Feeder Reconfiguration for Loss Reduction in Three Phase Distribution System Under Unbalanced Loading Conditions

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Abstract - **This paper presents a method to find the optimal implementation of feeder reconfiguration in unbalanced loading of distribution systems with the objective of power loss reduction. The optimization problem is subjected to system constraints consisting of load-point voltage limits, radial configuration format, no load-point interruption and feeder capability limits. The system power losses and bus voltages are solved by a three-phase power flow algorithm. The solution technique developed based on Tabu search is employed to search switch statuses for feeder reconfiguration under different unbalanced loading conditions. The performance of the developed methodology is demonstrated by a radial distribution system with 69 buses, 7 laterals and 5 tie-lines (looping branches). The study results show that the optimal on/off patterns of the switches can be identified which give the minimum power loss while satisfying all the constraints.**

Index Terms--**Feeder reconfiguration, Unbalanced distribution system, Loss reduction, Tabu search**

I. INTRODUCTION

Many methods have been employed for reducing active power loss in power systems, for example, increasing conductor size, shortening circuit lengths, adjusting transformer tap, and installing capacitors. Apart from these, one efficient operation that can improve the performance of distribution systems is feeder reconfiguration. Feeder reconfiguration refers to a process consisting of 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 customers. The advantages obtained from feeder reconfiguration are, for example, real power loss reduction, balancing system load, bus voltage profile improvement, and increasing system security and reliability [1-2].

There are two primary reasons to reconfigure a distribution network during normal operation, to avoid overloaded network branches and to reduce system losses. Depending on the current loading conditions, reconfiguration may become necessary in order to eliminate overloads on specific system components such as transformers or line sections. In this case it is known as load balancing. As the loading conditions on the system change, it may also become profitable to reconfigure in order to reduce the real power losses in the network [3]. The need for reconfiguration also occurs in emergency condition following a fault to isolate the faulted zone from the healthy areas and restore the areas outside the faulted zone.

The practical aspects of distribution system should be considered for the implementation of feeder reconfiguration. The actual distribution feeders are primarily unbalanced in nature due to various reasons, for example, unbalanced consumer loads, presence of single, double, and three-phase line sections, and existence of asymmetrical line sections. The inclusion of system unbalances increases the dimension of the feeder configuration problem because all three phases have to be simultaneously considered instead of a single phase balanced representation. Consequently, the analysis of distribution systems necessarily required a power flow algorithm with a complete three-phase model.

A great deal of work has been done on feeder reconfiguration in distribution systems mainly in the context of active power loss reduction because the cost of MW loss occupies considerable amount of operating cost in the system and therefore small amount achieved from loss reduction is still attractive for electric power utilities. A number of methods have been proposed to solve feeder reconfiguration for loss minimization, such as genetic algorithm [4] and simulated annealing [5] and heuristic methods [6].

The main contribution of this paper is to present an approach to finding the optimal solution of feeder reconfiguration in unbalanced loading distribution systems with the objective of power loss reduction. The optimization problem is subjected to system constraints consisting of load-point voltage limits, radial configuration format, no load-point interruption and feeder capability limits. The system power losses and bus voltages are solved by a three-phase power flow algorithm. The solution technique based on Tabu search is employed to search for switch statuses.

The performance of the developed methodology is demonstrated by a radial distribution system with 69 buses, 7 laterals and 5 tie-lines (looping branches). The study results with different unbalanced loading conditions show that the optimal on/off patterns of the switches can be identified which gives the minimum power loss while satisfying all the constraints.

II. FEEDER RECONFIGURATION

Feeder Reconfiguration is a very important and useful operation to reduce distribution feeder losses and improve system security. The configuration may be varied via switching operations to transfer loads among the feeders. Two types of switches are used: normally closed switches (sectionalizing switches) and normally open switches (tie switches) [7]. By changing the open/close status of the feeder switches load currents can be transferred to other feeders. During a fault, switches are used for fault isolation and service restoration. There are numerous numbers of switches in the distribution system, and the number of possible switching operations is tremendous. Feeder reconfiguration thus becomes a complex decision-making process for dispatchers to follow.

