Reconfiguration for Loss Reduction of Distribution Systems Using Selective Particle Swarm Optimization

Tamer M. Khalil, *Member, IEEE*, and Alexander V. Gorpinich, *Member, IEEE*

***Abstract*— This paper aims to present a new simple algorithm for solving the distribution network reconfiguration (DNR) problem. This algorithm is a simple modification to the binary particle swarm optimization (BPSO) called selective particle swarm optimization (SPSO). The search space for proposed algorithm is a set of branches (switches) which are normally closed or normally opened, this search space may be dissimilar for different dimensions. The process of solving DNR problem is divided to two steps. First, finding search spaces after closing all switches and second, using SPSO to find switches that would be opened. The presented technique is applied to a 33-node system and a 69-node system. The results obtained via SPSO are compared with some previous methods to demonstrate the effectiveness of the proposed algorithm.**

***Keywords*—** Distribution Network, Reconfiguration, Selective Particle Swarm Optimization and Power Losses Reduction

I. INTRODUCTION

Currently a significant amount of electric energy produced by power plants is lost during transmission and distribution to consumers. About 40 percent of this total loss occurs on the distribution network [1].

The distribution network usually operates in a radial configuration, with tie switches between circuits to provide alternate feeds. Whenever components fail, some of the switches must be operated to restore power to as many customers as possible. As loads vary with time, switch operations may reduce losses in the system and transfer of loads from heavily loaded feeder. All of these are applications for DNR [2]. DNR is a process of changing the status of the network topology through opening or closing tie switches to optimize the network parameters.

Thus, under normal operating conditions the network is reconfigured to reduce the system's losses and/or to balance load in the feeders. Under conditions of permanent failure, the network is reconfigured to restore the service, minimizing the zones without power [3].

DNR is a problem of complicated multi-objective integer combination optimization. The complexity of the problem arises from the fact that distribution network topology has to be radial and power flow constraints are nonlinear in nature. In recent years, many algorithms have been developed for power losses minimization in the field of distribution system reconfiguration. The first recognized work which attempts to solve the problem of distribution system reconfiguration for losses reduction was presented by Merlin and Back [4]. Since this work up to date many algorithms have been developed to solve this problem. Most of these algorithms are based on heuristic techniques and artificial intelligence methods. Merlin and Back [4] proposed a heuristic algorithm to determine the minimum losses configuration. In this algorithm, all network switches are first closed to form a meshed network. The switches are then opened successively to restore radial configuration.

Other heuristic algorithms were proposed Civanlar *et al.* [5] and Baran *et al.* [6]. These algorithms are based on the branch exchange heuristic method, where a simple formula has been derived to determine how a branch exchange affects the losses. Goswami and Basu [7] report a heuristic algorithm that is based on the concept of optimum flow pattern determined via power-flow program. The optimum flow pattern of a single loop formed by closing a normally-opened switch is found out, and this flow pattern is established in the radial network by opening a closed switch. This procedure is repeated until the minimum losses configuration is obtained. In [8], an exhaustive survey of the modern heuristic methods for the DNR is presented. In this paper the authors propose a two-stage method for the distribution system reconfiguration. The efficiency of the method stems from using real power losses sensitivity with respect to the impedances of the candidate branches. The proposed method uses these sensitivities in the first stage, and then a branch exchange procedure is used in the second stage to refine solution.

Artificial intelligence methods were also applied to DNR problem extensively, for example, simulated annealing [9], neural networks [10], genetic algorithms [11-14], tabu search

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Tamer M. Khalil is with Pryazovskyi State Technical University, Mariupol, Ukraine and Canal Co. for Electricity Distribution, Ismailia, Egypt (Email: tamerml@ yahoo.com).

Alexander .V Gorpinich is with Electrical Engineering Department, Pryazovskyi State Technical University, Mariupol, Ukraine. (Email: gorpinich@ieee.org).

[15, 16], ant colonies [17] and particle swarm optimization [18-24].

Particle swarm optimization is applied to the problems of power distribution system gradually. Recently, there are many applications of PSO algorithm in power systems [25], one of these applications is DNR.

