A comparison of two heuristic approaches for distribution feeder switching contingencies

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In this paper, a comprehensive comparison of two distinct heuristic search approaches to solve the distribution switching problem is presented. One approach is based on a priority list of switches of the main search path defined by the feeder tie switch upstream to the substation. The other approach uses evaluation functions to address the problem. Evaluation functions are defined based on feeder layout, load level, and abnormal condition of the system to guide the searching process. A practical distribution system is used to test these two approaches. Items discussed include computing time, number of switching operations, and indices for feeder load balancing, transformer load balancing, and three-phase current balancing of their solutions. Results indicate that the priority list approach exhibits very high efficiency and solutions are fairly reliable. The evaluation function approach is more likely to find a solution with a minimum number of switching operations. Furthermore, the evaluation function approach is more robust in the case of serious contingencies.

Keywords: heuristic search, inter-feeder switching operations, feeder load transfer, service restoration, phase current over-unbalance

I. Introduction
Main transformers, distribution feeders, distribution transformers, and customers constitute the main components of a distribution system. Main transformers play the role of power source in the distribution system. Distribution feeders constitute the skeleton of a distribution system for delivery of electric power to customers. Each main transformer usually provides electricity to several feeders and each feeder may include several normally closed switches or sectionalizing switches. There are also normally open switches or tie switches between feeders to allow load backup and power loss improvement. By changing the status of feeder switches, the distribution feeder configuration will be altered and the resulting line flow, bus voltage, and losses will be changed. Therefore, feeder reconfiguration has been exploited to solve system problems, such as overload of distribution feeders or main transformers.

Load profiles in a distribution feeder vary with time of day, week and season and also with the majority load types. For example in the Taipower Company (TPC), the peak loading usually occurs in summer at about 10 p.m. for residential load. Feeder loading may exceed its rated thermal capacity during such a heavily loaded period. In this case, some load of the abnormal feeder must be transferred to a nearby feeder or else load will be shed.

A main transformer usually serves several distribution feeders. A main transformer overloading problem may occur during a heavy loading period with or without feeder overload problems. To alleviate the loading of the main transformer, switching operations are also performed to transfer feeder loading to adjacent main transformers.

In distribution systems with open-phase distribution transformers used for three-phase power supply, feeder currents among the three phases are unbalanced. In the TPC distribution system, a large number of transformers...
are open-delta/open-Y connections. Thus unbalanced flows are a significant concern. This will result in a variety of problems. Particularly troublesome is that the over-unbalance cases will result in a large grounding current which may trip the circuit breaker through the grounding relay in a three-phase four-wire distribution system. In the phase current over-unbalance problem, load can be transferred from the abnormal feeder to the adjacent feeder, or from the adjacent feeder to the abnormal feeder depending on the nature of the imbalance.

When a fault occurs in a distribution system, switching operations can be applied to restore electricity for the unfaulted but out-of-service area after the faulted region has been isolated from the system. In the case of system maintenance, switching operations are used to reduce the out-of-service area. Therefore feeder switching is clearly an important aspect of the distribution operation.

Owing to the discrete load transfer and radial structure of distribution feeders, switching operation problems are essentially combinatorial. It is very difficult to derive a strictly mathematical approach to solve the switching operation problem. From the system operational point of view, a switching solution with reasonable efficiency and near-optimal performance is an adequate solution. Therefore heuristic search approaches are suitable for the switching problems.

There have been several papers concerning the problem of reconfiguration of distribution systems from the heuristic or expert system point of view. In order to aid the system operators in restoring customers through tie switches when a fault occurs on a feeder, Reference 2 described an application of an expert system to the restoration of distribution by group restoration, zone restoration, and/or load transfer. In Reference 3, a heuristic search approach based on a binary decision tree is proposed, and a heuristic search strategy to handle feeder reconfiguration for overloads, voltage problems, and load balancing simultaneously has been proposed in Reference 4.