Optimum operation of distribution systems can be achieved by reconfiguring the system to minimize the losses as the operating conditions change. Reconfiguration problem essentially belongs to combinatorial optimization problem because this problem is carried out by taking into account various operational constraints in large scale distribution systems. It is, therefore, difficult to rapidly obtain an exact optimal solution on real system [8].

A flowchart for feeder reconfiguration algorithm is shown in Fig. 1.

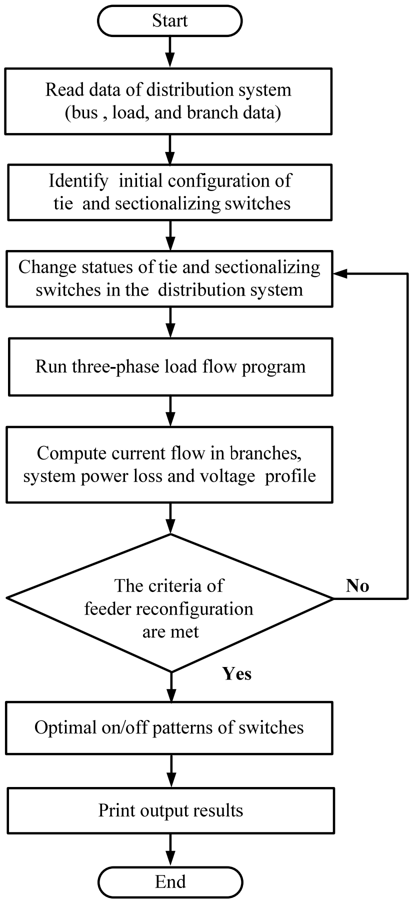

Fig. 1. Flowchart of feeder reconfiguration for loss reduction

III. THREE-PHASE POWER FLOW

Power flow is an essential tool for the steady state analysis of any power system. The main objective of the power flow analysis is to calculate the real and reactive powers flowing in each line along with the magnitude and phase angle of the voltage at each bus of the system for the specific loading conditions [9].

In general, power systems in steady state analysis are operated with balanced three-phase generation and loads by the transposition of transmission lines. However, it is not always the case, particularly for radial distribution systems, because of single-phase, two-phase and three-phase loads. As a result, the models based on single phase analysis are not adequate to represent unbalanced three phase networks. The method employed as a major tool to solve the unbalanced power flow problem is based on actual phase quantities with all the relevant equipment modelled in phase coordinates. Thus, power flow solution for unbalanced case and, hence special treatment is required for solving such networks [10, 11].

The conductors for each of the line sections in the network can be represented by the standard compound π-equivalent model. Fig. 2 shows a schematic representation of a line section between bus i and bus j. The series impedance and the shunt capacitance for a three-phase line are 3×3 complex matrices which take into account the mutual inductive coupling between the phases [3].

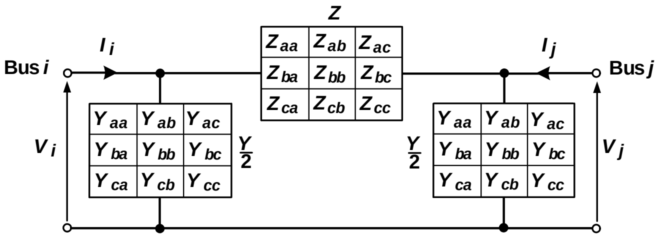

Fig. 2. Compound π-equivalent model for three-phase

If Z and Y are the 3×3 matrices representing the series impedance and shunt admittance, respectively, then the admittance matrix for a three-phase conductor between buses i and j is the 6×6 matrix in equation (1)

$$Y_{ij} = \begin{bmatrix} Z^{-1} + \frac{1}{2}Y & -Z^{-1} \\ -Z^{-1} & Z^{-1} + \frac{1}{2}Y \end{bmatrix} \tag{1}$$

