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Tabu Search Based Algorithm for Multi-Objective Network Reconfiguration Problem

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Abstract: The electric power distribution usually operates in a radial configuration, with tie switches between circuits to provide alternate feeds. The losses would be minimized if all switches were closed, but this is not done because it complicates the system's protection against over currents. 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. All of these are applications for reconfiguration.

The reconfiguration problem is combinatorial problem, which precludes algorithms that guarantee a global optimum. Most existing reconfiguration algorithms fall into two categories. In the first, branch exchange, the system operates in a feasible radial configuration and the algorithm opens and closes candidate switches in pairs. In the second, loop cutting, the system is completely meshed and the algorithm opens candidate switches to reach a feasible radial configuration. Reconfiguration algorithms based on neural network, heuristics, genetic algorithms, and simulated annealing have also been reported, but not widely used.

The objective of the paper presented in this work is to make a Tabu Search (TS) based algorithm for multi-objective programming to solve the network reconfiguration problem in a radial distribution system. Here six objectives are considered in conjunction with network constraints. The main objective of research is allocation of optimal switches to reduce the power losses of the system. It is tested for 33 bus systems. Simulation results of the case studies demonstrate the effectiveness of the solution algorithm and proved that the TS is suitable to solve this kind of problems.

Key words: Combinatorial optimization; Distribution system; Energy Loss minimization; Genetic Algorithm; Simulating Annealing; Tabu search

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1. INTRODUCTION

Distribution systems are critical links between the utility and customer in which sectionalizing switches are used for both protection and configuration management. Usually distribution systems are designed to be most efficient at peak load demand. Obviously, the network can be made more efficient by reconfiguring it according to the variation in load demand. Recent studies indicate that up to 13% of the total power generation is wasted in the form of line losses at the distribution level. Hence, it is of great benefit to investigate methods of network reconfiguration[1].

Electric power distribution networks reconfiguration means the reduction of losses or the minimization of losses in the distribution network through better feeder configuration[2]. Reduced losses can result in generator fuel saving and possibly some reduction in generation capacity, hence, proving the proverb “energy saved is energy produced” and moreover environmental cost for pollution. Reconfiguration can be used for isolating faulted feeder section and restore service to faulted section of distribution network after correction. Service restoration is achieved by switching loads on outage to adjacent energized feeders.

Modifying the radial structure of the distribution networks feeders from time to time, by changing the position of switches, to transfer from one feeder to another may significantly improve the operating condition of the overall system. Network reconfiguration allows the transfer of loads from heavily loaded feeder. Such type of transfer are not only effective in terms of altering the level of load on the feeder being switched, but also in improving the voltage profile along with feeders effecting reduction in the overall power losses in network, and the power factor of the system[3]-[4]. These switches can also be used to transfer loads among feeders to meet new load requirements, to make better use of system capacity, and to minimize I^2R losses in the distribution lines. For a given system, there will be a switching pattern that minimizes system losses[5]. If there are N switches in a system, then are 2N possible switching combinations. For modern distribution systems with thousands of load buses and hundreds or even thousands of switches, the challenge of finding the optimum switching pattern to multiobjective problem is formidable. The network reconfiguration problem is formulated as a multiobjective and nondifferentiable optimization problem in light of the above considerations.

Recently, it is found that modern heuristic methods such as SA[6], GA[7]-[9] and Tabu Search (TS)[10] can be used for large combinational optimization problem of distribution system. TS belong to a family of methods, which also include SA, and GA. TS explores the whole solution space definitely based on the local search in which controlled up-hill move is admitted.

The roots of the TS go back to the 1970’s; it was first presented in its presentable form by Glover[11] later it was formalized by him; the basic idea was sketched by Hansen. Up to now, TS is a strategy with more functions for solving combinatorial optimization problem and is applied to various fields to obtain high quality solutions within reasonable computing time. The TS method is built upon a descent mechanism of a search process, which biases the search toward, points with lower objective function values[12]-[14]. However special features can also be added to avoid being trapped in the local minima. Basic component requirement to implement the TS are: Moves and Selection, Tabu List Aspiration Criterion Intensification and Diversification. A large number of papers has been published so for on tabu search algorithm for various combinatorial optimization solution[15]-[17].

