Abstract—This paper presents an efficient algorithm for optimization of radial distribution systems by a network reconfiguration to balance feeder loads and eliminate overload conditions. The load-balancing index is used to determine the loading conditions of the system and maximum system loading capacity. The index value has to be minimum in the optimal network reconfiguration of load balancing. A method based on Tabu search algorithm, The Tabu search algorithm is employed to search for the optimal network reconfiguration. The basic idea behind the search is a move from a current solution to its neighborhood by effectively utilizing a memory to provide an efficient search for optimality. It presents low computational effort and is able to find good quality configurations. Simulation results for a radial 69-bus system with distributed generations and capacitors placement. The study results show that the optimal on/off patterns of the switches can be identified to give the best network reconfiguration involving balancing of feeder loads while respecting all the constraints.

Keywords—Network reconfiguration, Distributed generation Capacitor placement, Load balancing, Optimization technique

I. INTRODUCTION

THE electric power distribution systems consist of group of interconnected radial circuits and have a number of constraints like radial configuration, all loads served, coordinated operation of over current protective devices, and voltage drop within limits etc. Each feeder in the distribution system has a different mixture of commercial, residential and industrial type loads, with daily load variations. There are several operational schemes in electrical distribution systems; one of them is “distribution network reconfiguration”. There are some normally closed and normally opened switches (sectionalizing and the switches) in a distribution feeder [1], [2].

Network reconfiguration is very important for operating the distribution system. Generally, power distribution network reconfiguration provides services to as many customers as possible following fault coding and during planned outage for maintenance purposes with system loss minimization and load Balancing of the network [3].

Network reconfiguration problem is a complex non-linear combinatorial problem due to non-differential status of switches and the normally open tie switches, determined to satisfy system requirement. From optimization point of view, the reconfiguration method have been used for loss reduction using different techniques on the other hand from service restoration point of view, the reconfiguration allows to relocate loads by using an appropriate sequence of switching operations with operating constraints taken into account [4].

Network reconfiguration of an electrical distribution system is an operation to alter the topological structure of distribution system by changing status (open/closed) of sectionalizing and tie switches. By transferring loads from the heavily loaded feeders to the relatively lightly loaded feeders, the network reconfiguration can balance feeder loads and eliminate overload conditions [5]. The system load-balancing index (LBI) is used to determine the loading conditions of the system and maximum system loading capacity. The index value has to be minimum in the optimal network reconfiguration of load balancing.

For load balancing, the loads are required to be rescheduled more efficiently by modifying the radial structure of the distribution feeders. There are many existing methods for determining feeder configuration. A Neural Network based method with mapping capability to identify various network configurations corresponding to different load levels was proposed in [6]. An experts system using heuristic rules to shrink the search space for reducing the computation time was presented in [7]. Kashem et al. [8] proposed an algorithm called “distance measurement technique” (DMT) that found a loop first and then a switching operation was determined in that loop to improve load balancing. Aoki et al. [9] formulated the load balancing and service restoration problems by considering the capacity and voltage constraints as a mixed integer nonlinear optimization problem and converted the problem into a series of continuous quadratic programming sub problems. Baran and Wu [10] formulated the problem of loss minimization and load balancing as an integer programming problem. H. D. Chiang et al. [11] proposed a constrained multi objective and non differentiable optimization problem with equality and inequality constraints for both loss reduction and load balancing. G. Peponis et al. [12] developed an improved switch-exchange method for load balancing problem, using switch exchange operations. Mukwanga [13] proposed a new load-balancing index and applied it to the network for load balancing. In [14] presented a new load balancing and unbalanced algorithm in distribution system for loss reduction.
Increasing trend of load growth in distribution systems and
the necessity for constructing new power plants as its
consequence, tendency toward applying clean energies and
independence from fossil fuels, have caused distributed
generation (DG) to draw attention to a great extent.
Distributed generation (DG) is small-scale power generation
that is usually connected to or embedded in the distribution
system.

The benefits of DG are numerous and the reasons for
implementing DGs are an energy efficiency or rational use of
energy, deregulation or competition policy, diversification of
energy sources, availability of modular generating plant, ease
of finding sites for smaller generators, shorter construction
times and lower capital costs of smaller plants and proximity
of the generation plant to heavy loads, which reduces
transmission costs [15]. Among advantages of DGs one can
mention improvement in power quality and reliability
and reduction of loss, meanwhile using DGs leads to complexity in
operation, control and protection of distribution systems [16].
Injection of DGs currents to a distribution network results in
losing radial configuration and consequently losing
the existing coordination among protection devices.

The application of shunt capacitors in distribution systems
has always been an important subject to distribution engineers.
The general capacitor placement problem consists of
determining the number, location, type, size and control
settings at different load levels of the capacitors to be
installed. Capacitors are widely installed in distribution
systems for reactive power compensation to improve the
efficiency of power distribution via power and energy loss
reduction, to improve service quality via voltage regulation
and to achieve deferral of construction, if possible, via system
capacity release [17]. Capacitor placement in distribution
feeder is the well known efficient method for improving
overall power delivery in an electric distribution system. The
power loss in distribution system is determined as function of
square of branch current which consists of real and reactive
component.