The voltages and currents labeled by the 3×1 vectors V_i ,V_j , I_i and I_j in Fig 2. are related by

$$\begin{bmatrix} I_i \\ \hline I_j \end{bmatrix} = Y_{ij} \begin{bmatrix} V_i \\ \hline V_j \end{bmatrix} \tag{2}$$

Given a system with a total of *n* buses, a bus voltage vector (V_{bus}) and a bus injection current vector (I_{bus}), are defined as

$$V_{bus} = \left[V_1^a, V_1^b, V_1^c, V_2^a, V_2^b, V_2^c, \ldots, V_n^a, V_n^b, V_n^c\right]^T \tag{3}$$

$$I_{bus} = \left[I_1^a, I_1^b, I_1^c, I_2^a, I_2^b, I_2^c, \ldots, I_n^a, I_n^b, I_n^c\right]^T \tag{4}$$

where V_i^p and I_i^p are complex values representing the voltage and injected current, respectively, of phase *p* at bus *i*.

$$I_{bus} = Y_{bus} V_{bus} \tag{5}$$

where $Y_{bus} = \left[Y_{ij}^{pm}\right]$ is a $3n \times 3n$ complex matrix whose element relates the voltage V_j^m to the current I_i^p.

Rewriting (5) as a summation of the individual matrix and vector components gives the injected current of phase *p* at bus *i*. Equation (5) thus becomes (6).

$$I_i^p = \sum_{j=1}^{n} \sum_{m=a}^{c} Y_{ij}^{pm} V_j^m \tag{6}$$

Active and reactive powers for phase *p* at bus *i* in terms of the phase voltage magnitudes and angle are described in (7).

$$S_i^p = P_i^p + Q_i^p \tag{7}$$

$$P_i^p = \left|V_i^p\right| \sum_{j=1}^{n} \sum_{m=a}^{c} \left|V_j^m\right| \left[G_{ij}^{pm} \cos\theta_{ij}^{pm} + B_{ij}^{pm} \sin\theta_{ij}^{pm}\right] \tag{8}$$

$$Q_i^p = \left|V_i^p\right| \sum_{j=1}^{n} \sum_{m=a}^{c} \left|V_j^m\right| \left[G_{ij}^{pm} \sin\theta_{ij}^{pm} - B_{ij}^{pm} \cos\theta_{ij}^{pm}\right] \tag{9}$$

where p = phases *a*, *b* and *c*

P_i^p, Q_i^p = active and reactive power for phase *a*, *b* and *c* at bus $i = 1, 2, 3, \ldots, n$

$Y_{ij}^{pm} = G_{ij}^{pm} + jB_{ij}^{pm}$

V_i^p = voltage for phase *a*, *b* and *c* of bus *i*

$\theta_{ij}^{pm} = \theta_i^p - \theta_j^m$

IV. TABU SEARCH

Tabu search is meta-heuristic that guides a local heuristic search strategy to explore the solution space beyond local optimality. Tabu search was developed by Glover [12] and has a great variety of real-world problems, such as resource planning, telecommunications, financial analysis, scheduling, space planning, and energy distribution [13].

Tabu search is a local search technique that uses an iterative search procedure to progressively improve the solution by a series of local moves to neighborhood solutions. Tabu search has the ability to escape from local minima by effectively utilizing a memory to provide an efficient search for optimality. The memory is called "Tabu list", which stores attributes of solutions. In the search process, the solutions in the Tabu list cannot be a candidate of the next iteration. As a result, it helps inhibit choosing the same solution many times and avoid being trapped into cycling of the solutions [14]. The quality of a move in solution space is assessed by aspiration criteria that provide a mechanism for overriding the Tabu list [15].