In this paper, two heuristic approaches are compared from both qualitative and quantitative perspectives. A practical Taipower distribution system is used for the numerical test. Items discussed include the switching options solved, the computing time used, and the indices of switching performance. Performance indices are defined to indicate the unbalance degree of loading among feeders, main transformers, and the three-phase currents of feeders.

II. Problem formulation and feasible switching options

The goal of a feeder switching algorithm is to improve the reliability and efficiency of the power service for the distribution system. Theoretically, a distribution system with n switches would have 2^n states. This number is so large even in a moderate-sized distribution system that it is quite impractical to find the feasible switching options by searching the 2^n states. However, the allowable states under the radial constraint will be smaller and the search space will be reduced significantly. The present system configuration is one of the system states which not only fits the constraint of radial structure but also has the characteristic of being close to better solutions of the problem. Therefore, searching for a solution from the current state under the constraint of radial structure is obviously more appropriate. The actual number of switching possibilities under the radial constraint is difficult to express as it is dependent upon the feeder layout, the switch positions, and the loading through each switch.

To maintain feeder radial structure, switching operations can be performed by closing one tie switch and opening one complementary sectionalizing switch. Consider the sample distribution system shown in Figure 1. If load is to be transferred from Feeder no. 1 to Feeder no. 2, a switching pair can be selected as closing T2 and opening S3, hereafter expressed as (T2, S3). Other switching options can be (T2, S2) and (T2, S1). Also, if load is to be transferred from Feeder no. 1 to Feeders no. 2 and no. 3, then switching pairs [(T1, S6), (T2, S3)] and [(T1, S1), (T2, S2)] are feasible options. However, switching pairs [(T1, S2), (T2, S3)] are not feasible because Feeders no. 1 and no. 3 would lose their radial structure.

Determination of a solution for the switching reconfiguration problem involves a search through the feeder layout. For simplicity of discussion, some terminology is defined below:

- Abnormal feeder: a feeder with loading greater than its rated capacity or phase unbalance tolerance.
- Receiving feeder: a feeder to which additional load is added by transfer from its adjacent feeders.
- Exporting feeder: a feeder from which some load is transferred to its adjacent feeders.
- Solution feeder: a feeder which is used for either receiving or exporting load to normalize the abnormal feeder.
- Solution tie switch set: the set of tie switches which are connected between the abnormal feeder and the solution feeders.
- Residual capacity: the margin of the solution feeder (or main transformer) between its rating and the present loading.

For overloads of main transformers or feeders, some load must be transferred from the abnormal feeder/main transformer to their adjacent feeders; the solution feeders are the receiving feeders. In phase current over-unbalance cases, load may be transferred from the abnormal feeder to its adjacent feeders or from the adjacent feeders to the abnormal feeder. In this case, a solution feeder can be a receiving feeder or an exporting feeder.

Owing to the constraint of the radial structure in the load transfer process, the switch options will be determined by closing one tie switch and opening a complementary normally closed sectionalizing switch. Therefore an abnormal feeder with n tie switches has at most n solution feeders. Consider the system of Figure 1, if Feeder no. 1 is overloaded then Feeders no. 2, no. 3, and

![Figure 1. Sample distribution system: ](image)

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no. 4 are the solution feeders with tie switches T1, T2, and T3 respectively.

For each tie switch of the abnormal feeder, a main search path is defined by starting from the tie switch, and moving upstream along the abnormal feeder to its source, the circuit breaker of the feeder. Because the radial structure must be maintained, the switching actions can be obtained by combinations of the tie switch and one of the normally closed sectionalizing switches at various points of the main search path. In the simplest case, load transfer of a single switching pair can solve the problem, whereas in a more complex problem, several switching pairs must be appropriately selected. To illustrate this idea better, again consider the system in Figure 1. There are three main search paths as shown in Figure 2. It is obvious that a single switching pair can be found from these main search paths. For instance, by the first main search path, tie switch T1 and either sectionalizing switch S6, S7, or S1 constitute a switching pair. In other cases, switching pairs [(T1, S7), (T2, S2), (T3, S4)] may be required. However, switching pairs [(T2, S2), (T3, S1)] must not be selected due to the loss of radial structure.

