

Al - Kalij Sub-Station: Feeder Reconfiguration by Particle Swarm Optimization

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Abstract

This paper presents the solution approach for the optimal reconfiguration problem in distribution networks implementing Particle Swarm Optimization (PSO) technique.

Network reconfiguration in distribution system is changing the status of sectionalizing switches to reduce the power loss in the system. The main objective of network reconfiguration is to find the network topology which is having the minimum losses during any conditions exists in the network. A network configuration is a valid solution to the problem if it satisfies reliability, security and other operation constraints.

Particle Swarm Optimization is a robust stochastic evolutionary computation technique, which is based on the movement and intelligence of swarms.

A standard particle swarm optimization algorithm is adapted and used in this work. The primary case study is a part of the Baghdad area distribution network. It consists of four feeders and 102 buses. The algorithm validity is verified first via application to standard systems. Results show that the standard particle swarm optimization is suitable for off-line reconfiguration studies.

Keywords: Distribution system; loss minimization; network reconfiguration; Particle Swarm Optimization.

التشكيل الامثل لمغذيات محطة توزيع الخليج باستخدام تحقيق الحشد المثالي للجسيمات

الخلاصة

يقدم هذا البحث طريقة لحل مسألة إعادة التشكيل المثالية في شبكات التوزيع الكهربائية. استخدمت تقنية تحقيق الحشد المثالي للجسيمات (Particle Swarm Optimization) لحل المسألة اعلاه. اعادة تمثيل الشبكة في نظام التوزيع يعرف بتغيير حالة مفاتيح الفصل (switches sectionalizing) لغرض تقليل الخسائر الكهربائية في النظام. إن الهدف الرئيسي لاعادة تشكيل الشبكة هو ايجاد طوبوغرافية الشبكة التي سيكون فيها اقل الخسائر أثناء أي ظرف عمل في الشبكة. تقنية تحقيق الحشد المثالي للجسيمات هي تقنية حساب تطويرية واحصائية متينة ، التي تستند على حركة وذكاء الحشود. حورت خوارزمية تحقيق الحشد المثالي للجسيمات القياسية واستعملت في هذا العمل. استخدمت شبكة ذات اربعة مغذيات و 102 عمومي كجزء من شبكة بغداد-الرصافة للتوزيع وتابعة لمحطة توزيع الخليج. تم تصديق الخوارزمية أولاً عن طريق التطبيق على أنظمة قياسية ومطابقة للنتائج. الاستنتاج الاساسي هو امكانية استخدام طريقة تحقيق الحشد المثالي للجسيمات لحل مسألة تشكيل الامثل لمنظومات التوزيع.

List of symbols:

A	Branch incidence matrix
AI	Artificial Intelligence
C	Cost function
c1 , c2	The acceleration coefficients, that are usually set to 2.0
det(A)	Determinant of the branch incidence matrix
g(x)	Power flow equations
I_i	Line current at line i
I_i^{\min}	Lower current limit
I_i^{\max}	Upper current limit
$iter_{\max}$	Iteration by which inertial weight should be at final value
K	Iteration index
L	No. of sections
$pbest_i$	The personal best position in the ith dimension
P_i	Active powers flowing at the sending of section i (kW).
Q_i	Reactive powers flowing at the sending of section i (KVAr).
rand()	Random number between 0 and 1
r_i	Section resistance
s_i^k	The current position in the ith dimension
V_i	The voltage at bus i
v_i^k	The ith velocity component at iteration K
V_i^{\min}	Lower voltage limit
V_i^{\max}	Upper voltage limit
$w(i)$	The inertia weight at iteration i
w_{\min}	The minimum inertia weight (final)
w_{\max}	The maximum inertia weight (initial)
Δt	The time step

Introduction

Network reconfiguration refers to the closing and opening of switches in a power distribution system in order to alter the network topology, and thus the flow of power from the substation to the consumers. Distribution feeders contain number of switches that are normally closed (sectionalizing switches) and switches that are normally open (tie switches). When the operation conditions change, network reconfiguration is performed by the opening / closing of the network switches under a number of constraints. These are;

- i. Operating in radial configuration.
- ii. All loads are served.
- iii. Lines, transformers, and other equipments operate within their current capacity limits.
- iv. Bus voltage within regulatory limits.