This paper presents the Tabu Search Algorithm as meta-heuristic method for network reconfiguration problems in radial distribution system. This work has been tested on 33-bus RDS. System has five tie lines. The main advantage of TS with respect to conventional Genetic algorithm and Simulation annealing lies in the intelligent use of the past history of the search to influence its future search procedures.

2. PROBLEM FORMULATION OF THE OBJECTIVE AND CONSTRAINTS

One of the most relevant phases in the study here carried out concerns the analytic formulation of the objectives of the problem. For the six objective and the two constraints considered in the proposed formulation, in what follows, the analytical expressions and the relevant calculation hypotheses are reported.

2.1 Minimize Power Losses

The power losses vary with the network configuration and with the compensation level. They are associated with the resistive elements of lines and of HV/MV transformers. Assuming for the loads a constant current model, losses at MV/LV transformers can be neglected since they are not varying with current. Other losses terms like those due to insulation of lines and capacitors can be neglected too.

The minimization of the real power losses arising from feeders can be calculated as follows:

$$\text{Min } f_1(\bar{X}) = \sum_{i=1}^{N_b} r_i \frac{p_i^2+q_i^2}{v_i^2} \quad (1)$$

2.2 Ensuring Voltage Quality

The regular supply of the loads is guaranteed if the voltage value at the terminal nodes is as close as possible to the rated value. Bus voltage is one of the most significance security and service quality indices, which can be described as follows:

$$\text{Min } f_2(\bar{X}) = \max|V_i - V_{Rate}| \quad (2)$$

$$i = 1,2,3 \ldots, N_b$$

Where N_b is the total number of buses; V_i and V_{Rate} are the real and rated voltage on bus i, and $f_2(\bar{X})$ represents the maximal deviation of the bus voltage in the system of interest. Lower f_2 values indicate a higher quality voltage profile and better security of the considered system.

In order to quantify the extent of violation of limits imposed on voltages at buses in a RDS, the following Voltage Deviation Index (VDI) has been defined.

$$VDI = \sqrt{\frac{\sum_{i=1}^{NVB}(V_{Li} - V_{LiLIM})^2}{N}} \quad (3)$$

Subject to $V_{jMIN} \le V_j \le V_{jMAX} \quad j \in 1 \text{ to } \mathrm{N}$

Where NVB is the number of buses that violates the prescribed voltage limits and V_{LiLIM} is the upper limit of the I^{th} load bus voltage if there is upper limit violation or lower limit if there is a lower limit violation.

During reconfiguration, if the state of the system has voltage limit violations; the given solution must try to minimize the index VDI and thereby improve the power quality.

2.3 Service Reliability Assurance

The objective of network reconfiguration is to reduce power losses and improve reliability of power supply by changing the status of existing sectionalizing switches and ties. From the operator's prospective, service reliability in operating distribution systems refers to the ability to support unexpected increasing loads and to relieve other feeds following faults.

$$\text{Min } f_3(\bar{X}) = 1 - \min_i \left\{\frac{I_{iRate} - I_{iLoad}}{I_{iRate}}\right\}, \quad i = 1,2,3 \ldots, N_l \quad (4)$$

$$\text{Min } f_4(\bar{X}) = 1 - \min_i \left\{\frac{S_{iRate} - S_{iLoad}}{S_{iRate}}\right\}, \quad i = 1,2,3 \ldots, N_l \quad (5)$$

Selecting a specific index for ensuring reliability of service is utility-dependent and would not alter the basic formulation. It is necessary of substation to select the most suitable configuration satisfying the reliability requirement of customers.

2.4 Minimizing Switches Operation

Distribution systems can be reconfigured via a series of switches operations in order to reduce multi-objective problem. If any of the switch status is incorrect, then the application functions that use this data base will also produce incorrect results. One of the major obstacles in identifying errors in the switch statuses is the lack of sufficient real time measurement taken from the system. So it is better to use the minimize switches operation objective.