This paper proposes SPSO for distribution system reconfiguration. SPSO a simple modification to BPSO, this modification makes the algorithm very appropriate to solve DNR problems. In order to demonstrate the effectiveness of the proposed algorithm, the SPSO is applied to a 33-node system and a 69-node system. The results obtained via SPSO are compared with results obtained by other modern techniques.

II. PROBLEM FORMULATION

Feeder reconfiguration is performed by selecting, among all possible configurations, the one that incurs the smallest power losses and that satisfies a group of constraints. Usually minimum of network losses is considered to be objective. Thus objective function is to minimize the real power losses of distribution system P_L considering the following constraints.

1. Branch current constraint

$$I_b \le I_{b\max} \tag{1}$$

where I_b is the current of branch b, and $I_{bmax}$is the maximum permissible current of branch b.

2. Node voltage constraint

$$U_{j\min} \le \left|U_j\right| \le U_{j\max} \tag{2}$$

where U_{jmin} and U_{jmax} are the minimum and maximum permissible rms voltages of node j, respectively.

3. Load connectivity.

Each bus should be connected via one path to the substation.

4. Radial network structure.

This means that no loops are allowed in the network.

III. PROPOSED ALGORITHM

Particle Swarm Optimization was first introduced by Kennedy and Eberhart [26] in 1995. It was developed through simulation of a simplified social system, and has been found to be robust in solving continuous nonlinear optimization problems. One of reasons that PSO is attractive is that there are very few parameters [27]. There are different versions of PSO that aim to widen its applicability. Kennedy and Eberhart [28] proposed the first discrete version of PSO by adapting it to search in binary spaces, then Khalil and Gorpinich [29] proposed a simple modification to the binary PSO to search in a selected space.

The basic PSO technique is the real valued PSO, whereby each dimension can take on any real valued number. For d-dimensional search space the position, the velocity and the best previous position for each particle (*i-th particle*) and best position for all particles are represented by vectors and described as $X_i = [x_{i1}, x_{i2}, \dots, x_{id}]$, $V_i = [\upsilon_{i1}, \upsilon_{i2}, \dots, \upsilon_{id}]$, $PB_i = [pb_{i1}, pb_{i2}, \dots, pb_{id}]$ and $GB = [gb_1, gb_2, \dots, gb_d]$ respectively. At iteration k the velocity and the position for d-dimension of *i-th* particle are updated by (3) and (4) respectively:

$$\upsilon_{id}^{k+1} = w\upsilon_{id}^{k} + c_1 r_1 (pb_{id}^{k} - x_{id}^{k}) + c_2 r_2 (gb_d^{k} - x_{id}^{k}) \tag{3}$$

$$x_{id}^{k+1} = x_{id}^{k} + \upsilon_{id}^{k+1} \tag{4}$$

where $i=1, 2, \dots, n;$ n is the set of particles in swarm, (i.e. "population") described as $pop= [X_1, X_2, \dots X_n];$ w is the inertia weight; c_1 and c_2 are the acceleration constants; r_1 and r_2 are the two random values in range [0,1].

In 1997, Kennedy and Eberhart [28] have adapted the PSO to search in binary spaces, by applying a sigmoid transformation to the velocity component to squash the velocities into a range [0, 1], and force the component values of the locations of particles to be 0's or 1's (see (5)). The equation (4) for updating positions is then replaced by (6):

$$sigmoid(\upsilon_{id}^{k+1}) = \frac{1}{1+\exp(-\upsilon_{id}^{k+1})} \tag{5}$$

$$x_{id}^{k+1} = \begin{cases} 1, \text{ if } rand < sigmoid(\upsilon_{id}^{k+1}) \\ 0 \qquad\qquad \text{otherwise} \end{cases} \tag{6}$$

