경험적 탐색기법에 근거한 배전계통의 선로 재구성 알고리즘

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NETWORK RECONFIGURATION ALGORITHM FOR AUTOMATED DISTRIBUTION SYSTEM BASED ON THE BEST-FIRST TREE SEARCH

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ABSTRACT - This study develops an expert system which solves the problems of the MTr/feeder overloads and the feeder constraints in automated radial distribution systems. Then, the objective is to perform the network reconfiguration by switching the tie and sectionalizing switches which eliminates the system violation, while achieving the load balance of the MTrs/feeders.

To reduce the search space, an expert system based on heuristic rules is presented, and implemented in AI language Prolog. This system adopts the best-first tree search technique. The computational results are also prepared to show the performance of the heuristic algorithm developed.

1. INTRODUCTION

Some excessive phenomena of the operating states require the appropriate control strategies which can be performed either automatically or by the system operator at the distribution control center. Those strategies include service restoration [1], network reconfiguration [2,3], voltage/var optimization, transformer/feeder load balancing [4], loss reduction [5,6], load reallocation for a main transformer(MTr) fault [7], and other types simultaneously interconnected more than one of these strategies.

This paper develops an expert system to reconfigure the distribution network such that the constraints of the MTr/feeder are satisfied by transferring the load. To accomplish the network reconfiguration as one of the solution strategies, there are some constraints in the system to be considered.

For the most violated feeder whose load should be transferred, we select to change a normally-open tie switch to a closed state, while opening a sectionalizing switch installed on the interconnection point in order to maintain the radial tree structure. If the primary candidate set of MTrs/feeders which are directly connected through tie switches could not support the system violation, then the next candidate set should be considered.

The primary objective is to eliminate the MTr/feeder overload, and the violations of thermal and voltage constraints, by transferring the load from a MTr/feeder with the system problem. Then, heuristic rules are useful to find the quick and good enough practical solution. Furthermore, instead of using the full ac load flow solutions for the feeder reconfiguration, we will adopt the approximation approach (see [8]).

Secondly, it is to achieve the load balance among the MTr/feeder during the process of load transfer. When the load index of each feeder is approximately closed to the system load index, the load balance of a distribution system is achieved.

2. DESIGN OF EXPERT SYSTEM

The expert system for the network reconfiguration of automated distribution systems is structured as Figure 1, whose components are the knowledge base, the inference engine, and the user interface. The knowledge base composed of the dynamic database and the rule base is required by the inference engine during logical reasoning for the system reconfiguration. Network data in the rule base stores the network configuration data to represent the feeder connectivity, the characteristic of each system component, and the load data of the MTr/feeder, where MTr denotes the main transformer. And, the dynamic database stores both the load data searched from the network data and the new data generated from logical reasoning.

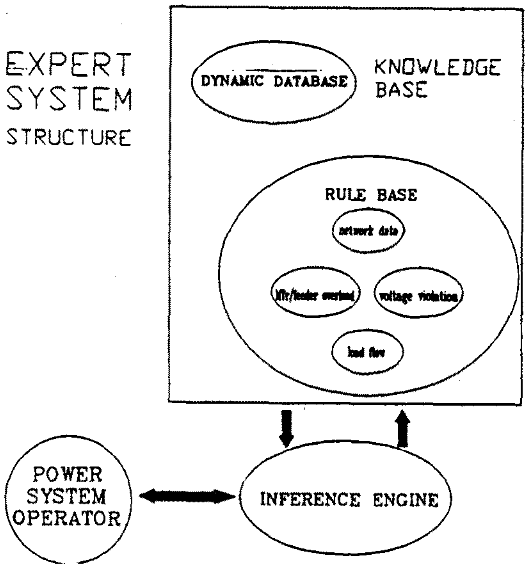

Fig. 1 Structure of Expert System for Network Reconfiguration

Rule base consists of the network reconfiguration rule to eliminate the MTr/feeder overload, and to provide the information about the operating tie/sectionalizing switches so that the system problem is cleared. However, we will consider only the voltage problem for the feeder constraints.

3. HEURISTIC SEARCH METHOD

To reduce the search space for the network reconfiguration, heuristics can be formulated as rules to select the branches which have more possibility as an acceptable solution. In this paper, the heuristic-guided best-first search method will be adopted. This procedure is continued until it reaches the optimum. However, this method does not always guarantee the optimal solution, although it provides at least the near-optimum which is a good enough practical solution.