Shirmomohammadi and Hong [1] proposed a branch and bound type heuristic method to reduce the resistive line losses under normal operating conditions. Because of its computational efficiency, this approach can be used in both the planning and operations environments. As a result, it has the two principle benefits of that methodology, convergence to the optimum or near optimum solution and the independence of the final solution from the initial status of the network switches.

V.Borozan and N.Rajakovic [2] proposes a new method for network reconfiguration; it raised the

reconfiguration problem from the theoretical solution level to the practical implementation assessment level. For that purpose, a complex methodology for operational and short-term planning analyses of distribution system was created.

Lin and Chin [3] developed a new approach for the distribution network reconfiguration to minimize losses. The algorithm adopts a switching index to get a proper set of switching operations. Switching indices were defined by using branch voltage drops and line constraints. In normal operational state, switches with the largest index in each loop were considered for switching

R. T. F. Ah King, B. Radha & H. C. S. Rughooputh, [4] described the electrical distribution network reconfiguration as a complex optimization process aimed at finding a radial operating structure that minimizes the system power loss while satisfying operating constraints.

Mortan and Marlees [5] suggested a brute force algorithm for determining a minimal loss radial configuration using an exhaustive search algorithm. The graph theory involving semi sparse transformations of a current sensitivity matrix were used which guaranteed a globally optimal solution but needed an exhaustive search.

Charles, Khan and Rarichandrson [6] proposed a new methodology based on ant colony system algorithm for the network reconfiguration. The method is very flexible and global optimum was obtained in presence of constraints.

In this work a Particle Swarm Optimization solver is adopted and used to find the optimal network

configuration. Obviously, based on satisfying many operational requirements and constraints. Primarily, the minimum loss is a target plus the radiality and voltage drop constraints.

The Power Loss Derivation

Consider a distribution system consists of a radial main feeder only. The one-line diagram of such a feeder comprising n-branches or nodes is shown in figure (1). [7]

Power flow equations for a radial distribution network using real power, reactive power, voltages at the sending and receiving ends of a branch are given in equations (1a, 1b, 1c):-

$$P_{i+1} = P_i - r_{i+1} \frac{P_i^2 + Q_i^2}{|V_i|^2} - P_{Li+1} \quad (1a)$$

$$Q_{i+1} = Q_i - x_{i+1} \frac{P_i^2 + Q_i^2}{|V_i|^2} - Q_{Li+1} \quad (1b)$$

$$|V_{i+1}|^2 = |V_i|^2 - 2(r_{i+1}P_i + x_{i+1}Q_i) + (r_{i+1}^2 + x_{i+1}^2) \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (1c)$$

Equations (1), are called the branch flow equations. Power flow in radial distribution network can be described by a set of recursive branch flow equations. The quadratic terms in the equations represent the losses in the branches. These terms are much smaller than the power terms P_i and Q_i , hence, they can be ignored. The set of new branch equations can be written as shown in equation (2):

$$P_{i+1} = P_i + P_{Li+1} \quad (2a)$$

$$Q_{i+1} = Q_i - Q_{Li+1} \quad (2b)$$

$$|V_{i+1}|^2 = |V_i|^2 - 2(r_{i+1}P_i + x_{i+1}Q_i) \quad (2c)$$

The real power loss in a branch is calculated as given by equation (3)

$$\text{Loss}_i = r_i [(P_i^2 + Q_i^2) / V_i^2] \quad (3)$$

The total system loss is the sum of all the branches loss given by equation (4):

$$\text{Total Loss} = \sum_{i=1}^L \text{Loss}_i = \sum_{i=1}^L r_i [(P_i^2 + Q_i^2) / V_i^2] \quad (4)$$

