Particle Swarm Optimization Applied to System Restoration

G. Lambert-Torres, H.G. Martins, M.P. Coutinho, C.P. Salomon and F.C. Vieira

Abstract--**The electrical power system restoration after an incident is a complex process involving decision-making problems of combinatory nature. In this case, the operator support systems play an important role in a performance of this process. This paper introduces a decision support tool based on Particle Swarm Optimization Technique (PSO). The technique is based on the change of system functional configuration and consists in the use of the maximization of power demand supplied and minimization of the number switched lines. This technique also avoids the overload of system lines. A case study is introduced.**

Index Terms—**Distribution Systems, Particle Swarm Optimization, Power System Restoration, Swarm Intelligence.**

I. Introduction

The electric power distribution system usually presents a radially topological structure. In this kind of system, if all the switches are closed, there will be formation of meshes. For a system with *k* meshes, *k* switches have to be open in order to preserve the radial structure of the topology. At least one switch must be open in each mesh, that is, there must be at least one normally open switch in each mesh. Thus, the reconfiguration of the system is done by closing these normally open switches in order to restore the system in an optimized way; however it retains the radial topology [6].

The present approach assumes the existence of lines with normally opened switches, normally closed switches and without switches. For an optimized reconfiguration, the decision-making involving the normally opened switches, which must be closed, is done so as to maximize the supplied loads, minimize the number of closed switches, and avoid de overload in the lines [6].

New technologies have been developed aiming at the operation of energy transmission and distribution systems in large scale. New technologies targets computational time efficiency, and are supplied with a certain degree of intelligence implemented through techniques that belong to the Artificial Intelligence area, such as Particle Swarm Optimization [1].

This paper proposes the application of PSO as tool of decision support of system operator. PSO is applied as an optimization technique to the restoration of distribution systems. The intended reconfiguration is an optimization and decision-making process which considers the maximization of the power demand supplied associated to the minimization of the numbers switched lines, and avoids the overload in the system lines. PSO is based on the behavior of animal groups which present some iteration and learning capacity, in such a way that it relates the individual development compared to the group or population [1], [2], [3], [4]. The distribution system tested was the Distribution_System_01 [5].

II. Overview of Particle Swarm Optimization – PSO

Swarm Intelligence is an optimization technique based on social behavior. It was developed by James Kennedy and Russel Eberhart in 1995 [3], [4]. Although the particle swarm optimization principle is relatively new, J. Kennedy and R. Eberhart's predecessor had already thought of alternative ways for application in biological research and animal swarm simulation [7]. The first computational work reported in this research area was an article about the simulation of bird flocks intended to simulate real flocks for application in movies and graph design, published by Craig Reynolds [7]. This led to the development of a group of individual governed by three main rules: separation, alignment and cohesion. Later, Frank Heppner worked with Reynolds' article in 1990, in order to obtain more detailed bird flocks to be applied in animation [8]. In mid 1990s, Jesper Hoffmeyer, a biologist, conceived one of the best definitions of swarms in terms of algorithm: a set of mobile agents presenting the ability to communicate to each other directly or indirectly in their environment and converge collectively for the solution of a given problem [9]. The research on the computational application of PSO actually started with James Kennedy and Russel Eberhart's publication in 2001 [3], [4], [7]. Since then, much has been published about the subject, with applications in several areas like function optimization, electric power systems, the traveling salesman problem, telecommunications, among others.

A. The PSO Algorithm Technique

PSO is an optimization algorithm based on a population of individuals that present the ability to interact among each other as well as with the environment. Since the individuals are social, they also have the knowledge about their neighbor's behavior and accomplishments in such a way that

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there exists individual learning and cultural transference [3], [4]. The cultural adaptation process is based on three fundamental principles: assessment, comparison, and imitation. The individuals assess their own behavior according to the environment, then compare themselves with the others and imitate the individuals, who are better [3], [4]. This is how the convergence of the group into a unique solution of the problem happens. In PSO algorithm, each particle swarm is a candidate solution to the problem. Such particles are distributed into a space of *n* dimensions (problem domain), each one having a determined position and velocity at each time instant. The best individual position of each particle is called *local best parameter* and the best position of all the particles is called *global best parameter*.