V. PROBLEM FORMULATION

The objective function of the network configuration problem in this paper is to minimize the total power loss in three-phase distribution system as:

$$\text{Minimize } L = \sum_{k=1}^{Nl} P_k \tag{10}$$

where L = total power loss in three-phase distribution system

Nl = number of branches in the system

P_k = power loss in branch k

The power loss in branch k is computed from loss in each phase of that branch. P_k in (10), therefore, can be written as [16]:

$$P_k = [I_k]^T [R_k][I_k] \tag{11}$$

where $[I_k]$ = three-phase current matrix in branch k

$[R_k]$ = three-phase resistance matrix of branch k

$[I_k]$ and $[R_k]$ are expressed as:

$$[I_k] = \begin{bmatrix} I_k^a \\ I_k^b \\ I_k^c \end{bmatrix} \tag{12}$$

$$[R_k] = \begin{bmatrix} r_k^{aa} & r_k^{ab} & r_k^{ac} \\ r_k^{ba} & r_k^{bb} & r_k^{bc} \\ r_k^{ca} & r_k^{cb} & r_k^{cc} \end{bmatrix} \tag{13}$$

where $[I_k^p]$ = current flow in phase p of branch k

r_k^{aa}, r_k^{bb}, r_k^{cc} = self resistance of conductor in phase a, b and c of branch k

r_k^{ab}, r_k^{ac}, r_k^{ba}, r_k^{bc}, r_k^{ca}, r_k^{cb} = mutual coupling resistance between phase conductor of branch k

The objective function in (10) is subject to the following constraints.

1) Three-phase power flow equations in (8) and (9)
2) Bus voltage limits:

$$V^{p,\min} \le V_i^p \le V^{p,\max} \tag{14}$$

3) Feeder capability limits:

$$\left|I_k^p\right| \le I_k^{p,\max} \quad k \in \{1,2,3,\ldots l\} \tag{15}$$

4) Radial configuration format
5) No-load point interruption

where Nl = number of feeders

$V^{p,\min}$ $V^{p,\max}$ = minimum and maximum voltage for phases a, b and c

$I_k^{p,\max}$ = maximum current capability for phases a, b and c of branch k

VI. SOLUTION METHODOLOGY

The Tabu search algorithm is applied to solve the optimal or near optimal solution of the feeder configuration problem by taking the following steps:

Step 1: Read the bus, load and branch data of a distribution system including all the operational constraints.

Step 2: Randomly select a feasible solution from the search space: $S_0 \in \Omega$. The solution is represented by the switch number that should be opened during network reconfiguration.

Step 3: Set the size of a Tabu list, maximum iteration and iteration index $t = 1$.

Step 4: Let the initial solution obtained in step 2 be the current solution and the best solution: $S_{\text{best}} = S_0$, and $S_{\text{current}} = S_0$.

Step 5: Perform a power flow analysis to determine power loss, bus voltages, and branch currents.

Step 6: Calculate L using (10) and check whether the current solution satisfies the constraints. A penalty factor is applied for constraint violation.

Step 7: Calculate the aspiration level of S_{best}: $f_{\text{best}} = f(S_{\text{best}})$. The aspiration level is the sum of L and a penalty function

Step 8: Generate a set of solutions in the neighborhood of S_{current} by changing switch numbers that should be opened. This set of solutions is designated as S_{neighbor}.

Step 9: Calculate the aspiration level for each member of S_{neighbor}, and choose the one that has the highest aspiration level, $S_{\text{neighbor\_best}}$.

Step 10: Check whether the attribute of the solution obtained in step 9 is in the Tabu list. If yes, go to step 11, or else $S_{\text{current}} = S_{\text{neighbor\_best}}$ and go to step 12.

Step 11: Accept $S_{\text{neighbor\_best}}$ if it has a better aspiration level than f_{best} and set $S_{\text{current}} = S_{\text{neighbor\_best}}$, or else select a next-best solution that is not in the Tabu list to become the current solution.

Step 12: Update the Tabu list and set $t = t + 1$.

Step 13: Repeat steps 8 to 12 until a specified maximum iteration has been reached.

Step 14: Report the optimal solution.

VII. CASE STUDY

The developed methodology is demonstrated by a radial distribution system with 69 buses, 7 laterals and 5 tie-lines (looping branches), as shown in Fig. 3. The current carrying capacity of branch No.1-9 is 400 A, No. 46-49 and No. 52-64 are 300 A and the other remaining branches including the tie lines are 200 A. The base values for voltage and power are 12.66 kV and 100 MVA, respectively. Each branch in the system has a sectionalizing switch for reconfiguration. The load data and branch data are provided in Tables AI and AII [17].

