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NOVEL APPROACH TO RECONFIGURATION POWER LOSS REDUCTION PROBLEM BY SIMULATED ANNEALING TECHNIQUE

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Abstract: *The network reconfiguration is done by changing the status of the switches, mainly for two reasons: an active power loss reduction and load balancing attracting the attention of distribution engineers for quite a long period of time. In this article solving method for the active power loss reduction is given. Searching for the relevant radial configurations is done by a simulated annealing technique. To aid the search, a programme for checking the connectivity of the power system, with imposed radiality constraint, is presented enhanced by a new approximate power flow method. The applied power flow programme is very efficient and fast but can be used only as an indication for the loss estimation because of the insufficient method accuracy. At the end of algorithm it is necessary to run efficient power flow programme to determine the real situation concerning the loss reduction. A numerical example for Baran and Wu network is analyzed. The developed method converges to the global optimum given in a numerical example. The time duration of the used method is of an hour order and does not depend on the fast manipulation of incoming data files. This advantage makes the method interesting in the planning stage as well as the application in real time.*

Main contribution of this paper is a novel approach which exploits mostly the following mechanisms: network connectivity checking matrix, Lavorato et al. criterion for imposing radiality constraint and efficient power flow algorithm combined with precise power flow for exact loss calculation.

Keywords: *network configuration, active power loss, connectivity, radial configuration, power flow algorithm, simulated annealing.*

1. INTRODUCTION

Network reconfiguration requires determination of the best combination of branches, one from each loop, to be switched out so that resulting radial distribution system incurs minimal kW losses. Reconfiguration of network is obtained by changing the status of sectionalizing (normally closed) and tie line (normally open) switches. Since the statuses of the tie switches and sectionalizing switches are binary (open or closed), the solution space is discontinuous. Owing to the discontinuous and discrete nature of the problem, classical techniques are rendered unsuitable and the use of global search techniques is warranted.

Network reconfiguration belongs to “minimum spanning tree“ problems (network looks like a spanning tree) known as NP - combinatorial optimization problems. Algorithm should find minimum loss configuration, system constraints being satisfied.

Numerous methods have been reported in the literature for radial distribution systems (RDS) reconfiguration. A branch exchange type algorithm has been proposed in **[1]** that suggests a formula for determination of change of power loss due to branch exchange. In **[2]** a different method for branch exchange using a heuristic approach is proposed. Most of these methods depend on some heuristics. Another limitation of these algorithms is that they give only a local minimum solution and the global optimum solution may not be found.

In **[3]** the authors start from network where all switches are closed and then they successively open them to eliminate loops regarding which switch to open, after an optimal flow pattern application. Using DISTOP programme the authors come to an interesting and true conclusion that weakly meshed configurations are with the lowest power loss. The implemented efficient power flow algorithm requires the renumeration of nodes in levels that is not solved accurately when there are a large number of configurations.

In **[4]** a new algorithm is constructed with no need of matrix operation, only building of network graph from no branch configuration. One-source node networks are studied. Approach to the optimal solution is direct, radial configuration is maintained during the whole process, voltage and current constraints are easily satisfied, initial feasible configuration is not necessary and optimal one with minimal losses can be achieved.

The heuristic method is described in **[5]** for obtaining minimum loss configuration. Merlin and Back approach is adopted. A fast and reliable new efficient power flow algorithm is applied for searching through feasible configurations applicable for real networks.

Systematic method in **[6]** for reconfiguration power loss reduction problem is suggested. Methodology has three basic parts. Load estimation in real time, building of minimum loss configuration and cost and benefit estimation. The authors conclude that reconfiguration on a daily basis is not economically justified. It is justified on seasonal level with each month small correction. In this sort of planning, a lot can be saved in price.

Simulated annealing is used for the first time to solve reconfiguration power loss reduction problem in **[7, 8]**. It is presented as a non-differentiable multiple objective function combinatorial optimization problem with constraints.

In **[9]** authors also apply simulated annealing for reconfiguration solution and discreet optimization algorithm for capacitor placement.

Authors in **[10]** use only simulated annealing for solving reconfiguration and capacitor placement.