The performance of each particle is measured through a function called *rule function*, which varies according to the problem being dealt with. It simulates the "environment" in which the individual is inserted [3], [4]. The learning of the particles is embedded in the position and velocity updating equations. At each time instant, the displacement of each particle is looking for the best position and its velocity is updated. The updating of velocity depends on a comparison of the particle current position with the local best and global best parameters. The velocity equation also depends on random constants and the inertia weight. The inertia weight is related to how the velocity preserves the characteristics of the previous instant, that is, how much it will influence the individual and collective knowledge, tending to a major or minor convergence [3], [4]. The importance of inertia lies in the fact that the function has to avoid the early convergence in a local best parameter and provides the particles ways to find the global best parameter. This process occurs continuously until all the particles converge to the found global best parameter, which is the best solution to the problem in question.

III. Definition of the Proposed PSO Algorithm

Particle Swarm Optimization Technique is applied to get a restoration solution based on the changing of system functional configuration.

It is obtained by Algorithm 1, Fig. 1, whose purpose is to close Normally Opened Switches, NO. When the solutions presents overloaded lines, the program makes use of the Algorithm 2, Fig. 2, whose objective is to open Normally Closed Switches, NC in order to remove the overload. In both of the algorithms each particle represents a solution of a given problem. In this proposed approach, the problem is defined as the restoration of electric power distribution system and the solution is defined as being the switches that must have their final status changed. Each particle is represented by a matrix, where the number of lines is equal to the total number of particles established and the number of columns is equal to the number of NO - Algorithm 1 – or NC – Algorithm 2. The switches may assume binary values, 0 or 1, where 0 means opened switch and 1 means closed switch. It was verified using tests accomplished empirically with the computer program that 7 particles is the ideal number to work with in both of the algorithms.

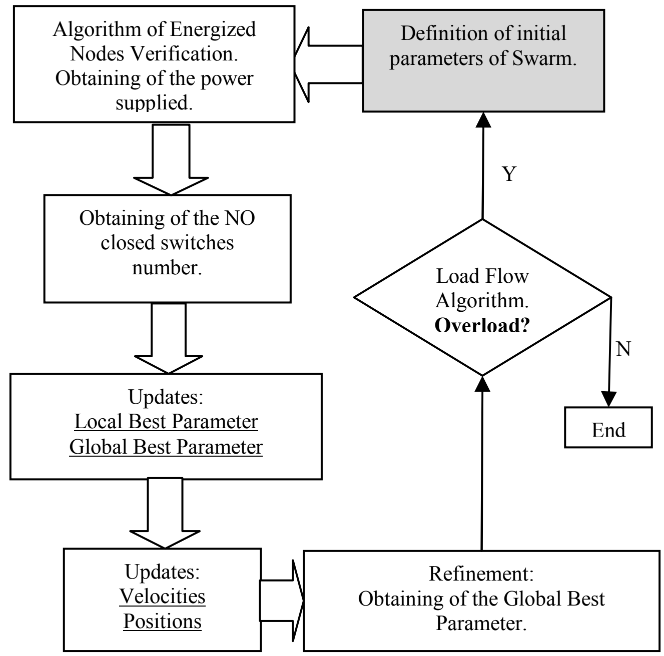

Fig. 1. Flowchart of Algorithm 1.