In [29] Khalil and Gorpinich proposed a simple modification to the binary PSO to search in a selected space. In the SPSO a search space at each d-dimension $S_d = [s_{d1}, s_{d2}, \dots, s_{dn}]$ is the set of dn positions, where dn is the number of the selected positions in dimension d. As in the basic PSO, a fitness function F must be defined. In this case it maps at each d-dimension from dn positions of the selective space S_d, where the position of each particle has been changed from being a point in real-valued space to be a point in selected space. Therefore, the sigmoid transformation has been changed to (7), and the *i-th* coordinate of each particle's position at a dimension d is a selective value, which updated by (8)

$$sigmoid(\upsilon_{id}^{k+1}) = dn\frac{1}{1+\exp(-\upsilon_{id}^{k+1})} \tag{7}$$

$$x_{id}^{k+1} = \begin{cases} s_{d1}, \text{ if } sigmoid(\upsilon_{id}^{k+1}) < 1 \\ s_{d2}, \text{ if } sigmoid(\upsilon_{id}^{k+1}) < 2 \\ s_{d3}, \text{ if } sigmoid(\upsilon_{id}^{k+1}) < 3 \\ \dots\dots\dots\dots\dots\dots \\ s_{dn}, \text{ if } sigmoid(\upsilon_{id}^{k+1}) < dn \end{cases} \tag{8}$$

Where $s_{d1}, s_{d2}, s_{d3}, \dots, s_{dn}$ are the selected values in dimension d. Velocity values are restricted to some minimum and maximum values $[V_{\min}, V_{\max}]$ using (9). Equation (10) used to avoid invariability of the value of *i-th* particle velocity in a *d*-dimension at the maximum or minimum values and force each particle going through the search space.

$$\upsilon_{id}^{k+1} = \begin{cases} V_{\max}, \text{ if } \upsilon_{id}^{k+1} > V_{\max} \\ \upsilon_{id}^{k+1}, \text{ if } \left|\upsilon_{id}^{k+1}\right| \le V_{\max} \\ V_{\min}, \text{ if } \upsilon_{id}^{k+1} < V_{\min} \end{cases} \quad (9)$$

$$\upsilon_{id}^{k+1} = \begin{cases} rand \times \upsilon_{id}^{k+1}, \text{ if } \left|\upsilon_{id}^{k+1}\right| = \left|\upsilon_{id}^{k}\right| \\ \upsilon_{id}^{k+1} \quad \text{otherwise} \end{cases} \quad (10)$$

IV. DISTRIBUTION NETWORK RECONFIGURATION USING SELECTIVE PARTICLE SWARM OPTIMIZATION

The solving DNR problem by SPSO can be divided to three steps:
A) Specifying the number of dimensions;
B) Finding the search space for each dimension;
C) Using SPSO to select the optimal solution from the search spaces.

A. Specifying the Number of Dimensions

Distribution network is designed as multiloop circuits but it runs in open loop to assure the network in the form of a tree. To specify the number of dimensions for DNR problem, all tie switches must be closed. It will give the number of loops. The number of dimensions equals the number of loops.

B. Finding the Search Space for Each Dimension

Fig. 1 will be used to explain finding the search space for each dimension as follows.

1. The system shown in Fig. 1 has 17 brunches, 15 sections and 2 tie switches.
2. Closing the tie switches will form 2 loops.
3. Accordingly the branches which don't belong to any loop will not represented in the search spaces, and therefore in optimization algorithm the test system shown in Fig. 1(a) can be simplified to Fig. 1(b).
4. The number of dimensions is equal to the number of loops so in this case we have two dimensions.
5. The search space for each dimension will be the branches which belong to the loop represented by this dimension. In this case d_1 = [14, 15, 16, 17, 6, 5, 4], d_2 = [3, 4, 5, 13, 12, 11, 10].
6. Branches no. *4* and *5* belong to the two loops and two dimensions. These two branches should be appearing in only one dimension, this will be done randomly.