In **[11]** sophisticatedly based simulated annealing method is presented (with special cooling and perturbation mechanism) for the large-scale systems reconfiguration problem. Authors in **[12]** use a combined simulated annealing method with taboo search for minimization of the losses in distribution systems.

Distribution system minimum loss reconfiguration in the Hyper-Cube Ant Colony Optimization framework is presented in **[13]**.

In recent years, evolutionary computational algorithms such as genetic algorithm (GA) **[14]** and evolutionary programming have been proposed for distribution system reconfiguration, with encouraging results. At every generation of the evolution, the chromosome structure must satisfy the radial property of the network without islanding any load point. The problem is highly significant since there is every probability that the genetic operators might disrupt the radial nature of the chromosome.

Only two works **[15 and 16]** analyze unbalanced networks. Borozan considers unbalanced Skoplje network and applies heuristics and Zimmerman solves unbalanced network with 144 branches, 9 normally closed and 3 tie switches by means of simulated annealing.

In all stated literature complicated software is applied that is not presented and is run on fast PC-s (Pentium-IV), especially in recent references.

As a cornerstone of this paper, the article of Nahman and Perić **[17]** is used. Connectivity check criterion (presented in Section 2) that was refined and efficient power flow algorithm also modified with basic ideas in **[17]**. Fundamentals for simulated annealing algorithm programming are borrowed from Masters work **[18]**.

Although in recent time distribution engineers turn to more complicated problems such as simultaneous reconfiguration and capacitor switching in the presence of renewable generation **[19, 20]** and not only minimization of losses bases for methods in mentioned references are laid out in this paper.

2. NETWORK CONNECTIVITY CHECK

Power network is connected if there is a path between any pair of its nodes. This means that all load nodes are connected to the source node and can be supplied from that node. Network connectivity can be easily checked by means of matrix *(NC)* defined as **[21]**:

$$(NC) = (B)\exp(n-1)\,, \qquad (2.1)$$

where n is the number of network nodes and *(B)* is $n \times n$ system connectivity matrix with elements *B(i,j)* equal to 1 if there is a line between nodes i and j, and 0 otherwise. When $i=j$ in accordance with convention **[21]** *B(i,j)* equals 1. Network is connected if all *(NC)* matrix elements equal 1 **[21]**. Arithmetic operations in (2.1) are Boolean, what means:

0+0=0;

0+1=1+1=1;

0*0=0 and

1*1=1.

One of applications of matrix B is to check if the distribution system is connected.

Distribution system topology can be presented by graph with *m* branches and *n* nodes (buses) **[22]**. It can be stated that distribution network topology is radial if it satisfies the following two conditions **[22]**:

1) configuration must have *n*-1 branches;
2) configuration must be connected.

3. MODIFIED EFFICIENT POWER FLOW ALGORITHM

Modified efficient power flow algorithm was borrowed from **[17]**.

Many problems related to the distribution system real application as optimization, capacitor placement, voltage regulation, planning, restauration, state estimation, and so on, seek efficient power flow algorithm for network voltage (branch current) and loss calculation.

Widely adopted is the forward/backward sweep method where cumbersome input data feeding for level drawn network is exploited. The biggest drawback of these procedures is that data input must be generated and fed all the time, for each new configuration, which makes them practically useless for dynamic problems such as network reconfiguration and expansion planning.

Algorithm proposed in this paper is novel and classical.

It involves the building of network node admittance matrix which is only input parameter that changes with reconfiguring while all other incoming data remain the same and no renumeration of nodes is necessary. Analyzed network can be radial or weakly meshed. The proposed method is robust but demands efficient power flow to be applied in the end **[23]** because of insufficient preciseness.

Applied programme is analyzed in **[24]**

4. THE BLOCK DIAGRAM

The block diagram of the proposed algorithm is given on Figure 1.

Programme starts with any initial feasible configuration. Adopted cooling schedule can be expressed as T=0.95*T, initial temperature T being 5000.

New feasible configuration is generated by means of random number generator.

Let Ei be the current solution and Ej a neighbor solution. $\Delta Eij = Ei - Ej$.