Based on the main search path defined above, a systematic search approach under the radial feeder constraint is proposed. Figure 3 shows a switching level diagram determined by the number of tie switches involved. Level 1 represents a switching operation by one switching pair, level 2, two switching pairs in conjunction, and so on. There are eight nodes in Figure 3. Each node represents a class of operations. The root node represents the no-switching action case. Each node in the level tree can be expanded into a subtree consisting of switching options at that level. To expand the tree, choose the first level tie switch, and determine the feasible switching operations as above. Repeat for the remaining tie switches at that level. For deeper levels, several switching pairs are selected simultaneously. Expand the tree based on the previous level. Determine the switching possibilities by only selecting switches which are not located in the main search path of higher levels in the tree. This ensures the radial constraint is satisfied.

Figures 4–6 show the expanded tree from the nodes of Figure 3. Each node in these figures represents one switching option. Figures 4(a), (b), and (c) show the first-level expanded tree for T1, T2, and T3, respectively. From these figures, it is shown that there are ten feasible options of single switching pairs in the simple system under the constraint of radial structure. Figures 4(a), (b), and (c) indicate the second level expanded trees for the solution tie switch set [T1, T2], [T2, T3], and [T3, T1], respectively. Similarly, there is only one expanded tree shown in Figure 6 representing the feasible switching options involving T1, T2, and T3 simultaneously. In this sample system, there are 10, 27, and 21 options in first-, second-, and third-level trees, respectively. The total switching options are 58 which represent all the feasible switching options for releasing load of the abnormal Feeder no. 1 to its neighbouring feeders under the constraint of radial feeder structure.

Although the number of switching options is greatly reduced by the radial constraint, it will still be very time-consuming to consider all solutions if the number of tie switches and sectionalizers is large. This is particularly true if a feasible solution cannot be found.
within the solution space of load transfer between the abnormal feeder and its closest neighbouring feeders.

### III. The priority list approach

In this section, a direct search method is presented to determine proper switching pairs. Heuristic rules are proposed to determine switching options with a process similar to that of field dispatchers. In this approach, only the most important factors of the corresponding problems are evaluated so that overall efficiency can be dramatically improved. Problems solved by this approach include feeder overloading, main transformer overloading, phase current overloading, and load restoration.

Feeder overloading is the fundamental case of switching problems; it is discussed first in this section. The abnormal feeder and the solution feeder are the major components to consider. If several feeders are overloaded simultaneously, the most apparent characteristics of the overall overload problem are the most seriously overloaded feeder and the neighbouring feeder with the largest residual capacity. Therefore the most serious abnormal feeder is considered in the solution process first and the neighbouring feeder with the largest residual capacity will be used to accept the overloading of this abnormal feeder. Furthermore, any load transfer should not give rise to any new problems. Therefore the maximum acceptable load of the solution feeder is the smaller quantity of the residual capacity of the solution feeder or the load margin of the associated main transformer. Once a solution is found then deeper search is performed along the same main search path to find other solutions with better performance. If the problem cannot be solved completely after load transfer to the neighbouring feeders of the abnormal feeder, further load transfer is considered by transferring load of the neighbouring feeder to its adjacent feeders. If no acceptable switch actions can be found, load shedding should be performed by tripping the smallest load of the abnormal feeder.