The Optimization Problem

This section describes the formulation of the distribution system reconfiguration problem. The objective of the feeder reconfiguration is to minimize the distribution system losses with turning on / off sectionalizing switches. Mathematically, the problem can be formulated as follows[8]:

Cost function:

$$\text{Min. } C = \sum_{i=1}^L r_i \frac{(P_i^2 + Q_i^2)}{V_i^2} \quad (5)$$

Subject to:

$$g(x) = 0 \quad (6)$$

$$V_i^{\min} < V_i < V_i^{\max} \quad (7)$$

$$I_i^{\min} < I_i < I_i^{\max} \quad (8)$$

$$\det(A) = 1 \text{ or } -1 \text{ radial system} \quad (9)$$

$$\det(A) = 0 \text{ not radial} \quad (10)$$

The check for the network reconfiguration constraints is divided into two subsets [9]:

- 'Before' the load flow, checking for the supply provision & radiality of the system, and,
- 'After' the load flow, checking for voltage drop and line capacity limits.

The above reconfiguration problem has the following constraints [10]:

(a) Radial network constraint;

Distribution network should be composed of radial structure considering operational point of

view. Therefore, each section has only one up-stream section.

(b) Power source limit constraint;

The total loads of each partial network cannot exceed the capacity limit of the corresponding power source.

(c) Voltage constraint;

Voltage magnitude at each section must lie within their permissible ranges.

(d) Current constraint;

Current magnitude of each branch (switch and line) must lie within their permissible ranges.

The Particle Swarm Optimization (PSO)

PSO is a fairly new AI technique that can be considered as a member of the wide category of swarm intelligence [11, 12]. It was used to solve a wide variety of optimization problems. PSO is a population-based optimization technique that was originally inspired by the sociological behaviour associated with bird flocking and fish schooling. The main elements of the algorithm are [13]:

- Particle or Agent: One single individual in the swarm.
 - Swarm: The entire collection of agents.
 - Fitness: A single number representing the quality of a given solution.
 - Pbest: The location of the best fitness returned for a specific agent.
 - Gbest: The location of the best fitness returned for the entire swarm.
 - Maximum velocity: The maximum allowed velocity in a given direction.
- Different variants of the PSO algorithm were proposed but the most standard one is introduced by Shi and Eberhart in [14]. Key attractive feature of PSO is its

simplicity as it involves only two model equations. In PSO, the coordinates of each particle represent a possible solution associated with two vectors, the position (S_i) and velocity (v_i) vectors. The size of vectors S_i and v_i is equal to the number of particles. A swarm consists of number of particles "or possible solutions" that proceed through the feasible solution space to explore optimal solutions. Each particle updates its position based on its own best exploration (best swarm overall experience) and its previous velocity vector according to the following model equations:

$$v_i^{k+1} = v_i^k + c_1 * rand() * \frac{(pbest - s_i^k)}{\Delta t} + c_2 * rand() * \frac{(gbest - s_i^k)}{\Delta t} \quad (11)$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} * \Delta t \quad (12)$$

Application of PSO to solve the reconfiguration problem

The proposed PSO algorithm, whose flow chart is shown in fig.2, is described as follows:

Step1: Input data of a distribution system including all the operational constraints and initialize a population of particles with random positions and velocities on dimensions in the space.

Step2: For each particle, evaluate the desired optimization fitness function (power loss) if it is better than the *pbest*, the value is set to *pbest*. If the best fitness better than the *gbest*, the value is set to *gbest*.

Step3: store the particle with the best fitness (*gbest*) value by running the load flow program after checking radiality.

Step4: Change the velocity and position of the particle according to equations (11) and (12).

Step5: If *gbest* is optimal solution then stop. Else go to Step 2.