Its solution scheme starts with a meshed network by initially closing all switches in the network. The switches are then open one at a time until a new radial configuration is reached. In order to accomplish the transition from the initial configuration to the optimal configuration with minimum switch operations, an effective switch plan needs to be developed such that unnecessary switch operations in the switch sequence can be avoided. Minimizing the number of switch operations can be denoted as follows:

$$\text{Min } f_5(\overline{X}) = \sum_{i=1}^{N_s} |S_i - S_{oi}| \quad (6)$$

Where Ns represents the total number of switch; S_i and S_{0i} are the new and original states of switch i, respectively; and $f_5(\overline{X})$ represents the number of switch operations under state $(\overline{X})$. Alower $f_5(\overline{X})$ value implies that less time is needed during the network reconfiguration process.

2.5 Lesser Solution Time

Especially with the introduction of remote control capability to the switches, lesser computational time configuration management becomes an important part of distribution automation. A salient feature of the solution methodology is that it allows the designers to find a desirable, global non-inferior solution for the problem. An effective scheme to speed up the simulation technique have been presented and analyzed.

2.6 Maximum Loading

The whole load of the network should be divided in a balanced way among the transformers, on the basis of their rated power. In this way, the optimal working condition for the transformer is ensured and any over-loading situation due to fault occurrence can be promptly faced. In the literature on the topic, different formulations have been proposed for the Load Balancing Index.

For load balancing, we will use the ratio of complex power at the sending end of a branch, Si over its KVA capacity, S_{imax} as a measure of how much that branch is loaded. The branch can be a transformer, a tie line with a sectionalizing switch or simply a line section. Then we define the load balance index for the whole system as the sum of these measures, i.e.

$$C_b = \sum \left(\frac{S_i}{S_i^{max}}\right)^2 = \sum \frac{P_i^2 + Q_i^2}{S_i^{max\ 2}} \quad (7)$$

This will be the objective function, Cb of load balancing.

When the general search algorithm introduced in section is used for load balancing, the calculations will be similar to that of the loss reduction case. The only difference will be in the calculation of the objective; for load balancing, we need to estimate the value of the new objective, load balance index, C_b for every branch exchange considered during the search. Once the new power flow in the branches, Pi', Qi' are estimated then the new load balance index can be computed by employing Eq. (7).

Having a network model, now we can express the power loss and measure the load balance in the system in terms of system variables.

2.7 Constraints

Two constraints are considered in the formulation of the problem, although other constraints could also be taken into account within the proposed solution procedure:

- The radial structure of the network must be maintained in each new structure.
- All loads must be served.

After studying the results of the optimal flow pattern, the branch having the lowest branch current is eliminated from the network for maintaining the network radial. As few branches have been removed, few have been added to the network, hence the network needs reconfiguration. Paths from the terminal nodes to the root nodes are to be specified.

In the iterative compensation procedure, after every solution of equations and before proceeding with the next step, the node power correction are to be calculated as network has been reconfigured, and the total power at the nodes has changed. In order to achieve that, it is necessary to solve the radial network.

In each iteration, all nodes power are to be added to the corresponding node load. Then in backward sweep, branch power losses and corresponding power at sending and receiving end of each branch are added to get the total power at that node. Similarly, the power at all the nodes is calculated using equation given below:

$$P_i^1 = P_i + P_{Li} \quad (8)$$

$$Q_i^1 = Q_i + Q_{Li} \quad (9)$$

$$P_{i-1} = P_i + r_i\left(\frac{P_i^{12}+Q_i^{12}}{V_i^2}\right) + P_{Li} \tag{10}$$

$$Q_{i-1} = Q_i + x_i\left(\frac{P_i^{12}+Q_i^{12}}{V_i^2}\right) + Q_{Li} \tag{11}$$

Starting from the last node, and moving towards the root node, assuming the variable P_i, Q_i, V_i at that nodes as given, and then proceed backward calculating the same quantity at the other nodes by successively applying above equation. Losses in the branches were much smaller than the branch power, hence these can be dropped so the above equation reduced as follow:

$$P_{i+1} = P_i + P_{Li+1} \tag{12}$$

$$Q_{i+1} = Q_i + Q_{Li+1} \tag{13}$$

Updating process end at first and then it will provide new estimated power at all network nodes are known. Before proceeding with the next iteration, the node voltage corrections are to be calculated. Then in the forward sweep, with known sending power at the nodes, the receiving node voltage can be expressed as

$$V_{i+1}^2 = V_i^2 - 2(r_iP_i + x_iQ_i) + \left(r_i^2 + x_i^2\right)\frac{(P_i^2+Q_i^2)}{V_i^2} \tag{14}$$

$$V_{i+1} = V_i\left[1 - \frac{P_ir_i+x_iQ_i}{V_s^2} + j\frac{Q_ir_i+P_ix_i}{V_i^2}\right] \tag{15}$$

After obtaining the new node voltage, it possible to calculate the new value of branch current uses the backward sweep.