For main transformer overloading, load of the abnormal transformer should be transferred to the other main transformers. The heaviest-loaded feeder of the abnormal main transformer will be selected to perform the load transfer. Since the number of switching actions is of great concern, to minimize the number of switching actions the amount of load transferred from the heaviest-loaded feeder is, if possible, matched to the amount of the overloading of the abnormal transformer. Again, the criterion during load transfer is that the candidate switching operation must not give rise to any new problems. Load transfer from another feeder should be performed if the problem cannot be solved from the previous load transfer. Similar to the approach for feeder overloading, if the problem cannot be solved by load transfer from the feeder of the abnormal transformer, load transfer from the neighbouring feeder to the outer neighbouring feeder/main transformer should be considered. Load shedding is also to be considered in the case of very serious problems.

The problem of phase current over-unbalance in a distribution feeder is generally very challenging. The factors influencing the phase current unbalance depend upon the arrangement of single/two-phase distribution transformers along the feeder and the load level of each load area. Each switch of the abnormal feeder along each main search path is evaluated to find a proper solution. Furthermore, switching options with load transfer from the solution feeder to the abnormal feeder are assessed if the solution cannot be found by the previous judgement. As in the above, causing new problems is always to be avoided.

Faults on the distribution system are the most important concern in the switching problem. After fault identification and fault area isolation, service restoration is performed by the inter-feeder switching operations. In this approach, the upstream area of the faulted area is restored by reclosing the circuit breaker of the abnormal feeder and the downstream area is pre-restored by selecting the solution with the largest residual capacity of feeder/main transformer. Thereafter, the service restoration problem is converted to the problems of feeder/main transformer overload or phase current over-unbalance problems.

### IV. The evaluation function approach

In this approach, search paths and switching options are determined based on the cost calculated by evaluation functions. Since the system solution depends closely upon the feeder configuration, position of each switch, and loading through each switch, the proposed evaluation functions are based on the following:

- loading condition of the abnormal and solution feeders;
- loading condition of the main transformer of the abnormal and solution feeders;
- number of switches in the main search path of the abnormal feeder and their neighbouring feeders;
- number of tie switches of the solution feeders.

The following information is considered to prioritize the search among switch options:

- solution feeders with larger feeder residual capacity and larger main transformer residual capacity;
- main search paths with more switches in the exporting feeder;
- neighbouring feeder with the highest number of tie switches;
- combined effect of the above three aspects;
- higher-level switching options in the level tree;
- most serious violation;
- switching options with minimum evaluation cost.

#### IV.1 A proposed evaluation function

The evaluation function is designed to estimate the effect of switching operations. Before a switching pair is operated to transfer load from a candidate feeder to a neighbouring feeder, the effect on both feeders and main transformer(s) must be evaluated. Two kinds of evaluation function are catalogued in this approach. The first is to determine the solution tie switch set before the search process on the main search paths. The second is to differentiate between feasible switch options in the main search path. As a reference for the heuristic rules, the evaluation function will not only reduce the search space but guide solutions toward a reasonable switching solution.

#### IV.1.1 Selection of the candidate tie switches

If every tie switch in the candidate feeder is taken into consideration for the load transfer, the resulting search will be too
involved. In this approach, an evaluation function is
defined to determine a candidate feeder to perform the
load transfer.
In the case of main transformer overloading, the
evaluation function is defined to select a candidate feeder
to proceed the load transfer and is determined based on
two factors: the feeder load level of the abnormal
transformer, and the number of switches on the candidate
feeder.
The evaluation function is expressed as:

\[
\text{Cost} = (I_{ta,\max} - 0.8*I_{ta,d}) + K*N_{sw}
\]  

(1)

where \(I_{ta,\max}\) is the maximum component of the
candidate feeder current, \(I_{ta,d}\) is the rated current of the candidate
feeder, \(N_{sw}\) is the number of switches in the candidate
feeder, and \(K\) is a weighting factor.

To release the loading of an abnormal feeder, the solution
tie switch set is determined by the following factors:
- number of switches in the main search path;
- residual capacity of the solution feeder;
- residual capacity of the main transformer of the
  solution feeder;
- number of tie switches in the solution feeder.