Step6: End

Algorithm Validation

The standard PSO algorithm is first used to find the optimal feeder configuration of a well documented systems. Three standard systems were considered [15, 16, and 17]. Table-1 shows the here used PSO algorithm results along with those obtained in the respective references. The results of Table.1 verifies the validity of the PSO algorithm adopted in this work.

Al-kalij Feeder System Case Study

In Al-Kalij substation there are three feeder station transformers of 132/33/11 kV with power rating of 63/50/25 MVA. Six feeders at the 33 kV level feed six 33/11 kV substations. Fifteen 11 kV feeders outgoing from Al-Kalij station serving a large area of mixed residential, industrial, and trading loads. Only four feeders of one of the three substation transformers are considered in this paper.

This system is rated at 11 kV with 101 sectionalizing switches, 102 buses, and 4 tie switches. A sample of the system data are given in Appendix A. The schematic diagram of the system is shown in Appendix B. The system real and reactive load demands of each bus are used without any change. Total loads are 17531 kW with initial system real power loss was 200.82 kW. Applying the proposed PSO algorithm, the final power loss is 155.2 kW. It is shown from the simulation results listed in Table.2 that the power loss

after reconfiguration is reduced by 22.7 % of its initial value, under normal loading conditions.

Figure-3 shows the voltage profile before and after feeder reconfiguration. As shown, most of the bus voltages have been improved after feeder reconfiguration. The minimum bus voltage was equal to 0.9769 p. u. and after reconfiguration; it is raised to 0.9818 p. u.

Figure-4 shows that during the search process there are 5 moves which lead to power loss reduction. The execution time of the PSO program is about 100 min.

For the system the control parameters are chosen as in Appendix C. Also, the total number of iterations of the program is 70 iterations and five of them lead to power loss reduction as shown in Fig. 4.

The ($iter_{max}$) iteration at which inertial weight (w) reached its final value is iteration no. 50 and after that number the inertial weight is held constant and equal to 0.2. Table.3 shows the statistics of the cost function in the simulation results.

Conclusions

In this work, a standard Particle Swarm Optimization method has been presented to solve the problem of optimal distribution network reconfiguration for loss reduction. The components of the proposed Particle Swarm Optimization based method, including evaluation function design, Particle, Swarm, Pbest, Gbest, maximum velocity etc., are described in detail. The proposed algorithm has been tested on standard systems. Results show that the proposed Particle Swarm Optimization based method is feasible, efficient and promising for

distribution system reconfiguration. Extensive series of simulation studies of Al-Kalij feeder system is performed considering different loading conditions as far as magnitude and power factor are concerned. The overall system reconfiguration pattern is almost as that of Table.2. In all the cases the four tie switches are closed and different section switch to open for different loading type and case. The general conclusion for the Al-Kalij feeder system is "better to keep the tie switches closed all the time and open the switches shown in Table.2 for all loading conditions".

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Appendix A

Table A.1: Al-Kalij Feeder System: Sample line & bus data

Line No.	From Bus	To Bus	R(Ω)	X(Ω)	End Bus	
					Real Power Load(kW)	Reactive Power Load(kVAr)
	0	1	0	0	0	0
	1	2	0.1749	0.1289	0	0
	2	3	0.0885	0.0971	200	150
	3	4	0.1026	0.1126	340	210
	4	5	0.0490	0.0538	200	150
	5	6	0.0106	0.0182	0	0
	6	7	0.1013	0.1111	200	150
	7	8	0.0350	0.0383	340	210
	8	9	0.0576	0.0632	200	150
0.	9	10	0.0618	0.0678	200	150
1.	3	11	0.0160	0.0176	0	0
2.	59	60	0.0141	0.0155	200	150
3.	53	61	0.0298	0.0327	340	210.71