If $\Delta Eij<0$ replace the solution j by solution i, if not find exp$^{(-\Delta Eij/T)}$. If exp$^{(-\Delta Eij/T)}$ is greater than the random number uniformly distributed in segment [0,1) replace the solution j by solution i. If not retain current solution j.

The algorithm stops in two cases, whichever occurs first:

1. The length of Markov chain at a certain temperature becomes greater than 3000 counted configurations.

2. Acceptance rate becomes less than 0.001.

The following data are in programme output file.

E- losses for the last generated configuration by simulated annealing (kW).

EOLD- losses for the last accepted configuration by simulated annealing (kW).

EOLDD- losses that are minimal during the whole procedure of performing simulated annealing (greedy search of all generated configurations) in kW.

niz- vector denoting open branches for the last generated configuration.

nizOLD- vector denoting open branches for the last accepted configuration.

nizOLDD- vector denoting open branches linked with EOLDD losses.

IMIN- number of generated minimal configurations (by monitoring greedy search) in descending order.

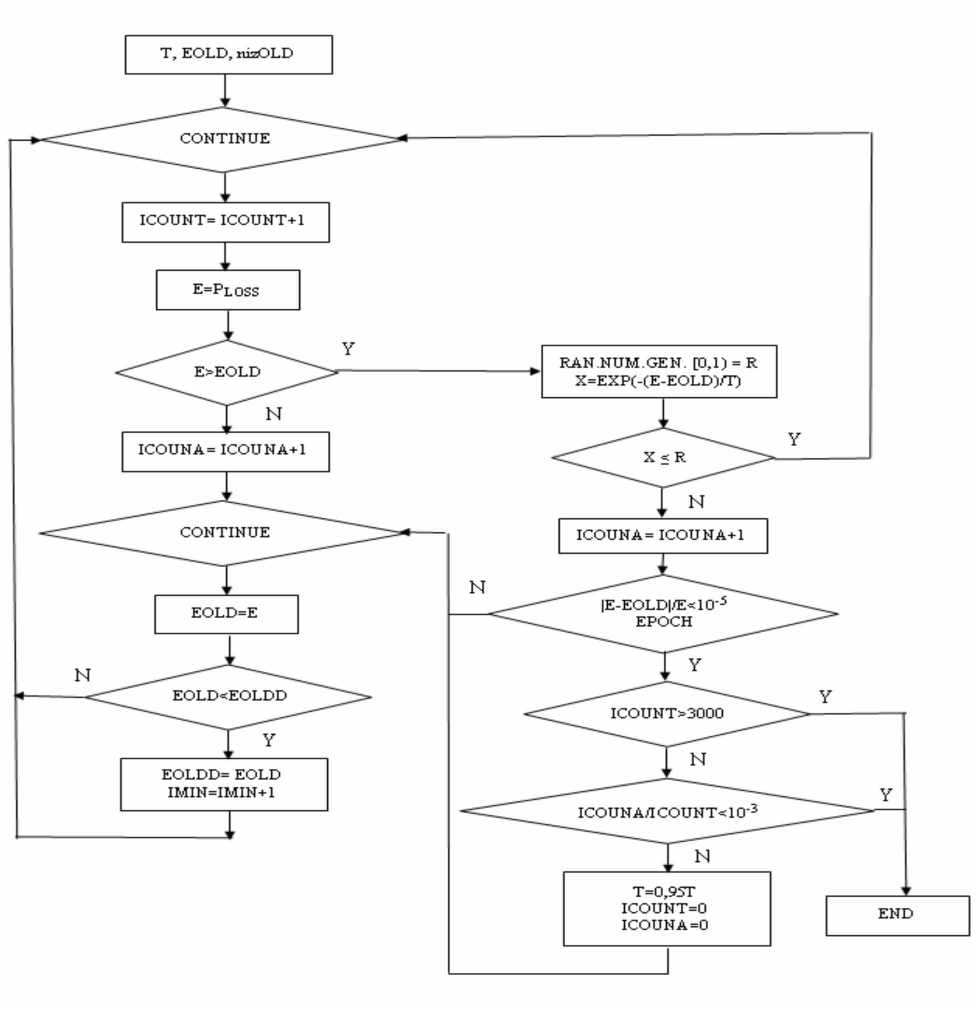

Figure 1. The programme block diagram

5. NUMERICAL RESULTS

Tested system is hypothetical 12.66 kV system **[2]** (given in Figure 2) comprising of 32 branches and 5 tie switches forming 5 different loops when closed. System data are given in Table 1. The summary of losses with data for open branches is given in Table 2. Total active and reactive load of tested network amount to 3715 kW and 2300 kVar respectively. Initial system active power loss is 202.675 kW (precise power loss **[3, 23]**) which is 5.5 % of total active power demand. The lowest voltage of the initial configuration is 0.9131 p.u. It is also supposed that each branch can be open or closed by the means of sectionalizing switch. Shaded figure in | V | p.u. column denotes the lowest node voltage.

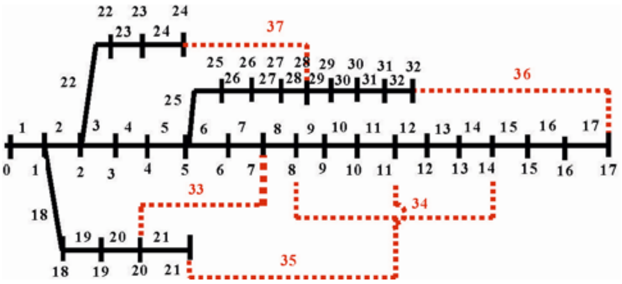

Figure 2. Network Baran and Wu **[2]**

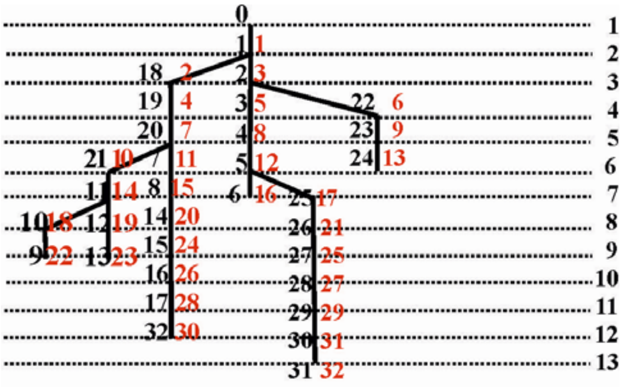

Figure 3. The optimal configuration

6. DISCUSSION AND CONCLUSIONS