3. SOLUTION ALGORITHM FOR NETWORK RECONFIGURATION

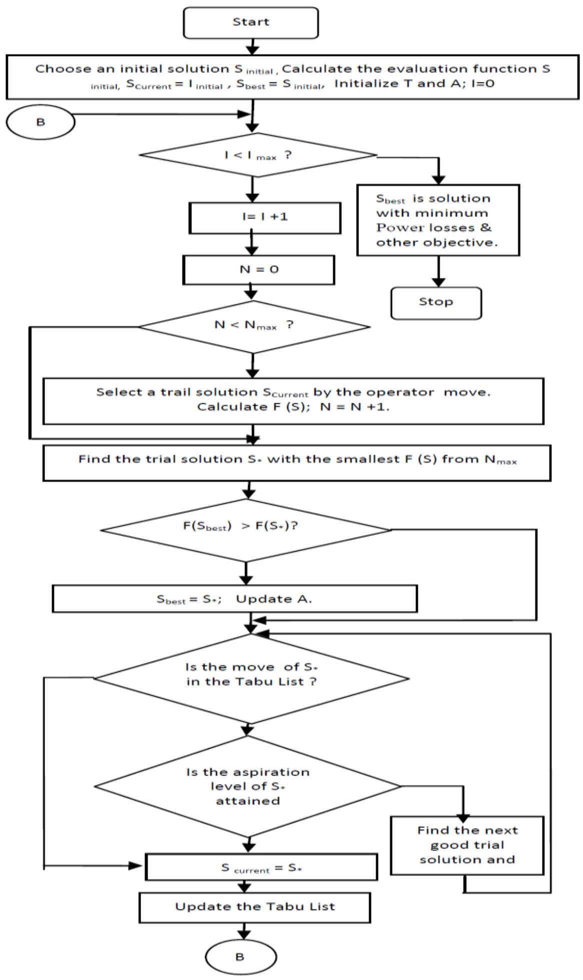

Fig. 1: Tabu Search for Network Reconfiguration Problem

The flow chart of the proposed Tabu Search based algorithm for the distribution network reconfiguration is shown in the Figure 1 and described as follows.

a. Choose current operating network as an initial solution $S_{initial}$ and calculate the evaluation function of $S_{initial}$. Let the current solution vector $S_{currrent}$ = $S_{initial}$ and the best solution vector S_{best} = $S_{initial}$. Initialize the Tabu List T and the aspiration function A. Set the iteration counter I=0.

b. If I is equal to pre-specified maximum permitted iteration number I_{max}, then output S_{best} as the final result and stop. Otherwise, set I=I+1, and go to step 3.

c. Select a trial radial solution from the neighborhood of $S_{current}$ by the operator move, which will be defined later, and calculate the evaluation function f(S) of the corresponding solution S. Repeat the process until the specified neighborhood sampling number N_{max} has been reached.

d. If S_{best} is not better than the best trial solution that has the minimum evaluation function value, and then assign this best trial solution to S_{best} and update the aspiration function A. Otherwise, go to step 5.

e. $S_{current}$ is updated to the best trial solution that has the minimum evaluation function value as evaluated in the step 3 if the corresponding move is not in the Tabu List or its aspiration level is attained. Then, include the move in the Tabu List and update the Tabu List T. Go to step 2. If the best trial solution corresponds to a Tabu move and its aspiration level is not attained, then check the next trial solution, and repeat this step.

4. TEST SYSTEM FOR RESULT ANALYSIS

Test sample system is considered for simulation, one 33 bus radial distribution system, 12.66 KV. Computer software has been developed for the test system in MATLAB to examine the efficiency of the proposed algorithm.