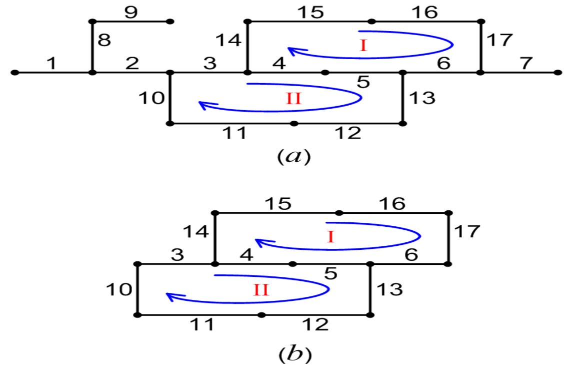

Figure 1. Simplification of distribution network

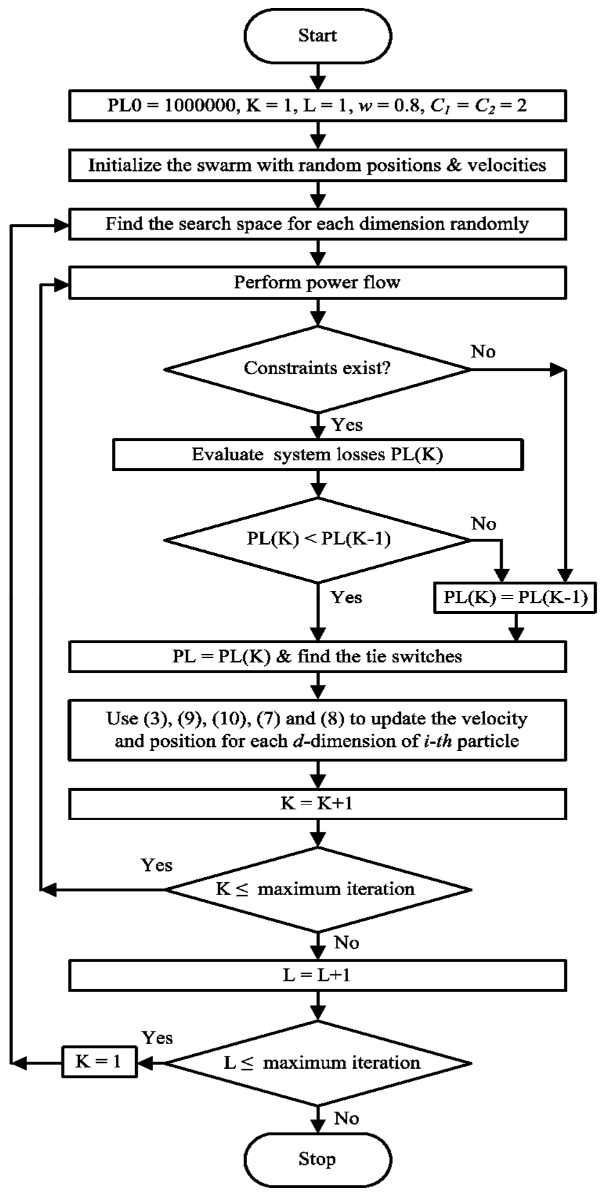

Figure 2. Flow chart of the proposed method

C. Using Selective Particle Swarm Optimization to Select the Optimal Solution from the Search Spaces

After specifying the number of dimensions, and finding the search space for each dimension, SPSO would be used to select the optimal solution from the search space for each dimension by (3), (9), (10), (7) and (8) respectively. Fig. 2 shows flow chart for the proposed method.

V. TEST RESULTS

The proposed method has been tested on two systems published in literature to ascertain its effectiveness (see Figs. 3 and 4). For these two systems, all tie and sectionalizing switches which belong to any loop are considered as candidate switches for reconfiguration problem.

The 33-Bus System

The 33-bus, 12.66-kV system presented by Baran and Wu [6] consists of one main feeder, 3 laterals, and 5 tie lines. The schematic diagram of the system is shown in Fig. 3. The normally open switches are s33, s34, s35, s36 and s37. For this case the initial real power losses is 202.6 kW. The optimal configuration obtained by applying the proposed algorithm is to keep s37 open and close s33, s34, s35 and s36, and open s7, s9, s14 and s32. The percentage reduction in the real power losses is equal to 31%. Table I shows test system results. The optimal configuration obtained by SPSO is identical to those obtained in [6], [7], and [30].