The evaluation function is:

\[
\text{Cost} = ((R_{rt,d} + R_{rt,f})/2 + K*N_{tie}) - I_{ta} + L*L
\]

(2)

where \(R_{rt}\) is the residual capacity of the solution feeder,
\(R_{rt,d}\) is the residual capacity of the main transformer of the
solution feeder, \(K\) is a weighting factor, \(N_{tie}\) is the number of tie switches of the solution feeder, \(I_{ta}\) is the
amount of overloading in the abnormal feeder, and \(L\) is the
number of switches in the candidate main search path.

In the case of faults, after the faulted area is isolated
from the healthy system, the unfa ulted but out-of-service
areas are pre-restored through the tie switch which is
connected with the neighbouring feeders. This receiving
feeder is determined by the smaller quantity of the
residual capacity of the receiving feeders or the associated
main transformer. The evaluation function can be
expressed as:

\[
\text{Cost} = \min (R_{ta,d}, R_{ta,f})
\]

(3)

IV.1.2 Determination of switching pairs. In the second
category of evaluation function, the switching options of load transfer on the receiving side and the exporting side
are evaluated separately. System constraints on feeder thermal
capacity, main transformer capacity and phase
current unbalance limitation are individually considered.
All the evaluation functions are defined with similar
formulæ. For example, in feeder overloading, the
receiving feeder cost is:

\[
C_{tr,f} = \begin{cases} 
I_{ta,f} & \text{for } I_{ta,f} \leq R_{ta,f} \\
R_{ta,f} - (I_{ta,f} - R_{ta,f}) \star W_{tr,f} & \text{for } R_{ta,f} < I_{ta,f}
\end{cases}
\]

(4)

where \(I_{ta,f}\) is the maximal value of \(I_{ta} + I_{ta,f}, I_{ta} + I_{ta,f}\), and \(I_{ta} + I_{ta,r}\) \(R_{ta,f}\) is the current rating of the receiving feeder,
\(I_{ta}, I_{ta,f}, I_{ta,r}\) and \(I_{ta,f}\) are the phase current at the circuit breaker
of the solution feeder, \(I_{ta}, I_{ta,f}, I_{ta,r}\) are the phase current
at the candidate switch, and \(W_{tr,f}\) is a weighting factor
to reflect the seriousness of the violation.

For each switching option, the evaluation function
should include the effects of feeder loading, main
transformer loading and the degree of phase current
unbalance simultaneously. The overall switching cost is
calculated by:

\[
C = K_1 \cdot C_{tr,t} + K_2 \cdot C_{tr,e} + K_3 \cdot C_{tr,u}
\]

(5)

where \(C_{tr,t}, C_{tr,e},\) and \(C_{tr,u}\) represent the receiving cost of the
candidate feeder, main transformer, and the
three-phase unbalance; \(C_{tr,e}, C_{tr,u},\) and \(C_{tr,u}\) are for the
exporting side. The constants \(K_1, K_2, K_3\) are the weighting factors which should be carefully determined by experience
and operation criteria of the distribution system.

V. Development

V.1 Implementation

To implement a system of heuristic or expert-type
approaches, rule-based programming languages such as
PROLOG and OPS5 are often more appropriate than
general procedural languages. In this paper, both
approaches are implemented in PROLOG. The list
structure and recursive strategies of PROLOG are
particularly suitable for AI programming. However,
recursion should be properly controlled with 'cut', 'fail'
and 'tail-recursive' techniques to improve the computa-
tional and storage efficiency. Further discussion of
these techniques is beyond the scope of this paper.

V.2 Performance indices of switching operations

Switching operations problems are discrete and may have
multiple solutions. Several sets of switching options can
satisfy the requirement of the system constraints. However,
the performance of the solution should be evaluated. In
this study, three indices for load balance among feeders,
main transformer, and three phase currents are proposed
to evaluate the performance of the heuristic search
method.