The expert system developed here utilizes a heuristic algorithm to reconfigure the network so that the MTr/feeder overloads are relaxed and the violations of the feeder constraints are eliminated. The procedure of inference for the network reconfiguration of distribution systems with the MTr overload and the feeder constraint violation problems can be shown as Figure 2.

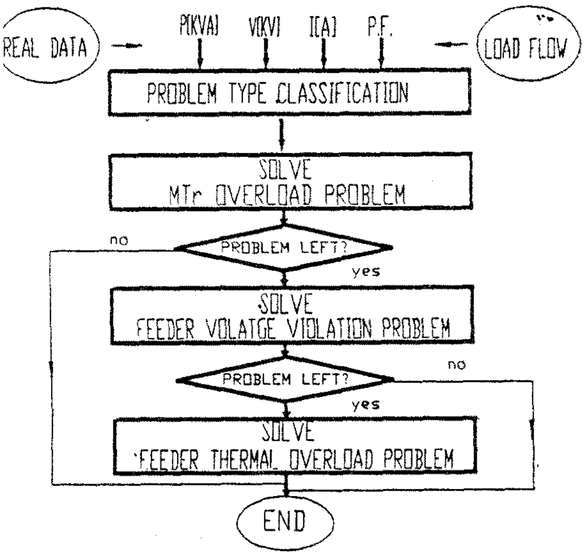

Fig. 2 Inference Procedure of Network Reconfiguration for Distribution System Violations

In the following subsections, we will present heuristic rules to solve the overload of MTr/feeder and the low voltage problem, respectively.

3.1 Relaxation of MTr/Feeder Overloads

First, heuristic rules to relax the MTr/feeder overloads will be defined to enhance the system performance, while achieving the load balancing among the MTr/feeder in a distribution system.

[Rule 1] Among the overloaded MTrs/feeders, remove the most overloaded one according to a decreasing sequence of the overloads, $(AL_i - NC_i)$, where AL_i and NC_i are the actual load and the normal capacity of MTr/feeder i, respectively.

[Rule 2] The primary candidate MTr/feeder set to be loaded for the overloaded MTr/feeder k, is composed of ones whose load indices are $(AL_i/NC_i) < 1$, and adjacent to MTr/feeder k. Then, assign the one with maximal load margin $(NC_i - AL_i)$ of the normal capacity in the primary candidate MTr/feeder set.

If the primary candidate set can support all the overload of the overloaded MTr/feeder, it should be satisfied that $LI_s \le 1$ where the load index of system for the set S, LI_s, is defined as : $LI_s = \sum_{j\in S} AL_j / \sum_{j\in S} NC_j)$, where S is composed of all the MTrs/feeders in the candidate set and the overloaded MTr/feeder. Otherwise, it requires to select some other supporting MTr/feeder set so that the overload can be cleared by the load transfer, that will be described in Rule 3.

To determine how much load should be transferred to the one with the maximum load margin, let us define that LI_j is the load index of MTr/feeder j such that $LI_j = AL_j/NC_j$. Since the secondary objective is to achieve the load balance, the load index of each candidate MTr/feeder has been pursued to reach the mean load index of the system, LI_s, so that its load index becomes $(LI_s \pm \varepsilon)$ for a nonnegative real value ε.

The overloaded amount of MTr/feeder k is $(AL_k - NC_k)$, and the acceptable load of a supporting MTr/feeder j is $(LI_s * NC_j - AL_j \pm \varepsilon)$. Therefore, the magnitude to be loaded at MTr/feeder j is the minimum of $(AL_k - NC_k)$ and $(LI_s * NC_j - AL_j \pm \varepsilon)$ for nonnegative ε. If $(AL_k - NC_k)$ is the minimum of $\{AL_k - NC_k, LI_s * NC_j - AL_j \pm \varepsilon\}$, then the overload of MTr/feeder k can be eliminated by transferring the load $(AL_k - NC_k)$ to MTr/feeder j.

Otherwise, transfer the load $(LI_s * NC_j - AL_j \pm \varepsilon)$ to MTr/feeder j, and select another supporting MTr/feeder whose load margin is the maximum in the remaining supporting set. Then, determine the load to be loaded and repeat the above process until the overload of MTr/feeder k is cleared.

[Rule 3] If the primary candidate MTr/feeder set could not support all the overload of the overloaded MTr/feeder, then select the secondary candidate MTr/feeder set whose component is directly connected to each element of the primary candidate set through circuit breakers or line switches.

If not being completely supported by the secondary candidate set, then continue the selection process of the candidate MTr/feeder set as above until the overload of MTr/feeder k is removed. To reduce the possibility of the successive overload for a certain MTr/feeder which was recently overloaded, the following rule is required.