The 69-Bus System

The 69-bus, 12.66-kV system consists of one main feeder, 7 laterals, and 5 tie lines. The system data are given in [31]. The schematic diagram of the system is shown in Fig. 4. The normally open switches are s69, s70, s71, s72 and s73. For this case the initial real power losses is 224.96 kW. The optimal configuration obtained by applying the proposed algorithm is to keep s69 and s70 open and close s71, s72 and s73, and open s14, s56 and s63. The percentage reduction in the real power losses is equal to 44%. The test system results (see Table I) obtained by SPSO are the same as in [20] and [31].

To explain the steps mentioned in section IV, the IEEE 69-bus test system would be used. Fig. 5 illustrates the simplification of the test system shown in Fig. 4. It is clear from Fig. 4 and Fig. 5 that there are five loops. The switches which not belong to any loops are s1, s2, s27, s28, s29, s30, s31, s32, s33, s34, s50, s51, s65, s66, s67, s68. The switches which belong to only one loop will present the dimensions of the algorithm:

d1= [s46, s47, s48, s49, s72];

d2= [s3, s35, s36, s37, s38, s39, s40, s41, s42];

d3= [s43, s44, s45, s71];

d4= [s21, s22, s23, s24, s25, s26, s59, s60, s61, s62, s63, s64, s73];

d5= [s15, s16, s17, s18, s19, s20].

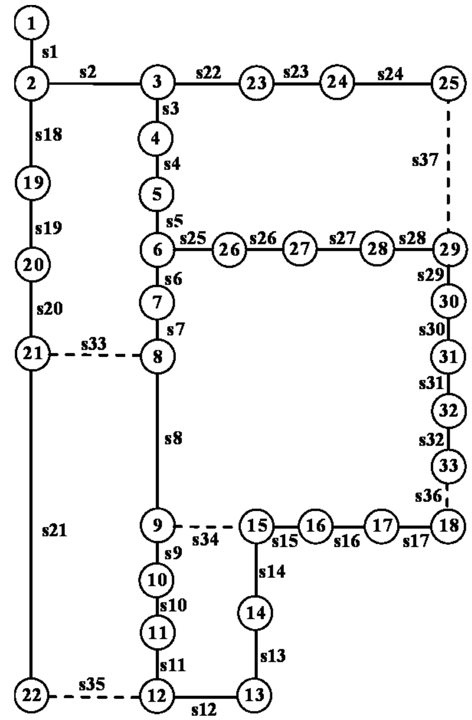

Figure 3. 33-node distribution system

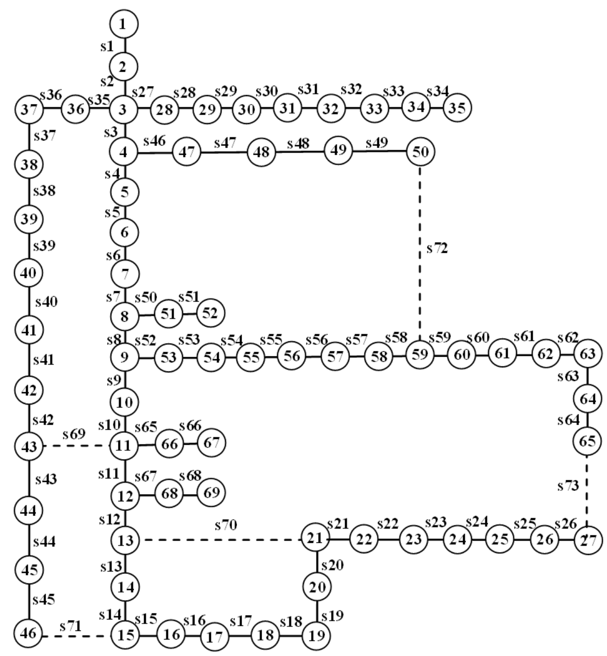

Figure 4. 69-node distribution system

The switches which belong to more than one loop will be added to one of these dimensions randomly. As an example, switches s4, s5, s6, s7 and s8 belong to loop I and loop II. These switches could be appearing in d1 for the one iteration and in d2 for another one.