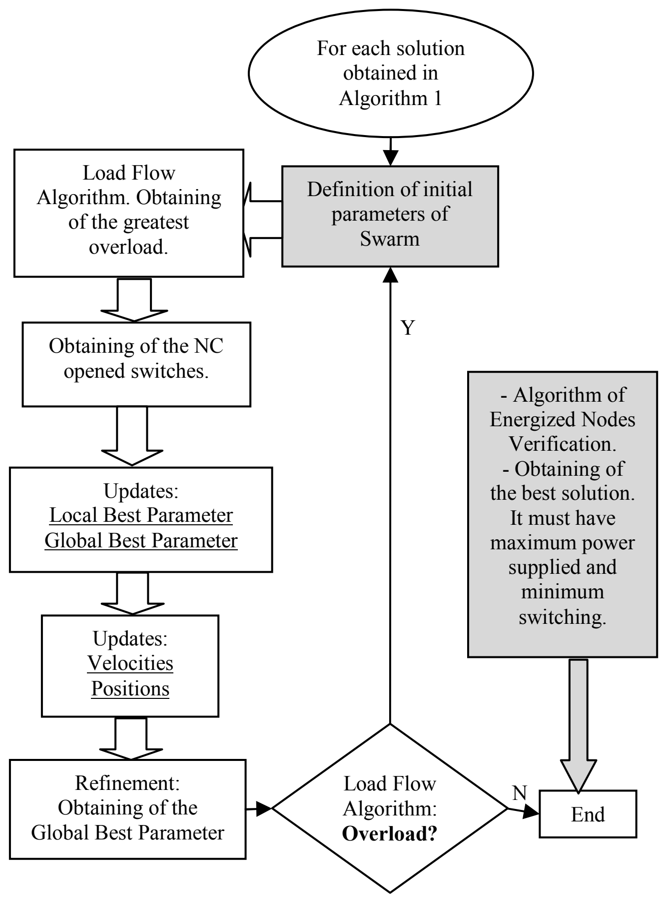

Fig. 2. Flowchart of Algorithm 2.

Firstly, in each algorithm the numbers of particle colony is generated randomly, as well as the velocities, local best and global best parameters. This is done by using random constants and considering the initial velocities equals to zero. Then, at each iteration of the process, the velocities are updated and also the positions of the particles based on the velocities. The local best and the global best parameters are only updated in case they are considered better than the previous iteration. This is established by the *rule function*, which measures the quality of each individual in the swarm. The proposed velocity equation is normalized due to work with discrete numbers, 0 or 1. At the end of each particle position updating, if the velocity value is lower than 0.5, it is rounded to 0, otherwise it is rounded to 1. However, the interval is extended to [-1;1] with the purpose of increasing the number velocity values number and improving the program efficiency during its execution. This means that: closed switch is equal to 1 and opened switch is equal to -1. This new interpretation may be explained as: at the end of a particle position updating, if the velocity value is lower than 0.6 (in case of Algorithm 1) or -0.6 (in case of Algorithm 2), then it is rounded to -1, otherwise to 1.

The velocity equation is written so as to converge more slowly at the beginning of the iteration and more quickly at the end of the iteration. This guarantees the approximation of the particles to the global best parameter and not to the local best parameter. The formulas used in PSO are [11]:

$$v(t+1) = w * v(t) + (1-w) * [\, r * (l(t+1) - x(t+1)) + (1-r) * ((g(t+1) - x(t+1))] \quad (1)$$

$$v(t+1) = (1 - w/1.5) * v(t) + (w/1.5) * [\, r * (l(t+1) - x(t+1)) + (1-r) * ((g(t+1) - x(t+1))] \quad (2)$$

$$x(t+1) = x(t) + v(t+1) \quad (3)$$

$$w = (1 - t / ni) \quad (4)$$

Where: i = counter for the number of particles; t = counter for the number of iterations; $v(t)$ = particle velocity i in the iteration t; $x(t)$ = particle position i in the iteration t; r = random constant, random number between 0 and 1; $l(t)$ = local best parameter of particle i found in the iteration t; $g(t)$ = global best parameter found in the iteration t; w = inertia weight in the velocity equation; ni = total number of iterations.