4.1 Original Configuration Case

In test system, the power loss minimization technique is applied on a 12.66KV, 1MVA base hypothetical system as shown in Figure 2. It consists of 33 buses and 32 branches. The test system have five tie lines i.e. the system have five loops. Five tie switches exist between nodes (20,33), (14,34), (21,35), (32,36), and (28,37), which are normally open. Sectionalizing switches are also assumed to be associated with all other branches. Appendix A gives the data for the hypothetical system under consideration, with the values of load, branch impedances and voltage at nodes. Loads are converted into nodal current injection. Branch current are calculated by summing the nodal current from last node and moving towards the root node using the backward sweep. In the present condition the resistive line losses are coming out to be 203.059KW.

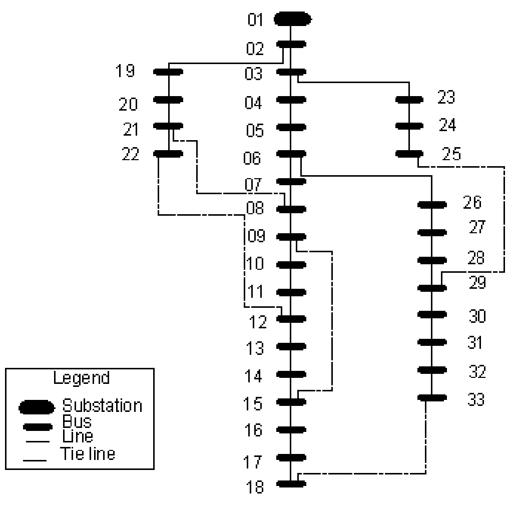

Fig. 2: A 33-bus Radial Distribution System

4.2 TS Reconfiguration Case

Problem is to reconfigure the system to another form, so that the total resistive line losses are minimized without violating the current and voltage limit, no nodal load is isolated. Convert the system into a meshed one by connecting the tie lines in the system i.e. branch number 33, 34, 35, 36 and 37 between their respective nodes.

Next step is to carry out a load flow analysis of the system to determine the optimal flow pattern and find the line carrying the minimum current. Line 6 was carrying a minimum current of 9.3706 Amp in loop 1, so it was removed. Line 14 was carrying a minimum current of 0.4813 Amp in loop 2 and line 11 was carrying a minimum current 2.59 Amp in loop 3. But in loop 4 the line 31 was carrying a minimum current of 6.624 Amp and in loop 5 lines 28 was carrying a minimum current of 0.86 Amp. So, branch 6, 14, 11, 31 and 28 were deleted and the tie lines of network now become the branch of the system. Now, the network has to be reconfigured for the change that place in the network. So, the branches current are again calculated after calculating the node voltage using the backward and forward sweep. Final losses that come out of the configuration are 136.4791 KW. Thus the losses are reduced from 203.0590KW to 136.4791 KW resulting in percentage loss reduction of about 14.82 percent.

Tab. 1: Loop Number after Reconfiguration

No. of loops = 5

S.No.	Loop No.	Branch In	Branch Out	Current in Branch out
1	1	33	6	9.3706
2	2	34	11	0.4813
3	3	35	31	2.5900
4	4	36	28	6.6240
5	5	37	14	0.8600