TABLE I. TEST SYSTEMS RESULTS

Test System	Opened Switches		Losses Reduction (%)
	Initial configuration	*After reconfiguration using SPSO*	
IEEE 33-bus	s33, s34, s35, s36, s37	s7, s9, s14, s32, s37	31
IEEE 69-bus	s69, s70, s71, s72, s73	s69, s70, s14, s56, s63	44

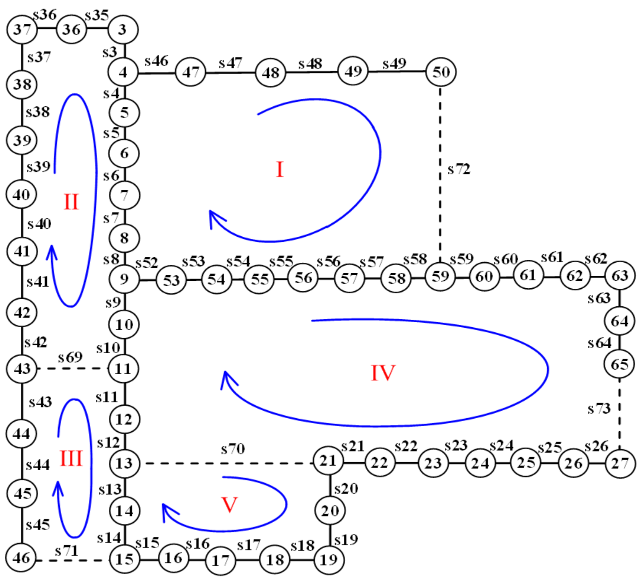

Figure 5. Simplification of the 69-node distribution system

VI. CONCLUSION

This paper proposed a simple modification of binary particle swarm optimization to solve the distribution network reconfiguration problem in a simple and proper way. This algorithm, called in this paper selective particle swarm optimization, can be used in many engineering applications where the search space consists of specific values. For example, authors applied selective particle swarm optimization in other paper to select optimal capacitor placement and conductor sizing for maximum losses reduction and voltage profile improvement. The main advantage of this algorithm is its simplicity. Presented algorithm can be easily realized in only few tens lines by means of any high-level programming language with low computational time. Low algorithmic complexity favors the employment of selective particle swarm optimization in practical real-time applications like SCADA, Smart Grid, etc.

The technique proposed in this paper divided to two steps. The first step is to simplify the network and specify the number of dimensions and search space for each dimension. The second step is to apply the selective particle swarm optimization to choose the optimal branch from each dimension to be opened. In order to demonstrate the effectiveness of the presented algorithm, it has been tested on IEEE 33-bus and 69-bus systems. Results for two test systems confirmed the accuracy and efficiency of the selective particle swarm optimization.

Future work will be addressed to application of the selective particle swarm optimization in solving capacitor placement, conductor selection and reconfiguration problems simultaneously.

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Tamer M. Khalil (M'10) was born in Ismailia, Egypt in 1976. He received his B.Sc. degree in electrical engineering from Benha Higher Institute of Technology, Benha, Egypt in 1999 and M.Sc. degree from Cairo University, Cairo, Egypt, in 2007. He is currently pursuing the Ph.D. degree in electrical engineering at Pryazovskyi State Technical University, Mariupol, Ukraine.
He joined Canal Company for Electricity Distribution, Egypt in 2001, where he is working in the technical affairs. His areas of interests are power system losses, power system quality, optimization and Artificial Intelligence

Alexander V. Gorpinich (M'97) was born in Mariupol, Ukraine in 1976. He received his degree of Electrical Engineer with honor from Pryazovskyi State Technical University, Mariupol, Ukraine in 1998, and the Ph.D. degree in electrical engineering from the Donetsk National Technical University, Donetsk, Ukraine, in 2005. Currently, he is Assistant Professor of Electrical Engineering Department at Pryazovskyi State Technical University, Mariupol, Ukraine. His research interests include power system reliability and power quality.