Appendix B

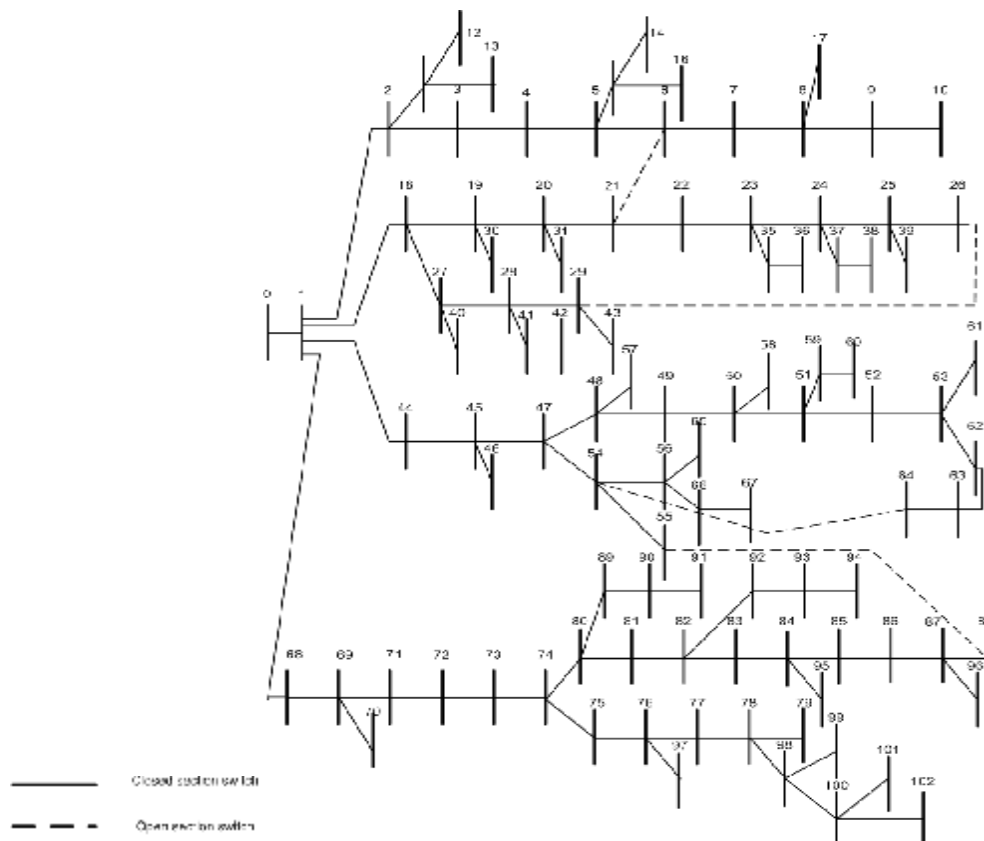


Figure B.1 Initial configuration of the Al-Kalij Feeder System

Appendix C

Table C.1: PSO Parameters Used During the Simulation

Parameter	Value
Number of particles	5.0
Initial velocity of the agent	0.0
Maximum inertia weight	0.9
Minimum inertia weight	0.2
C_1 & C_2	2.0
$w(i)$	1.0

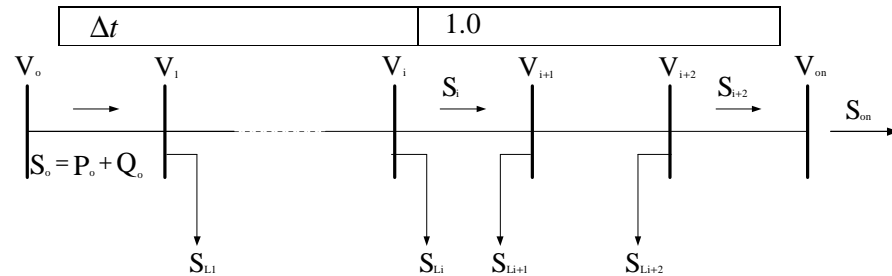


Figure 1: One line diagram of a main distribution feeder.