The main transformer load unbalance index is defined
as the average deviation of feeder loading from the
reference load level which is defined as the relative value
of the system actual loading to the system total rated
capacity and expressed as:

\[
PI_{ta} = \sum_{I} \frac{|I_{ta,I} - |I_{ta,I}|/N_{ta}}{I_{ta}} * 100\%
\]

(6)

where \(PI_{ta}\) is the main transformer load unbalance index,
\(I_{ta}\) is the actual transformer loading, \(I_{ta}\) is the
actual system total loading, \(I_{ta}^*\) is rated capacity of the main
transformer, \(I_{ta,\max}\) is the total rated main transformer
capacity of the system, and \(N_{ta}\) is the number of main
transformers in the distribution system.

Similarly, the system feeder load unbalance index \(PI_{ta}\)

is defined as:

\[
PI_{ta} = \sum_{I} \frac{|I_{ta,I} - |I_{ta,I}|/N_{ta}}{I_{ta}} * 100\%
\]

(7)

where \(PI_{ta}\) is the feeder load unbalance index, \(N_{ta}\) is
number of feeders in the distribution system, \(I_{ta}\) is the
actual candidate feeder load level, \(I_{ta}\) is the rated capacity
of the feeder, and \(I_{ta}\) is the total feeder capacity of the
system.

The phase current unbalance index is defined as the
average zero-sequence current of the distribution system:

\[
PI_{ph} = \sum_{I} \left( \frac{(I_c - I_a)^2}{2} \right)^{1/2}/N_{ta} * 100\%
\]

(8)
VI. Comparisons

Since heuristic rules are usually used to solve problems of a combinatorial nature without a strictly mathematical model, it is very difficult to judge the performance of the search rules. As a result, comparison is performed in this section both qualitatively and quantitatively.

VI.1 Qualitative comparison

The following sections summarize characteristics of the two approaches.

VI.1.1 Priority list approach. Only the most dominant factors are involved in the search process. This approach evaluates each switching option for a single reason and further load transfer is not involved. Simple judgment is used and as a result should be very fast.

With intuitive search solutions, each switching option is evaluated with a single cause each time. If a switching option is not found to be useful, the reason can be listed directly.

Each individual switching operation is an improvement; for each switching option, any new problem is avoided as discussed above.

For further load transfer, if all the closely adjacent feeders cannot solve the problem associated with the candidate feeder, load transfer to the outer adjacent feeder is performed.

VI.1.2 Evaluation function approach. Several factors are involved for further load transfer: this helps to solve more serious problems.

Several factors are involved for each switching option: each switching option is evaluated by considering the composite effect of all factors.

Overall performance is better: the switching options with minimum cost are selected, and solutions will result in better system performance.

The approach is flexible: weighting factors involved in the evaluation function can be changed to adjust the importance of various factors.

Further load transfer is easily judged: if the minimum cost of the evaluated switching pair is greater than a specified value then the system problem hasn’t been solved yet, and further load transfer is considered.

VI.2 Quantitative comparison

In this section, a practical distribution system of Taipower is used for the comparison and discussions.

Figure 7. Partial Taipower distribution system
of the proposed heuristic approaches. The computing time, number of switching operations solved, and indices proposed for the practical system are listed.

A practical distribution system is selected to test the accuracy and performance of the proposed method. Figure 7 is the one-line diagram of a portion of the Kaohsiung City distribution system. There are 10 main transformers located at different substations, 31 feeders, 135 normally closed sectionalizing switches, 63 normally open tie switches and 165 zones. Each zone is defined as the continuous area bounded by sectionalizing switches and/or tie switches. The total system capacity is 193.75 MVA. There are five feeders loaded more than 80%, and only one feeder (no. 25) is loaded less than 50%. The average main transformer loading is 78%, and 58% of the main transformers are loaded more than 80%.