4.3 Results of multiobjectives problem

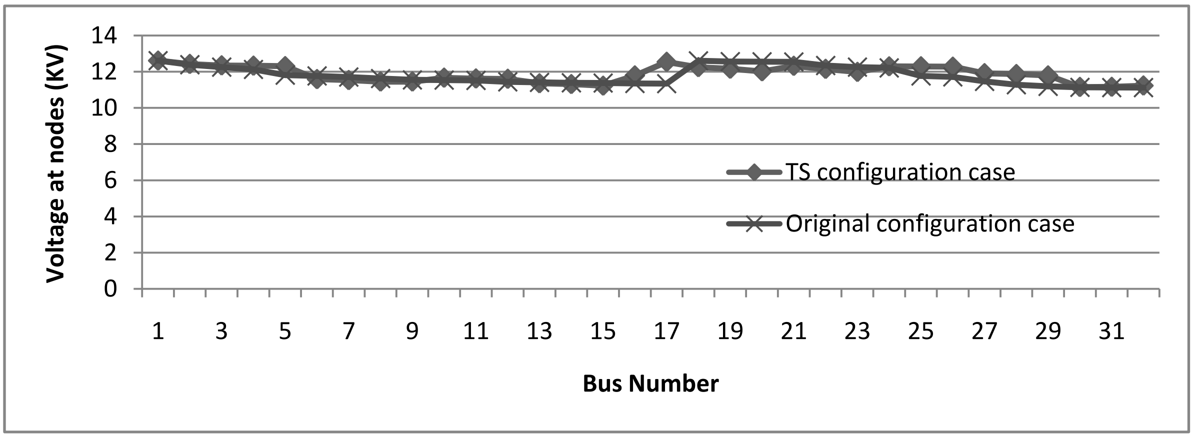

Fig. 3: Voltage Comparison of Original and TS Proposed Configuration

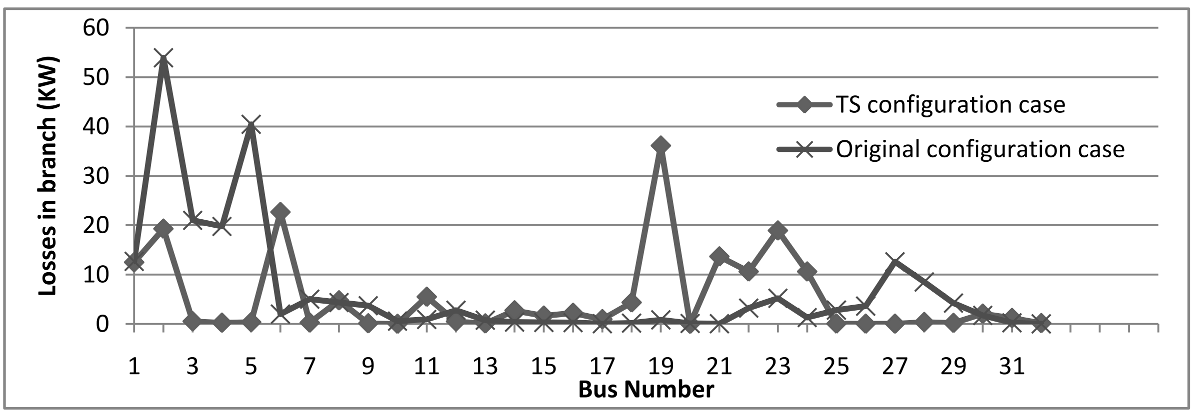

Fig. 4: Power Losses Comparison of Original and TS Proposed Configuration

Figure 3 and 4 are showing the comparisons between voltage and losses respectively flowing through the lines in original and TS configuration cases. In TS configuration, lesser power is required because the losses have been decreased. This was the main objective to be achieved through reconfiguration.

Tab. 2: Comparison of Multi-objective Results in 33 Bus System

Loading Level	33 Bus System	
	Original configuration	TS Reconfiguration
Power losses (KW)	203.0590 KW	136.4791 KW
Ensuring Voltage Quality (KV)	11.0757	11.1252
Service Reliability Assurance :		
Minimum Capacity		
Margin Among feeder (%)		
Minimum Capacity Margin	44.60%	65.13%
Among Transformers (%)		
	54.12%	56.39%
No. of switches operations	33, 34, 35, 36, 37	6, 11, 14, 28, 31
Maximum Deviation of bus voltage (pu)	0.0498	0.0253
Maximum Loadability	10368.10	16583.57

4.4 Comparison with other Reference Results

Tab. 3: Simulation Results Comparison with Other Reference of 33-Bus System

Item	Tie switches	Power loss(KW)	Power loss reduction(%)	CPU Time(s)
Original configuration	33, 34, 35, 36, 37	203.05	--	--
Method in[6]	7, 10, 14, 32, 37	137.37	30.21	25.3
RGA in[8]	7, 9, 14, 32, 37	139.5	31.2	13.8
GA in[9]	33, 9, 34, 28, 36	140.6	30.6	15.2
TS Proposed configuration	6, 11, 14, 28, 31	136. 4791	31.5799	0.25