Equation (1) is only used in Algorithm 1 and (2) is only used in Algorithm 2. Equation (3) is position updating and (4) is inertia weight updating, and they are used in both of the algorithms. The program will repeat Algorithm 1 until a NO switch to be closed or the maximum iteration number is reached. The rule function is related on the restoration problem. First, the Algorithm 1 uses the *Algorithm of Energized Nodes Verification*, which creates a list of the status of each node, with or without energy. Each line of the system is represented by two consecutive nodes. All the status nodes are verified. The analysis is done with the status of the initial node and the status of its subsequent line. If the node is energized and its subsequent line is switch on then the final node is also energized. If the line is NO, then the analysis depends on the position of the particle related to it for present iteration. By applying this analysis to the whole system, then the power of the energized nodes are added. One of the criteria specified for the algorithm optimization is to maximize the amount of the power demand supplied to the system. Finally, the Algorithm 1 applies the criterion of the minimization of the NO closed switches number. The local best and the global best parameters update if the current position presents better performance in relation to the previous iteration.

Next step, the Algorithm 1 verifies if there are overloaded lines using an adapted Load Flow Algorithm. This algorithm has been adapted to work for radial systems and line losses are not considered. The adapted algorithm strategy consists of carrying the power from the end nodes to the subsequent lines and to add this power with the power of the next nodes and lines, successively. And then, the algorithm deletes the preprocessed lines and looks for the other end nodes. This process continues until it reaches the primary power source (a main substation in distribution system cases).

Thus, the computational program obtains the power flow in each line of the distribution system. The current power flow in each line is compared with its maximum capacity. In case there are overloaded lines, the program saves this solution and returns to Algorithm 1 in order to try another solution. If there are solutions without overload lines, the best solution is produced by PSO algorithm.

The Algorithm 2 is used when only overloaded line solutions are produced by Algorithm 1. The Algorithm 2 searches a solution with maximum power supplied and minimum number of NC opened switches. The goal of the Algorithm 2 is to remove overload of each distribution line opening NC switches. The Algorithm 2 computes a list of the overloaded lines and tries to eliminate the overload of the line with the greatest value in each iteration of each particle.

The best solution is chosen after an association of each possible NO closed switch (Algorithm 1) with NC opened switches (Algorithm 2). This solution is made by the Algorithm of Verification of Energized Nodes and Load Flow Algorithm in order to classify the solutions according to the previous defined criteria. In the case where no solution exists or the proposed algorithm finds a not appropriated solution, the methodology always blocks system restoration with power demand supplied lower than power in failure situation.

IV. Numerical Experiments – Cases Study

The practical results associated to proposed PSO are obtained in this section. For this proposal, the large scale Distribution_System_01 is used [5], Fig. 3. The proposed methodology aims to restore the system, providing the switches that must have the modified state, that is, if the switches are NO then they will be closed, and if the switches are NC then they will be opened. Four types of cases are illustrated as follows.

A. Type 1 Case Study – Several Solutions

This is the type of case in which the failure on the line causes a reduction in the number of loads supplied in the system and there are several solutions of closing and opening the switches which enable to find an optimized restoration of the system. Table I presents several failure simulations on the system's lines and the PSO solutions to these failures.

TABLE I
TYPE 1 CASE STUDY – SOME SIMULATIONS – SEVERAL SOLUTIONS

Examples		*PSO Restoration Situation*			
Failure Line	P (%)	NO	NC	P(%)	t [s]
1 - 91	82.62	2 - 19	64 - 68	96.16	35.950
		58 - 76	16 - 201	96.51	32.660
93 - 118	62.98	58 - 76	21 - 32 47 - 49 118 - 199	80.67	30.053
13 - 201	99.51	15 - 18	None	100.00	0.260
		13 - 86	None	100.00	0.134
16 - 201	96.51	2 - 9	None	100.00	0.200
		2 - 19	None	100.00	0.134
19 - 32	93.91	33 - 46	None	100.00	0.189
		2 - 19	None	100.00	0.231
99 - 100	98.66	83 - 98	None	100.00	0.150
		98 - 120	None	100.00	0.150
123 - 157	98.41	126 - 127	None	100.00	0.150
		126 - 177	None	100.00	0.140
		125 - 200	None	100.00	0.150
153 - 155	97.03	56 - 147	None	100.00	0.134
		142 - 149	None	100.00	0.201
158 - 198	98.89	189 - 190	None	100.00	0.180
		182 - 191	None	100.00	0.270

P=Power Demand Supplied; NO= Normally Opened Switch Closed; NF= Normally Closed Switch Opened; t= solution time.