1) In this example target optimum is reached in the following manner. Of all programme runs select lowest suboptimum. Open branches are 7, 9, 13, 32 and 37. On network figure close branch 13 and perform branch exchange by opening branch 14 which is the adjacent one. The target optimum is achieved.

2) The lowest voltage of the target optimum configuration is 0.938 p.u. which is better than the previous value 0.913 p.u. of initial configuration. The same applies for suboptimal configurations, so that with reconfiguration the voltage picture is only improved.

3) Currents of branches 15, 16, 17, 18, 19, 20 and 21 of the target optimum configuration are higher than in initial configuration. That shows that conclusion of Padilha Feltrin **[25]** is only partly true. The target optimum currents are mainly lower than in initial configuration but for minimum incremental loss branches. By rising losses of these branches and lowering losses of high current branches optimal configuration is achieved. Similar applies for suboptimal configurations.

Voltage and current constraints are not incorporated in authors' programme.

4) Second duration execution time of reconfiguration problems is ridiculous. In such cases the time for preparation of input data is of greater importance. In this example CPU time is of an hour order. With rising complexity of the system the time increases. With more rigorous parameters of simulated annealing time rises as well. Sometimes the quality of solution with moderate demands (epoch < 0.001, a.r. < 0.001 and ICOUNT=3000) gives for an acceptable time (2 hours) the best result. The reason for this is that obtained suboptimum is the result of hybrid and not alone simulated annealing algorithm. Suboptimum of implemented algorithm is more than desirable when having in mind that obtaining target optimum lasted several months, for example, in question in **[26]**.

5) The CPU time can be less without improving of optimum when switched to inhomogeneous algorithm which decreases temperature after each transition (before applying Metropolis criterion).

6) Besides the fact that many algorithms are applied for the reconfiguration in distribution networks traceability and repeatability of the method exposed in this paper make it different and unique.

