+1) = W \cdot V_{id}(t) + c_1 r_1 \left(P_{id}(t) - X_{id}(t)\right) + c_2 r_2 \left(P_{gd}(t) - X_{id}(t)\right) \tag{6}$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t+1) \tag{7}$$

where c_1 and c_2 refer to the acceleration parameters, r_1 and r_2 represent random numbers (r_1, r_2 is belonged to [0, 1]). Furthermore, $P_i = (P_{i1}, P_{i2}, \ldots, P_{in})$ means to the Pbest value of the i^{th} particle and $P_g = (P_{g1}, P_{g2}, \ldots, P_{gn})$ refers to the Gbest value for the best particle.

It can be observed from Section 3 that the smart grid planning problem is a typical multi-objective optimisation problem, which contains n decision variables and m objectives. Multi-objective optimisation can be described as follows.

$$Min\ F(x) = \left\{f_1(x), f_2(x), \cdots, f_m(x)\right\} \quad \text{s.t. } x \in \Omega \tag{8}$$

where Ω refers to the feasible region of an n dimension decision space. $x = \{x_1, x_2, \ldots, x_3\}$ represents a decision variable vector. Therefore, we find that $F(x)$ is made up of m objective functions.

In this section, we present a novel multi-objective PSO algorithm which integrates the estimation of distribution algorithm (EDA). Main idea of the propose method lies in that we divide the particle population into a lot of sub-populations and then construct probability models for each population. In particular, with the probability model, each sub-population can generate new offspring based on the hybrid PSO/EDA model.

In the proposed algorithm, we suppose that there is an evolving particle population with the size *N* and an external elite population with the size *M* and the number of sub-population is *S*.

The proposed the hybrid PSO/EDA algorithm is illustrated as follows:

Algorithm 1 The hybrid PSO/EDA algorithm

1. Create the initial particle population $P(t) = \{Q_1(t), Q_2(t), \ldots, Q_N(t)\}$, where *N* is a random number.
2. The velocity of each particle in $P(t)$ is randomly initialised and then the velocity vector $V(t) = \{V_1(t), V_2(t), \ldots, V_n(t)\}$
3. Let $p_{best}(t) = P(t)$, which is obtained by initialising the personal best position for each particle to the current position.
4. Define the initial elite population $E(t)$ as the non-dominated ones in the initial particle population $P(t)$.
5. If the pre-defined condition is satisfied, algorithm ends and individuals in $E(t)$ are output.
6. Divide $P(t)$ to *S* sub-populations $SP_1, SP_2, \ldots, SP_s$ and then compute centroids for all these clusters.
7. Implement the reproduction operation with the EDA algorithm and then obtain the offspring set $P_E^1, P_E^2, \cdots, P_E^S$
8. Implement the reproduction operation with the PSO algorithm and then obtain the offspring set $P_{Pso}^1, P_{Pso}^2, \cdots, P_{Pso}^S$
9. Implement the selection operation as follows:

$$P(t+1) = P_{Pso}^1 \cup P_{Pso}^2 \cup \cdots \cup P_{Pso}^S \tag{9}$$

$$P_E = P_E^1 \cup P_E^2 \cup \cdots \cup P_E^S \tag{10}$$

10. Update the elite population as follows.

$$E(t+1) = P(t+1) \cup E(t) \cup P_E \tag{11}$$

11. If E (t + 1) > *M*, reserve the top ranked *M* individual in the set $E(t + 1)$
12. *t*++ and then jump to (2)

5 Experiment

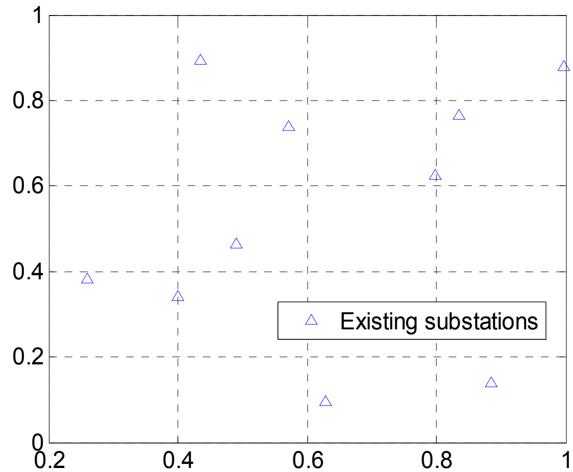
In this experiment, we conduct an experiment in a virtual simulation environment.