[Rule 4] In a decreasing order of the load margins in the candidate supporting set, the MTr/feeder which has been recently overloaded is reset to the end.

3.2 Elimination of the Voltage Violations

Since the violation of voltage influences on distribution systems more severely than that of thermal constraints, and the solution of the voltage problem can also eliminate the thermal violation, this section will deal with only the process of removing the voltage violation.

In order to solve the voltage problem, it is required to determine the amount of load to be transferred so that the constraint of the voltage drop limit is satisfied. In addition, the acceptable load magnitude of the adjacent feeder to be loaded should be decided within the voltage drop limit over a direct path from the source to the new end node. For a feeder with the voltage violation, we will start to solve the most violated problem, which is described in the following rule.

[Rule 5] Solve each voltage problem according to a decreasing sequence of the violation magnitudes from the voltage drop limits.

The switching operation does not cause the large change of voltage, and therefore, if the power remains constant, the current change is assumed to be ignored for a small voltage change. For any direct path from the source s to the end node e, P(s,e), it can be approximately said that the voltage drop at node e is within the limit if the following equation is satisfied:

$$\sum_{j\in LS(s,e)} \Big(\sum_{\substack{i\in LS(s,e)\\ i\ge j}} I_i \Big) Z_j \le V_s$$

where

LS(s,e) : the sequentially ordered set of all line sections over a direct path P(s,e) from the source s to the end node e.

I_i : the load of line section i

$\sum_{i\in LS(s,e),\ i\geq j} I_i$: sum of all line section loads from line section i to the end line section where the range of i from the j^{th} line section to the end line section on P(s,e)

Z_j : the impedance of line section j

V_e : voltage drop limit at the end node e.

For the subset of *LS(s,e)*, *LS(y,e)*, over a direct path P(y,e) whose loads are to be transferred, y^* is said to be an optimal solution which minimizes the voltage magnitude to be compensated : $\sum_{j\in LS(s,e)} \left(\sum_{i\in LS(y,e),\ i\geq j} I_i \right) Z_j$ such that the voltage violation at the end node e is removed. After transferring the loads of all line sections in LS(y,e), the voltage drop limit for the set *of remaining line sections* $LS(s,y) = LS(s,e) \setminus LS(y,e)$ should be satisfied on a direct path $P(s,y) = P(s,e) \setminus P(y,e)$, where y is the new end node for the path P(s,y), and the currents are assumed to be the same as before transferring.

This approximation method for each switching operation is very efficient, rather than using the full ac load flow method which provides the exact solution. However, the ac load flow solution will be performed at the final stage, in order to examine whether there exists any feeder violation in a distribution system. Once the load amount to be transferred is determined, it is required to choose the feeder to be loaded, based on the following rule.

[Rule 6] The candidate feeder set (CFS_e) is composed of all feeders which are directly connected with the voltage violation node e through tie lines installed normally-open tie switches, and whose load indices are less than 1.

While achieving the load balance in a system, the feeder selection process will be done according to the following rule.

[Rule 7] *For* CFS_e, *select each supporting feeder j to be* loaded according to a decreasing order of load margins, and assign as much load as possible within the load magnitude to be transferred, ($LI_e * NC_j - AL_j \pm \varepsilon$) where LI_e is the load index for the sum of all feeders in CFS_e and violated feeder.

Let us be assumed that for a selected feeder F_1 with the source s_1 in CFS_e, the end node e_1 is adjacent to e through a tie line. Then, the minimum margin of line sections on a direct path $P(s_1,e_1)$ can be utilized to determine the load magnitude to be loaded. The minimum margin for line sections of path $P(s_1,e_1)$ is min {$LC_i - I_i$: $i \in LS(s_1,e_1)$ } where LC_i is the capacity of line section i, and $LS(s_1,e_1)$ the set of line sections on the path $P(s_1,e_1)$. Also, the load to be transferred through tie line $LS(e,e_1)$ has to satisfy the thermal constraint of $LS(e,e_1)$.

Furthermore, not to violate the voltage drop limit, a supporting feeder F_1 should be loaded within the positive margin of voltage drop limit for the direct path $P(s_1,e_1)$. Also, for the subset of L(s,e), L(x,e), which is transferred to F_1, the new path $P(s_1,x) = P(s_1,e_1) \cup P(e_1,x)$ has to satisfy the voltage constraint. Then, to assign as much load as possible to the feeder with the maximum margin so that the number of switching operations is minimized, we need to find the optimum of x, x^*, that maximizes the sum of loads in L(x,e) under the constraints described above.