In the Table I, the PSO restoration requires the status changing of one more switch. In the example *1-91*, the PSO suggests closing and opening switches, whereas for the other examples of this table, PSO only suggests closing switches. The biggest computational time of the example *1-91* is due to the use of the Algorithm 2. The computational time of this algorithm is usually much bigger than the Algorithm 1. However, considering the complexity of the system, this computational time is still lower than the operator's decision-making time.

Table II presents all solutions computed by the program for two examples (*1-91* and *93-118*) presented in Table I. For example, in the first solution of the failure line *1-91*, the following switching must be made: NO 58-76 is closed by NC 16-201(is opened) or NC 64-68 (is opened). The optimal solutions are presented in italics numbers and according to Table I.

B. *Type 2 Case Study – No Possible Solution*

This is the type of case analyzed in which the failure on the line causes the reduction in the number of loads supplied in the system, but there is no possible solution to the restoration problem. In other words, there is no switch to be closed or opened which will maximize the loads supplied.

Thus, at the end of the solution the situation of the system remains the same as presented initially. Table III presents some failure simulations on the system's line and the PSO responses to these failures as "No solution".

TABLE II
TYPE 1 CASE STUDY – FOUND SOLUTIONS

Examples		*Restoration Situation*			
Failure Line	P(%)	NO	NC	P(%)	t [s]
1-91	82.62	58-76	16-201	96.51	30.143
			64-68	96.16	32.056
		2-19	*64-68*	*96.16*	*35.950*
		19-57	64-68	86.46	28.345
			12-201 64-68	86.46	30.164
93-118	82.62	83 - 98	32 - 83 71 - 72 83 - 103 117 - 121 188 - 189	63.90	44.595
		2 - 19	19 - 50 20 - 71 21 - 32 47 - 49 188 - 189	71.92	26.968
		58 - 76	*21 - 32* *47 - 49* *118 - 199*	*80.67*	*30.053*
		2 - 19	13 – 201 21 – 32 83 – 106 117 – 121	73.12	27.129

P=Power Demand Supplied; NO= Normally Opened Switch Closed; NF= Normally Closed Switch Opened; t= solution time.

C. *Type 3 Case Study – Unique Solution*

In this case, it is analyzed the failure on the line that causes a reduction in the number of the system loads and there is unique solution of closing and opening the switches that restores the system. Table IV presents several failure simulations on the system's lines and the PSO solutions to these failures.

TABLE III
TYPE 2 CASE STUDY – SOME SIMULATIONS – NO SOLUTION

Examples		*Restoration Situation –No Solution*			
Failure Line	P(%)	NO	NC	P(%)	t [s]
128 - 140	93.62	None	None	93.62	280.864
160 - 184	98.32	None	None	98.32	322.704
76 - 77	98.16	None	None	98.16	288.916
93 - 110	95.68	None	None	95.68	310.367
158 - 183	73.12	None	None	73.12	270.028

P=Power Demand Supplied; NO= Normally Opened Switch Closed; NF= Normally Closed Switch Opened; t= solution time.