Table 1 Parameters of the newly built substation are listed as follows

Load value (MW)	*Current capability (MW)*	*Required capacity (MVA)*		*New added capacity (MVA)*		*New added substation*	
		Upper limit	*Lower limit*	*Upper limit*	*Lower limit*	*Upper limit*	*Lower limit*
224	0.00	415.6	368.1	447.5	350.8	1.17	1

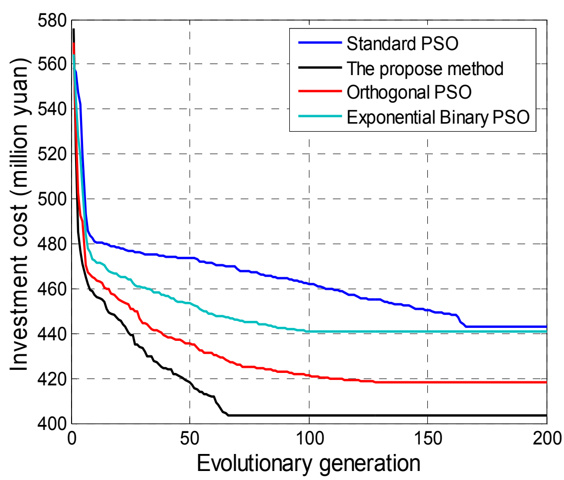
As is shown in Figure 1, we normalise a scheme of geographical location distribution of existing substations in a specific area.

Figure 1 Geographical location distribution of existing substations (see online version for colours)



Afterwards, the parameters of the newly built substation are listed as follows.

Figure 2 Investment cost for different methods (see online version for colours)



To make performance comparison, we choose two related methods about the application of PSO algorithm on the smart grid planning, which are named as orthogonal PSO (Al Bahrani and Patra, 2017) and exponential binary PSO (Maji and Acharjee, 2017). Orthogonal PSO aims to solve the problem of the global PSO algorithm and it divides several particles of the swarm are divided into two groups:

1 active group

2 passive group.

Binary PSO refers to an effective exponential binary PSO, in which a nonlinear inertia-weight-coefficient is used to improve the searching capability. In order to combine previous position of particle, two novel mathematical equations which are able to update particle's position are defined.

Next, we compare the investment cost of the proposed multi-objective PSO algorithm with the standard PSO and experimental results is shown in Figure 2.

Figure 2 shows that the proposed multi-objective PSO algorithm can not only achieve fast convergence but also can obtain lower investment cost than the standard PSO, the orthogonal PSO and the exponential binary PSO.

Apart from the above experiment of cost optimisation, reliability is also a main reason affecting the cost of smart grid planning. Therefore, we test the reliability of smart grid planning using different methods in a year and experimental results are shown as follows.

Table 2 Reliability of smart grid planning using different methods

Method	*System failure rate*
Standard PSO	92.6%
The propose method	96.7%
Orthogonal PSO	93.3%
Exponential binary PSO	94.8%

It can be seen from Table. 2 that the proposed method can achieve lower system failure rate than other methods. That is to say that the proposed can effectively promote the reliability of smart grid planning.

As is shown in Figure 3, we can see that the newly built substation can effectively make up for deficiencies of current existing substations and performs better than others. Therefore, it can be observed that the proposed method is able to effectively plan smart grid.