The total loads for this test system are 3,801.89 kW and 2,694.10 kVAr. The minimum and maximum voltages are set at 0.95 and 1.05 p.u., respectively. The initial statuses of all the sectionalizing switches (switches No. 1-68) are closed while all the tie-switches (switch No. 69-73) are open. With this switch pattern, the system power loss is 673.89 kW. The maximum iteration for the Tabu search algorithm is 100.

In order to examine the effects of unbalanced loading on the implementation of feeder reconfiguration, four cases are investigated with different values of unbalanced loading as follows.

Case 1: The system is balanced.
Case 2: 5% unbalanced loading.
Case 3: 30% unbalanced loading.
Case 4: 50% unbalanced loading.

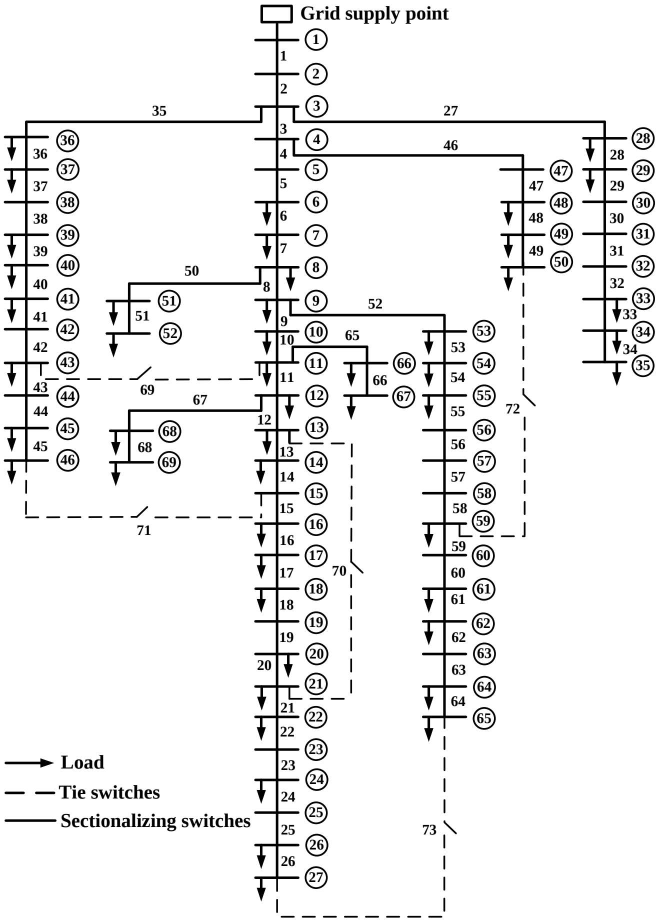

Fig. 3. Single-line diagram of 69-bus distribution system

Case 1 represents the base case in which all three phase loads are balanced. For other cases, for example in case 2, 5% unbalanced loading indicates that the load of phase *b* is 5% greater than that of phase *a* but lower than that in phase *c* by the same amount.

The numerical results for the 4 cases are summarized in Table I.

TABLE I
RESULTS OF CASE STUDY

	Opened switches	Closed switches	PL-B (kW)	PL-A (kW)	% R	Min Voltage (p.u.)
Case 1	14, 56, 61	71, 72, 73	622.342	277.572	55.399	0.986
Case 2	14, 56, 61	71, 72, 73	624.962	278.557	55.429	0.984
Case 3	12, 53, 61	71, 72, 73	720.662	352.206	54.874	0.969
Case 4	10, 18, 45 58, 61	69, 70, 71 72, 73	905.113	436.732	51.748	0.953

Note: Opened switches = sectionalizing switches to be opened
Closed switches = tie switches to be closed
PL-B = system power loss before reconfiguration
PL-A = system power loss after reconfiguration
% R = percentage of loss reduction

Comparing case 1 (balanced system) with case 2 (5% unbalanced loading), the power loss before feeder reconfiguration of these two cases are slightly different. The minimization of system power loss in cases 1 and 2 is achieved by opening switches No.14, 56, and 61 and closing switches No. 71, 72, and 73, giving power losses of 277.572 kW and 278.557 kW respectively. The power losses after reconfiguration of these two cases are still only 1 kW different due to a small amount of unbalance loading.