This paper emphasizes the advantage of network
reconfiguration to the distribution system in the presence of
DG units and capacitors placement for load balancing and bus
voltage improvement. The application of Tabu Search is
applied to determine the optimal on/off patterns of the
switches to minimize the load balancing index subject to
system constraints. The effectiveness of the methodology is
demonstrated by a practical distribution system consisting of
69 buses.

II. POWER FLOW EQUATIONS

Power flow in a radial distribution network can be
described by a set of recursive equations called dist flow
branch equations that use the real power, reactive power and
voltage at the sending end of a branch to express the same
quantities at the receiving end of the branch [3]. Considering
the single-line diagram depicted in Fig. 1

III. TABU SEARCH

A. Background

Tabu search is a meta-heuristic that guides a local heuristic
search strategy to explore the solution space beyond local
optimality. Tabu search was developed by Glover and has
been used to solve a wide range of hard optimization
problems, such as resource planning, telecommunications,
financial analysis, scheduling, space planning, and energy
distribution [18].

The basic idea behind the search is a move from a current
solution to its neighborhood 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 are 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 [19].
The quality of a move in solution space is assessed by aspiration criteria that provide a mechanism for overriding the Tabu list shown in Figure 2. Aspiration criteria are analogous to a fitness function of the genetic algorithm and the Boltzmann function in the simulated annealing.

B. Neighborhood

In the search process, a move to the best solution in the neighborhood, although its quality is worse than the current solution, is allowed. This strategy helps escape from local optimal and explore wider in the search space. A Tabu list includes recently selected solutions that are forbidden to prevent cycling. If the move is present in the Tabu list, it is accepted only if it has a better aspiration level than the minimal level so far. Fig. 3 [20] shows the main concept of a search direction in Tabu search.

IV. PROBLEM FORMULATION

Loading balance index (LBI) represents the degree of loading among feeders. The objective of this optimization problem can be expressed by the minimization of the load balancing index (LBI) as in equation (5) [12]:

\[ \text{Min LBI} = \sum_{k \in B} \left( \frac{I_{k,t}}{I_{k,\text{max}}} \right)^2 \]  

(5)

where

- \( B \) = set of network branches forming loops
- \( I_k \) = length of branch \( k \)
- \( I_{k,t} \) = current capability of branch \( k \) for feeder reconfiguration pattern \( t \)
- \( I_{k,\text{max}} \) = maximum current capability of branch \( k \)

The objective function in (5) is subject to the following constraints.

1) Power flow equations.
2) The voltage magnitude at each bus must be maintained within its limits expressed as follows:

\[ V_{\text{min}} \leq |V_i| \leq V_{\text{max}} \]  

(6)

3) Feeder capability limits:

\[ |I_k| \leq I_{k,\text{max}} : k \in \{1, 2, 3, \ldots l\} \]  

(7)

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

where \( V_i \) = voltage at bus \( i \)
\( V_{\text{min}}, V_{\text{max}} \) = minimum and maximum voltage
\( I_k \) = current flow in branch \( k \)
\( I_{k,\text{max}} \) = maximum current capability of branch \( k \)

A flowchart for solving the problem is shown in Figure 4.

V. CASE STUDY

The test system for the case study is a 12.66 kV radial distribution system with 69 buses, 7 laterals and 5 tie-lines (looping branches), with distributed generation and capacitor placements as shown in Figure 5. 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. Each branch in the system has a sectionalizing switch for reconfiguration purpose. The load data are given in appendix Table AI and branch data in Table AII [21].

DGs are 4 small power producers who can provide only firm active power to the system by their DG units. The producers are located at buses 14, 35, 36, and 53 with capacities of 300, 200, 100, and 400 kW, respectively.

Capacitor located at buses 24, 45, 49, and 61 with capacities of 100, 200, 300, and 400 kVAR, respectively.

The test results for the five cases are summarized in Table II and Table III. In case 1, the system power loss and the LBI are highest, and the minimum bus voltage in the system violates the lower limit of 0.95 p.u. It is confirmed from case 3 that the distributed generation help reduce the system loss from 224.68 kW to 84.38 kW. The minimum load balancing index (LBI) is 1.442 and power loss is 77.604 kW seen in case 5, where there are changes in branch currents after the reconfiguration. In cases 2 and 5, all bus voltages satisfy the 0.95 p.u-voltage constraint.

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. The total loads for this test system are 3,801.89 kW and 2,694.10 kVAR. The feeder configuration algorithm, based on Tabu search is used to search the most appropriate topology of the system. The minimum and maximum voltages are set at 0.95 and 1.05 p.u. The maximum iteration for the Tabu search algorithm is 100.

The five cases are examined for network reconfiguration for load balancing in distribution system with distributed generation and capacitor placement in Table I.