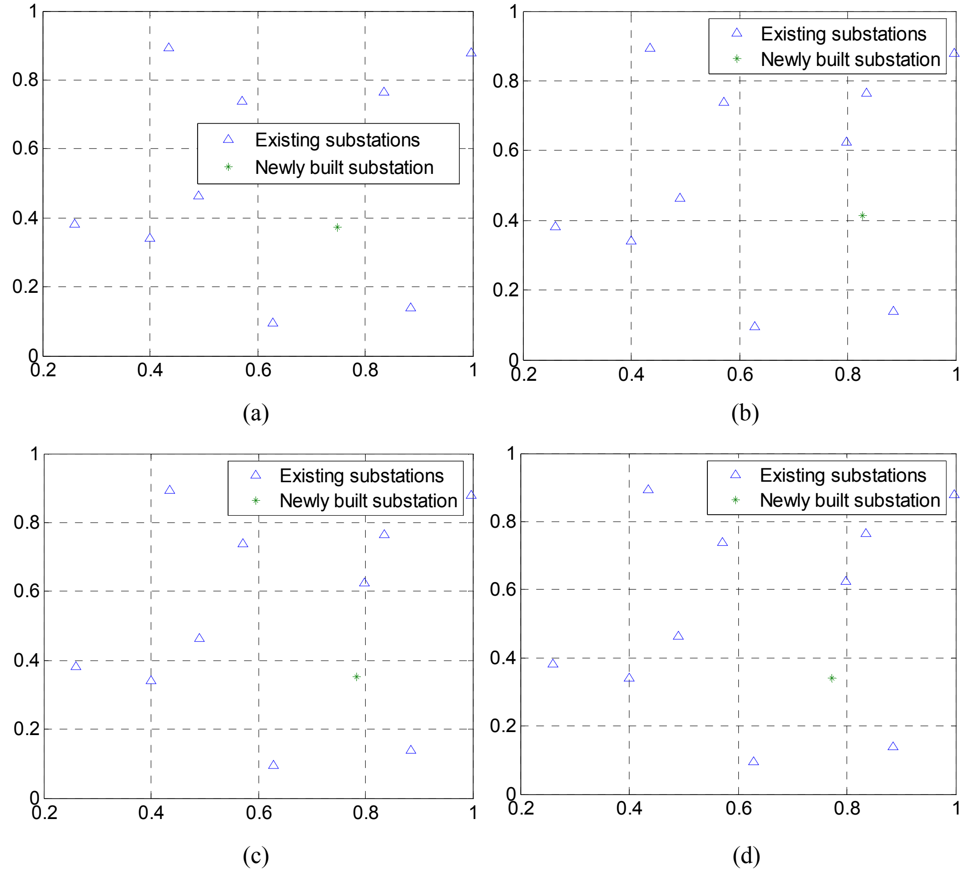
From the above experimental results, we can see that the proposed algorithm performs better than other methods for both investment cost and reliability and reasons are listed as follows:

1 In the proposed method, a novel multi-objective PSO algorithm is given and it combines the estimation of distribution algorithm.

2 The propose method divides the particle population into a lot of sub-populations and then establish probability models for each population.

3 In our method, with the probability model, each sub-population is able to provide new offspring based on the hybrid PSO/EDA model.

Figure 3 The scheme of newly built substation, (a) the proposed method (b) standard PSO (c) orthogonal PSO (d) exponential binary PSO (see online version for colours)



6 Conclusions

This paper proposes a novel smart grid planning algorithm based on multi-objective PSO algorithm. Smart grid aims to compute the minimum investment and annual operating costs, if the planning level of load distribution, substation capacity and power supply area is known. Next, we propose a multi-objective PSO algorithm which combines the estimation of distribution algorithm. In the end, experimental results prove that the proposed method is able to find suitable location to build new substation to make up for deficiencies of current existing substations.

In the future, we will extend our works in the following aspects:

1 we will study on the adaptive parameter setting method

2 we will try to use other optimisation methods in our study.

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