Table 1 - Input data and results of precise power loss programme (Ploss=202.6 kW) for the initial configuration 33, 34, 35, 36 and 37 branches open (zeros in A, kW and kVar column)

branch	R (Ω)	X (Ω)	PLoad (kW)	QLoad (kVar)	| V | p.u.	Ibranch module (A)	Branch Ploss (kW)	Branch Qloss (kVar)
0-1	0.0922	0.0470	100.00	60.00	0.9970	364.3	12.2	6.2
1-2	0.4930	0.2511	90.00	40.00	0.9829	324.1	51.7	26.3
2-3	0.3660	0.1864	120.00	80.00	0.9755	233.1	19.9	10.1
3-4	0.3811	0.1941	60.00	30.00	0.9681	221.5	18.6	9.5
4-5	0.8190	0.7070	60.00	20.00	0.9497	216.1	38.2	33.0
5-6	0.1872	0.6188	200.00	100.00	0.9462	101.1	1.9	6.3
6-7	0.7114	0.2351	200.00	100.00	0.9413	82.4	4.8	1.5
7-8	1.0300	0.7400	60.00	20.00	0.9351	63.7	4.1	3.0
8-9	1.0440	0.7400	60.00	20.00	0.9292	58.4	3.5	2.5
9-10	0.1966	0.0650	45.00	30.00	0.9284	53.0	0.5	0.1
10-11	0.3744	0.1238	60.00	35.00	0.9269	48.5	0.8	0.2
11-12	1.4680	1.1550	60.00	35.00	0.9208	42.6	2.6	2.0

12-13	0.5416	0.7129	120.00	80.00	0.9185	36.6	0.7	0.9
13-14	0.5910	0.5260	60.00	10.00	0.9171	24.5	0.3	0.3
14-15	0.7463	0.5450	60.00	20.00	0.9157	19.4	0.2	0.2
15-16	1.2890	1.7210	60.00	20.00	0.9137	13.9	0.2	0.3
16-17	0.7320	0.5740	90.00	40.00	0.9131	8.5	0.05	0.04
1-18	0.1640	0.1565	90.00	40.00	0.9965	31.3	0.1	0.1
18-19	1.5042	1.3554	90.00	40.00	0.9929	23.5	0.8	0.7
19-20	0.4095	0.4784	90.00	40.00	0.9922	15.6	0.1	0.1
20-21	0.7089	0.9373	90.00	40.00	0.9916	7.8	0.04	0.05
2-22	0.4512	0.3083	90.00	50.00	0.9794	83.9	3.1	2.1
22-23	0.8980	0.7091	420.00	200.00	0.9727	75.6	5.1	4.0
23-24	0.8960	0.7011	420.00	200.00	0.9694	37.9	1.2	1.0
5-25	0.2030	0.1034	60.00	25.00	0.9477	113.1	2.6	1.3
25-26	0.2842	0.1447	60.00	25.00	0.9452	108.2	3.3	1.6
26-27	1.0590	0.9337	60.00	20.00	0.9337	103.3	11.3	9.9
27-28	0.8042	0.7006	120.00	70.00	0.9255	98.6	7.8	6.8
28-29	0.5075	0.2585	200.00	600.00	0.9220	87.6	3.8	1.9
29-30	0.9744	0.9630	150.00	70.00	0.9178	40.4	1.5	1.5
30-31	0.3105	0.3619	210.00	100.00	0.9169	26.2	0.2	0.2
31-32	0.3410	0.5302	60.00	40.00	0.9166	6.2	0.01	0.02
7-20, 33	2.000	2.000				0	0	0
8-14, 34	2.000	2.000				0	0	0
11-21, 35	2.000	2.000				0	0	0
17-32, 36	0.500	0.500				0	0	0
24-28, 37	0.500	0.500				0	0	0

Table 2 - Results of precise power loss programme calculating Ploss for the initial, suboptimal and optimal configuration

Configuration	Initial	Suboptimal	Optimal
Open branch	33, 34, 35, 36 and 37	7, 9, 13, 32 and 37	7, 9, 14, 32 and 37
Ploss	202.6 kW	143 kW	139.5 kW

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