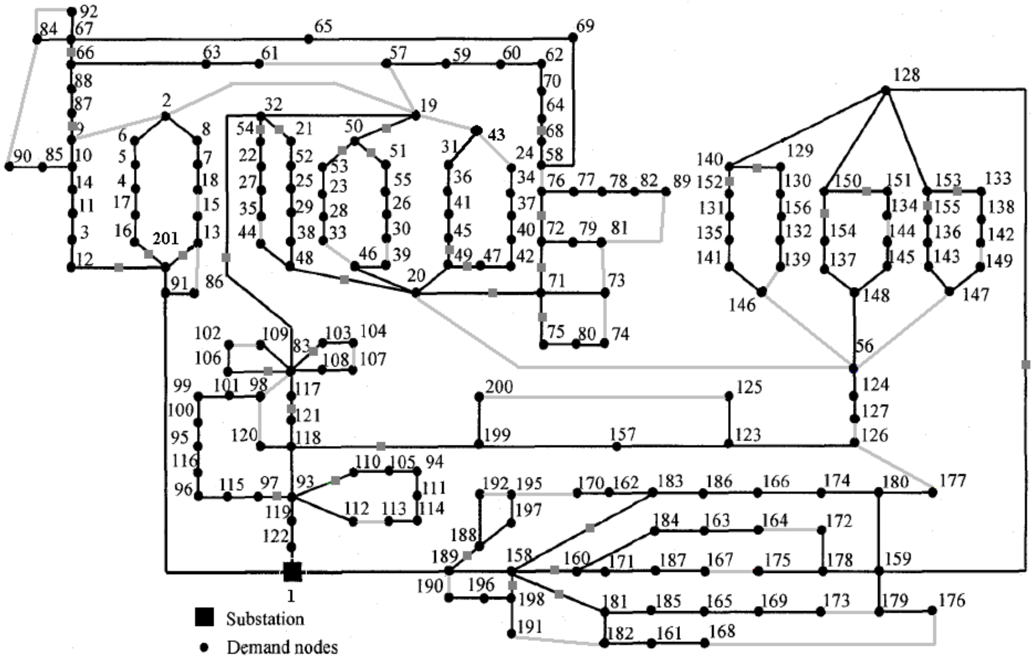

Fig. 3. Distribution_System_01with all the possible lines, including functional configuration information [5]. Light lines are NO and dark lines with gray marker are NC.

TABLE IV
TYPE 3 CASE STUDY – SOME SIMULATIONS – UNIQUE SOLUTION

Examples		*Restoration Situation*			
Failure Line	P(%)	NO	NC	P(%)	t [s]
1 - 189	62.87	20 - 56	150 – 154	66.36	29.052
2 - 8	99.18	15 - 18	None	100.00	0.170
10 - 85	99.10	84 - 90	None	100.00	0.150
63 - 66	98.91	57 - 61	None	100.00	0.140
111 - 114	98.91	112 - 113	None	100.00	0.150
83 - 106	99.08	102 - 109	None	100.00	0.171
83 - 108	99.57	104 - 107	None	100.00	0.431
199 - 200	99.62	125 - 200	None	100.00	0.150
32 - 54	98.24	35 - 44	None	100.00	0.170
50 - 53	97.99	33 - 46	None	100.00	0.170
50 - 51	96.89	30 - 39	None	100.00	0.150
40 - 42	97.12	24 - 43	None	100.00	0.150
78 - 82	99.08	81 - 89	None	100.00	0.190
71 - 75	98.22	73 - 74	None	100.00	0.150
188 - 189	99.55	170 - 195	None	100.00	0.250
196 - 198	99.04	189 - 190	None	100.00	0.331
161 - 168	99.85	168 - 176	None	100.00	0.150
165 - 185	98.27	173 - 179	None	100.00	0.151
160 - 171	98.58	167 - 175	None	100.00	0.180
172 - 178	99.25	164 - 172	None	100.00	0.180
132 - 156	98.85	139 - 146	None	100.00	0.631
145 - 148	99.16	134 - 144	None	100.00	0.280
138 - 142	97.69	142 - 149	None	100.00	0.231
12 - 201	86.75	58 - 76	None	100.00	0.220
20 - 48	84.81	58 - 76	None	100.00	0.281

P=Power Demand Supplied; NO= Normally Opened Switch Closed; NF= Normally Closed Switch Opened; t= solution time.

V. CONCLUSION

This paper presents an intelligent tool to help power system operators in reconfiguration problems. This tool based on Particle Swarm Optimization provides a list of switches that must be operated (open or close) in order to give the best solution for the system reconfiguration. The criterion used in the judgment is based on maximization of power demand supplied, minimization of the number closed switched, and avoids the overload lines. An illustrative example is shown and some results are presented and discussed.

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