### Table I

<table>
<thead>
<tr>
<th>Case</th>
<th>Network Reconfiguration</th>
<th>DGs Placement</th>
<th>Capacitor Placement</th>
</tr>
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<tr>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
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<td>-</td>
</tr>
<tr>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
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<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
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<td>✓</td>
<td>✓</td>
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</tbody>
</table>

### Table II

**RESULTS FOR CASE STUDY 1, 2 AND 3**

<table>
<thead>
<tr>
<th>Case</th>
<th>Load balancing index (LBI)</th>
<th>Minimum voltage (p.u.)</th>
<th>Total power loss (kW)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.796</td>
<td>0.956</td>
<td>224.68</td>
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<td>2</td>
<td>1.442</td>
<td>0.955</td>
<td>77.604</td>
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<tr>
<td>3</td>
<td>1.340</td>
<td>0.956</td>
<td>84.38</td>
</tr>
<tr>
<td>4</td>
<td>1.340</td>
<td>0.956</td>
<td>84.38</td>
</tr>
<tr>
<td>5</td>
<td>1.340</td>
<td>0.956</td>
<td>84.38</td>
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</table>

**RESULTS FOR CASE STUDY 4 AND 5**

<table>
<thead>
<tr>
<th>Case</th>
<th>Load balancing index (LBI)</th>
<th>Minimum voltage (p.u.)</th>
<th>Total power loss (kW)</th>
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<tr>
<td>4</td>
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<td>77.604</td>
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### Table III

<table>
<thead>
<tr>
<th>Case</th>
<th>Substation Placement</th>
<th>Tie switches to be closed</th>
<th>Sectionalizing switches to be open</th>
<th>Total power loss (kW)</th>
<th>Minimum voltage (p.u.)</th>
<th>Load balancing index (LBI)</th>
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</thead>
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<tr>
<td>1</td>
<td>C1= 100 kVAR</td>
<td>14, 20, 52, 61</td>
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<td>108.94</td>
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<td>2</td>
<td>C2= 200 kVAR</td>
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<td>C3= 300 kVAR</td>
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<td>70, 71, 72, 73</td>
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<td>0.955</td>
<td>1.340</td>
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<tr>
<td>4</td>
<td>C4= 400 kVAR</td>
<td>70, 71, 72, 73</td>
<td>70, 71, 72, 73</td>
<td>84.38</td>
<td>0.955</td>
<td>1.340</td>
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<tr>
<td>5</td>
<td>C4= 400 kVAR</td>
<td>70, 71, 72, 73</td>
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<td>84.38</td>
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### Appendix I

**LOAD DATA OF 69-BUS DISTRIBUTION SYSTEM**

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>$P_{L}$ (kW)</th>
<th>$Q_{L}$ (kVAR)</th>
<th>Bus Number</th>
<th>$P_{L}$ (kW)</th>
<th>$Q_{L}$ (kVAR)</th>
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<td>37</td>
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<td>24.00</td>
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<td>8</td>
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<td>54.00</td>
<td>40</td>
<td>24.00</td>
<td>17.00</td>
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<tr>
<td>10</td>
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<td>19.00</td>
<td>43</td>
<td>6.00</td>
<td>4.30</td>
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<tr>
<td>11</td>
<td>145.00</td>
<td>104.00</td>
<td>45</td>
<td>39.22</td>
<td>26.30</td>
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</tbody>
</table>

### VI. Conclusion

In this paper, an efficient joint strategy for network reconfiguration in distribution systems with distributed generation and capacitor placements. The application of Tabu Search is applied to determine the optimal on/off patterns of the switches to minimize the load balancing index subject to system constraints. Load balancing are important complement to network and feeder reconfiguration. Test results indicate that the method can identify the most effective network reconfiguration for improvement in load balancing. It is found that the optimal or near optimal configuration for load balancing also loss reduction and improves the voltage profile of the network while satisfying all the constraints. Simulations for a test system as well as a realistic system demonstrated the potential of use of the proposed technique that can be an useful tool for distribution systems planning and operation.
### APPENDIX II (Continued)

<table>
<thead>
<tr>
<th>Branch Number</th>
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<th>X (Ω)</th>
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<td>49</td>
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<td>8</td>
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<td>0.0473</td>
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### APPENDIX II (Continued)

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Thong Lantharthong received his M.Eng in Electrical Engineering from Rajamangala University of Technology Thanyaburi, Thailand in 2010. He is currently a lecturer at the Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Phra Nakhon (RMUTP), Bangkok, Thailand. His research interests include, power system planning, optimization technique, and renewable energy.

Nattachote Rugthaicharoencheep (M’10) received his Ph.D. in Electrical Engineering from King Mongkut’s University of Technology North Bangkok (KMITNB), Thailand in 2010. He is currently a lecturer at the Department of Electrical Engineering, Faculty of Engineering Rajamangala University of Technology Phra Nakhon (RMUTP), Bangkok, Thailand. His research interests include power system operation, optimization technique, and distributed generation.