Tables 1–4 list the simulation results of the test system for both less and more serious fault cases. The more

<table>
<thead>
<tr>
<th>Fault zone</th>
<th>Restoration load (A)</th>
<th>Restoration switch</th>
<th>Switching-pair options</th>
<th>CPU time</th>
<th>Unbalance index</th>
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<td>DPI&lt;sub&gt;irf&lt;/sub&gt;</td>
</tr>
<tr>
<td>z43*</td>
<td>22</td>
<td>8L</td>
<td>(16F, 16D)</td>
<td>1.70</td>
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<tr>
<td>z57*</td>
<td>42</td>
<td>10F</td>
<td>(11I, 11E)</td>
<td>1.64</td>
<td>-0.41</td>
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<tr>
<td>z4</td>
<td>65</td>
<td>1H</td>
<td>(1E, 20E)</td>
<td>1.59</td>
<td>-0.13</td>
</tr>
<tr>
<td>z10</td>
<td>35</td>
<td>2L</td>
<td></td>
<td>1.42</td>
<td>-0.09</td>
</tr>
<tr>
<td>z35</td>
<td>70</td>
<td>7G</td>
<td></td>
<td>1.42</td>
<td>-0.52</td>
</tr>
<tr>
<td>z49</td>
<td>64</td>
<td>8H, 9K</td>
<td></td>
<td>1.48</td>
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<tr>
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<td>(9K, 112F), (11I, 11E)</td>
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<td>-0.09</td>
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<td>12E</td>
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<tr>
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<tr>
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<tr>
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<td>1E, 2F</td>
<td>(20C, 20A)</td>
<td>1.53</td>
<td>1.50</td>
</tr>
</tbody>
</table>

* Cases having different switching options from that of the evaluation function approach

<table>
<thead>
<tr>
<th>Fault zone</th>
<th>Restoration load (A)</th>
<th>Restoration switch</th>
<th>Switching-pair options</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DPI&lt;sub&gt;irf&lt;/sub&gt;</td>
</tr>
<tr>
<td>z1*</td>
<td>172</td>
<td>1C</td>
<td>(2D, 2B), (1H, 1G), (2I, 2C)</td>
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<td>157</td>
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<td>(17D, 17C)</td>
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<td>(6G, 6D)</td>
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<td>-0.23</td>
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<tr>
<td>z28*</td>
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<td>5G</td>
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<td>1.81</td>
<td>-0.43</td>
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<tr>
<td>z79*</td>
<td>215</td>
<td>15E</td>
<td>(15I, 15D), (15G, 15F)</td>
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<td>27D</td>
<td>(24K, 25E)</td>
<td>1.59</td>
<td>2.01</td>
</tr>
<tr>
<td>z151*</td>
<td>193</td>
<td>24J</td>
<td>(28C, 29B), (29D, 29C), (24D, 24C)</td>
<td>2.08</td>
<td>3.07</td>
</tr>
<tr>
<td>z8</td>
<td>122</td>
<td>2I</td>
<td></td>
<td>1.42</td>
<td>-0.11</td>
</tr>
<tr>
<td>z12</td>
<td>208</td>
<td>2D</td>
<td>(2I, 2C)</td>
<td>1.70</td>
<td>0.02</td>
</tr>
<tr>
<td>z13</td>
<td>129</td>
<td>3E, 2G, 2D</td>
<td>(4E, 4D)</td>
<td>1.59</td>
<td>0.26</td>
</tr>
<tr>
<td>z21</td>
<td>183</td>
<td>4C</td>
<td>(4E, 4B)</td>
<td>1.70</td>
<td>-0.30</td>
</tr>
<tr>
<td>z33</td>
<td>180</td>
<td>7E, 6C</td>
<td>(8K, 8G), (6G, 6E)</td>
<td>6.37</td>
<td>0.83</td>
</tr>
<tr>
<td>z40</td>
<td>137</td>
<td>8K</td>
<td></td>
<td>1.42</td>
<td>1.10</td>
</tr>
<tr>
<td>z46</td>
<td>207</td>
<td>8D</td>
<td>(8K, 8E)</td>
<td>2.30</td>
<td>3.94</td>
</tr>
<tr>
<td>z60</td>
<td>217</td>
<td>11I</td>
<td>(8K, 13B), (10D, 11F)</td>
<td>1.97</td>
<td>3.45</td>
</tr>
<tr>
<td>z68</td>
<td>187</td>
<td>12E</td>
<td>(8K, 13B)</td>
<td>1.53</td>
<td>1.80</td>
</tr>
<tr>
<td>z85</td>
<td>207</td>
<td>16F</td>
<td>(15G, 16B)</td>
<td>1.81</td>
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</tr>
<tr>
<td>z90</td>
<td>152</td>
<td>17D</td>
<td></td>
<td>1.48</td>
<td>0.25</td>
</tr>
<tr>
<td>z106</td>
<td>140</td>
<td>2H</td>
<td></td>
<td>1.42</td>
<td>2.55</td>
</tr>
<tr>
<td>z117</td>
<td>168</td>
<td>19F</td>
<td>(22F, 22C)</td>
<td>1.70</td>
<td>0.59</td>
</tr>
<tr>
<td>z126</td>
<td>205</td>
<td>22E</td>
<td>(19F, 22C)</td>
<td>1.81</td>
<td>2.00</td>
</tr>
<tr>
<td>z133</td>
<td>143</td>
<td>18C</td>
<td>(19C, 25C)</td>
<td>1.64</td>
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</tr>
<tr>
<td>z145</td>
<td>227</td>
<td>27D</td>
<td>(28C, 28D)</td>
<td>1.75</td>
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<tr>
<td>z147</td>
<td>133</td>
<td>27D</td>
<td></td>
<td>1.42</td>
<td>0.71</td>
</tr>
<tr>
<td>z156</td>
<td>217</td>
<td>30C, 29D</td>
<td></td>
<td>1.37</td>
<td>2.11</td>
</tr>
</tbody>
</table>