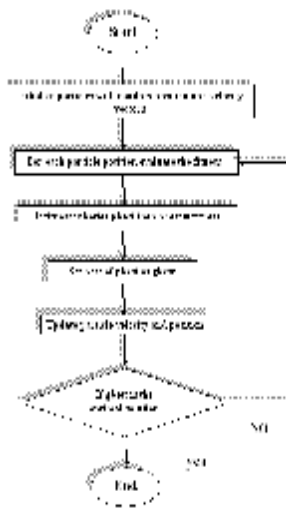


Figure 2: Flow chart of Standard Particle Swarm Optimizer

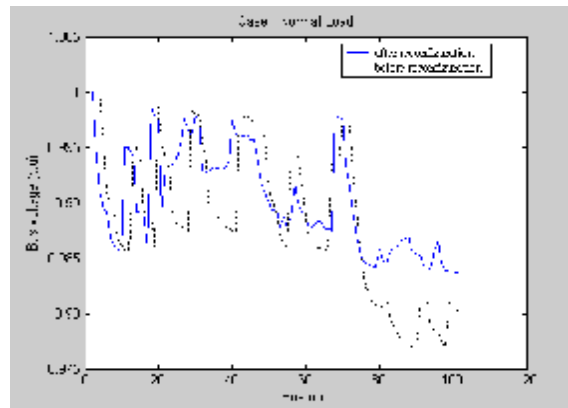


Figure3: Voltage profile for the Al-Kalij feeder system using PSO algorithm

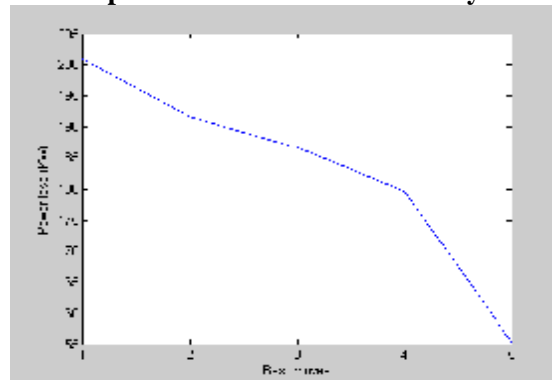


Figure 4: The best moves recorded during the search process for the Al-Kalij feeder system using the PSO algorithm

**Table . 1: (16-18-32)-bus system results using PSO algorithm
in comparison with other techniques**

System	Losses	Tie switches
16- bus system	Before reconfiguration=511.435 kW After reconfiguration using (SA)[15]= 466.1 kW After reconfiguration using proposed PSO=466.1 kW	[(5-11), (10-14), (7-16)] Before [(8-10), (9-11), (7-16)] After
18- bus system	Before reconfiguration=112.34 kW After reconfiguration using (GA)[16]= 107.48 kW After reconfiguration using proposed PSO=103.7 kW	[(6-10), (13-17)] Before [(6-10), (16-17)] After
32- bus system	Before reconfiguration=202.6 kW After reconfiguration using Artificial Bee Colony Algorithm [17]= 139.5 kW After reconfiguration using proposed PSO=139.5 kW	[(8-21), (9-15), (12-22), (18-33), (25-29)] Before [(7-8), (14-15), (9-10), (32-33), (25-29)] After

Table. 2: Al-Kalij feeder system results using PSO algorithm

System Type	Power Loss	%power loss	Voltage Profile (p. u.)	Tie Switches
Before reconfiguration	200.82 kW	1.145%	$V_{\max} = 1$ $V_{\min} = 0.9769$	6-21 26-29 54-64 55-88
After Reconfiguration using PSO	155.2 kW	0.885%	$V_{\max} = 1$ $V_{\min} = 0.9818$	5-6 21-22 52-53 82-38

Table. 3: Cost function statistics for the Al-Kalij feeder system

Best cost function	Average cost function	Worst cost function
155.2 kW	173. 4kW	191.6 kW