When the system unbalanced loading is increased to 30% as in case 3, the power loss before feeder reconfiguration is about 16% higher than that of case 1. To minimize the power loss by feeder reconfiguration in this case, the statuses of 6 switches should be changed. The opening of switches No. 12, 53, and 61 are required together with the closing of switches No. 71, 72, and 73 to reduce a power loss of 368.456 kW. The switches to be closed in case 3 are the same switches as in cases 1 and 2, but the switches to be opened in this case differ from those in cases 1 and 2 for two locations.

For a relatively high value of unbalanced loading (50%) as in case 4, the power loss before reconfiguration is increased by 45% compared to the base case. The test results in Table I show that loss minimization by feeder reconfiguration in case 4 should be implemented by the closing of all tie-switches (switches No. 69-73) and the opening of switches No. 10, 18, 45, 58, and 61 as shown in Fig 4. Feeder reconfiguration in this case results in a power loss of 436.732 kW.

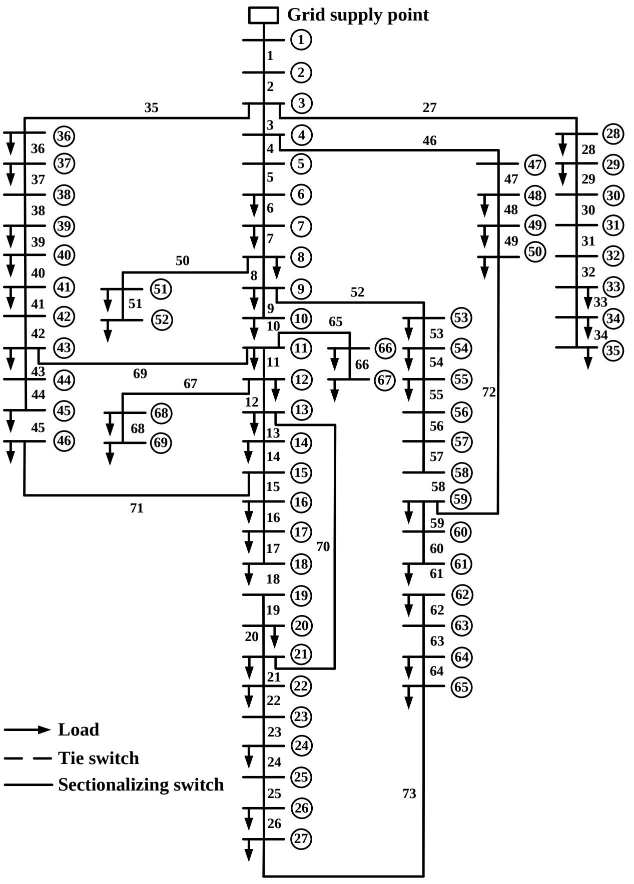

Fig. 4. Pattern of feeder reconfiguration for case 4

The observations from the numerical results in Table I indicate that for this particular test system, more percentage of unbalanced loading condition introduces more power loss to the system while decreasing the saving of power loss by feeder reconfiguration.

VIII. CONCLUSION

A Tabu search-based optimization technique has presented in this paper to find the most appropriate topology of the distribution system under unbalanced loading conditions. With the presence of unbalanced distribution systems, three phase power flow analysis is required. The objective function of feeder reconfiguration is to minimize the total system active power loss. The objective function is subjected to the three-phase power flow equations, bus voltage limits, current transfer capability of feeders, radial configuration format, and no load-point interruption. A 69-bus distribution system is used to demonstrate the effectiveness of the proposed technique. The study results with different unbalanced loading conditions show that the optimal on/off patterns of sectionalzing switches and tie switches can be identified to give the minimum power loss, introducing significant savings on the annual cost of energy loss in the system.