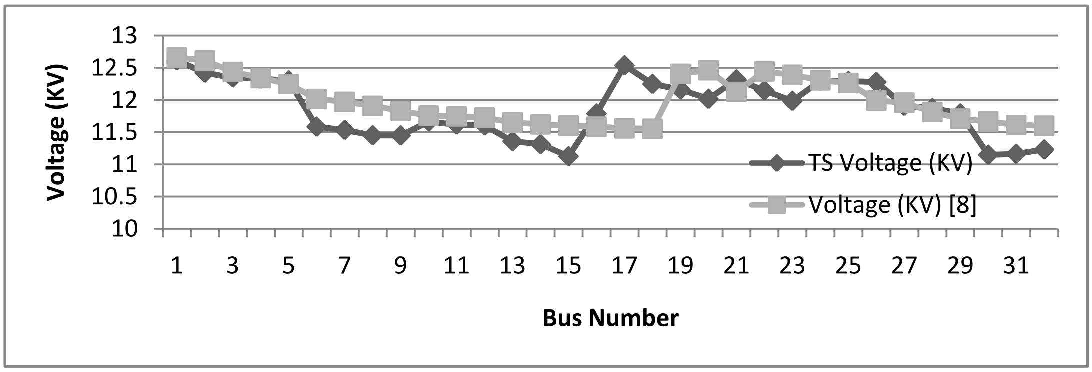

Fig. 5: Voltage Comparison of TS Configuration and Other [8]

Figure 6. compares the results obtained for TS configuration and that given in the [8] are considered. It is concluded from the results that voltages at the buses in case of TS configuration is better than that in the [8] for the majority of buses. Few buses have lower voltages than that in [8]. It was also recorded that the voltage deviation value (VDI) improves from 0.0498 to 0.0253, and thereby improve the voltage and power quality.The capacity margin of feeders and transformer is taken as service reliability to specify the security of the distribution system as shown in Table 2.

The proposed algorithm also tries to minimize the number of tie-switches operations, but here, the branch having the lowest current has to be opened, eliminating one of the network loop. So, 6, 11, 14, 28, 31 switches were deleted and the tie lines of network now become the branch of the system.

In order to quantify the maximum loadability of the RDS, the total additional load that may be drawn from the RDS before it suffers a collapse is determined. This additional load is referred to as maximum loadability and is increased while retaining the existing power factor of the loads and load distribution in the RDS. In the original configuration case, maximum loadability value is 10368.10 KVA. After reconfiguration using TS approach, the maximum loadability value is increased to 16583.57 KVA.

The results obtained as shown above by the TS reconfiguration are very satisfying which encourage further research work with more multiobjective functions. The proposed work is to be carried out with the evolution of Tabu Search method, which is best for finding out such multiobjective solution as compared to other heuristic methods in respect to research space. Thus it may be concluded that the TS approach can be used to get the optimum configuration of any test system for the multi-objective purpose for electric power distribution system.

5. CONCLUSION

This paper proposes the TS as meta-heuristic method for network reconfiguration multi-objective problems in radial distribution system. This work investigates six objectives that are: minimizing power losses, ensuring voltage quality, service reliability assurance, minimizing switches operation, lesser solution time, and maximum loadability for distribution system. The proposed methods has compared modern heuristic algorithms genetic algorithm, simulation annealing and tabu search, for network reconfiguration. This work has been tested on 33-bus RDS with five tie lines.

Particularly nice feature of TS is that, like all approaches based on Local Search, it can quite easily handle the “dirty” complicating constraints that are typically found in real-life applications. It is thus, a really practical approach. It is not, however, a panacea: every reviewer or editor of a scientific journal has seen more than his/her share of failed TS heuristics. These failures stem from two major causes: an insufficient understanding of fundamental concepts of the method but also, more often than not, a crippling lack of understanding of the problem at hand. One cannot develop a good TS heuristic for a problem that he/she does not know well! This is because significant problem knowledge is absolutely required to perform the most basic steps of the development of any TS procedure, namely the choice of a search space and of an effective neighborhood structure. If the search space and/or the neighborhood structure are inadequate, no amount of TS expertise will be sufficient to save the day. All meta-heuristics need to achieve both depth and breadth in their searching process; depth is usually not a problem for TS, which is quite aggressive in this respect (TS heuristics generally find pretty good solutions very early in the search), but breadth can be a critical issue. To handle this, it is extremely important to develop an effective diversification scheme. So, a properly designed distribution system alone can render efficient and fault-free service to the consumers and at the same time reduce distribution losses to the minimum economically optimum level.

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