* Cases having different switching options from that of the evaluation function approach
serious faults are defined as those where the load to be restored is greater than 120 A which is about one-third of the average loading per feeder of the system. Notice that the seriousness of a fault depends on more than just the overload current; nevertheless this criterion has been used. In these tables, the first column represents the fault area. The second column indicates the loading of the tripped but out-of-service area. Columns 3 and 4 list the switches selected for the pre-restoration and switches solved for the service restoration. The fifth column shows the CPU time used. Columns 6 to 8 list the deviation of the proposed unbalance index for the main transformer unbalance index DPI_{lf}, feeder unbalance index DPI_{ld}, and phase current unbalance index DPI_{lp}, respectively. They are calculated from the performance indices of the system after the switching operation minus that of the original system.

From the tables, it is seen that both approaches solve the problem properly within a reasonable CPU time and most of the switching options selected are the same for the less serious fault cases. Since there are many DPI with negative values in these tables, the resulting system after switching operation maintains better balance performance than that of the original system. By comparing the tables, it is found that the CPU time used by the priority approach is smaller than that used by the evaluation function approach. This implies that the priority approach is in general faster than the evaluation approach. However, the evaluation approach may provide better performance because it searches in a more general search space. For example, from the tables, the number of switching operations by the evaluation function approach is less than that by the priority list approach when a fault occurs at zone z1 or zone z151.

VII. Discussion and conclusions
In this paper, a comprehensive comparison of two heuristic search approaches is performed. The priority list approach searches solutions in a more direct fashion. This approach exhibits high efficiency for less serious problems, and for most of the serious problems as well. The evaluation function approach considers more factors during the search and a more general solution space is considered. Thus it provides more reliable solutions for very serious problems. However, it is more time-consuming. It is constructive to develop a system which combines the merits of the approaches and avoids the individual drawbacks. For example, one could use the priority list approach for the first two switching options and then use the evaluation function approach to assess a better receiving feeder for further load transfer if the problem cannot be solved within two switching options.

VIII. References
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