REFERENCES

[1] F M. A. Kashem, V. Ganapathy and G. B. Jasmon, “Network reconfiguration for load balancing in distribution networks,” *IEE Proc.-Gener. Transm. Distrib.,* vol. 146, no. 6, pp. 563-567, November 1999.

[2] T.P. Wagner, A.Y. Chikhani, R.Hackam, “Feeder reconfiguration for loss reduction: an application of distribution automation,” *IEEE Trans. Power Delivery*, vol. 6, no. 4, pp. 1922-1933, October 1991.

[3] R. D. Zimmerman, “Network reconfiguration for loss reduction in three-phase power distribution system,” *Thesis of the Graduate School of Cornell University*, May, 1992.

[4] P. Subburaj, K. Ramar L. Ganesan and P. Venkatesh, “Distribution system reconfiguration for loss reduction using genetic algorithm,” *J. Electrical Systems,* vol. 2, no. 4, pp. 198-207, December 2006.

[5] Young-Jae Jeon and Jae-chul Kim, “Network reconfiguration in radial distribution system using simulated annealing and tabu search,” in *Proc. Power Engineering Society Winter Meeting, Conf*, vol. 4, pp. 2329-2333, April 2000.

[6] T. Taylor and D. Lub Keman, “Implementation of heuristic search strategies for distribution feeder reconfiguration”, *IEEE Trans. on Power Delivery*, vol. 5, no. 1, pp. 239-246, January 1990.

[7] “Network reconfiguration in distribution systems for loss reduction and load balancing,” *IEEE Trans. on Power Delivery*, vol. 4, no 2, pp. 1401-1407, April 1989.

[8] Chung-Fu Chang, “Reconfiguration and capacitor placement for loss reduction of distribution systems by ant colony search algorithm,” *IEEE Trans. on Power Systems*, vol. 23, no. 4, pp. 1747-1755, November 2008.

[9] J. B. V. Subrahmanyam, “Load flow solution of unbalanced radial distribution systems,” *J. Theoretical and Applied Information Technology,* vol. 6, no. 1, pp. 40-51, August 2009.

[10] R. Ranjan, B. Venkatesh, A. Chaturvedi and D. Das, “Power flow solution of three-phase unbalanced radial distribution network,” *Electric Power Components and Systems*, vol. 32, no.4, pp.421-433, 2004.

[11] F. Hosseinzadeh, B. Alinejad and K. Pakfar, “A new technique in distribution network reconfiguration for loss reduction and optimum operation,” in *Proc. Electricity Distribution Conf*, Prague, June 2009.

[12] F. Glover, “Tabu search-part I,” *ORSA J. Computing*, vol. 1, no.3, 1989.

[13] B. Dengiz, and C. Alabas, “Simulation optimization using tabu search,” in *Proc. Winter Simulation Conf.*, pp. 805-810, 2000.

[14] T. Thakur, and Jawanti, “Application of tabu-search algorithm for network reconfiguration in radial distribution system” in *Proc. Power Electronics, Drives and Energy Systems Conf.*, December 2006.

[15] H. Mori, and Y. Ogita, “Parallel tabu search for capacitor placement in radial distribution system,” in *Proc. Power Engineering Society Winter Meeting Conf.*, pp 2334-2339, 2002.

[16] H.D. Chiang, J.C. Wang, J. Tong, and G. Darling, “Optimal capacitor placement, replacement and control in large-scale unbalanced distribution system: system modeling and a new formulation”. *IEEE Trans. on Power Systems*, vol. 10, no.1, pp.356-362, February 1995.

[17] J. S. Savier, and D. Das, “Impact of network reconfiguration on loss allocation of radial distribution systems,” *IEEE Trans. on Power Delivery*, vol. 22, no.4, pp. 2473-2480, October 2007.

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