Once the optimum x^* is found, then close the tie switch installed on a tie line (e,e_1) and open the sectionalizing switch adjacent to x^* on the $LS(s,x^*)$. If the sum of all loads in $LS(x^*,e)$ is less than that of $LS(y^*,e)$, then select the next supporting feeder to be loaded from the sequence of candidate supporting feeders. This procedure is continued until all the loads of $LS(y^*,e)$ are transferred so that the voltage problem is cleared. Finally, the full ac load flow solution will be performed to check if there exists any violation of the feeder constraints.

4. COMPUTATIONAL RESULTS

To show the performance of expert systems developed here, the test distribution system of Figure 3 is considered, which is composed of 4 main transformers (MTr) and 6 distribution lines. Note that the dotted lines represent the tie lines.

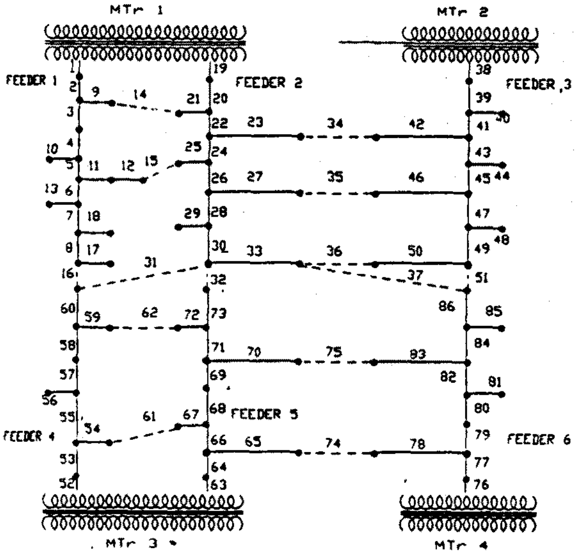

Fig. 3 Test System for Network Reconfiguration

Here, let us test the performance of expert systems for two problems such as the first is the MTr overload, and the second the low voltage of line sections. Table 1 shows the normal and firm capacities of each MTr with the actual load.

Table 1. Capacity and Actual Load of MTr

KVA MTr #	Normal Capacity	Firm Capacity	Actual Load
1	30,000	40,000	31,250
2	45,000	60,000	37,000
3	45,000	60,000	38,100
4	30,000	40,000	26,700

Firstly, the problem-solving capability of expert systems is evaluated for the MTr overload problem. From Table 1, it is obvious that MTr 1 is on the overloaded state. To eliminate the overload of MTr 1, several solution strategies are searched by using the heuristic-guided best-first search technique, which is implemented in this study. Figure 4 shows all the feasible solutions obtained through the searching process. It takes approximately 0.87 second to reach the first solution, by using COMPAQ 386. Thus, the first solution strategy has the capability to quickly solve the MTr overload problem and to achieve the near-optimal balance of load. According to the first solution, the switches 35, 36, and 31 are closed, and the 27, 33, and 30 opened.

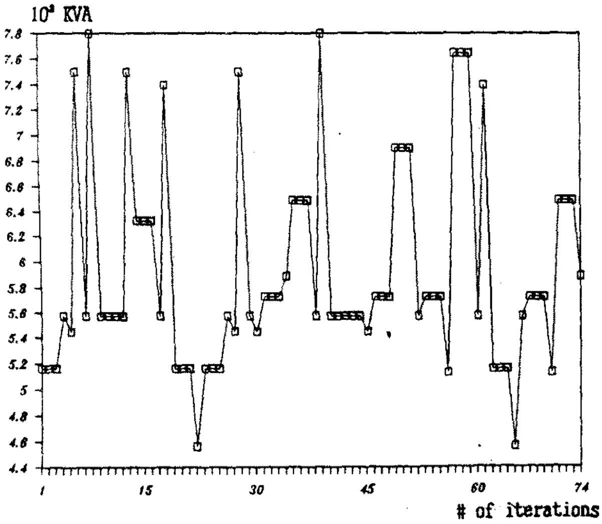

Fig. 4 Feasible Solutions for the MTr Overload Problem

Now, the capability of low voltage problem-solving will be evaluated. Table 2 shows each strategic result of the feeder reconfiguration with the sum of ($LI_s * NC_j - AL_j$) of all feeders j for the first 8 strategies of expert systems.

Table 2. Feeder Reconfiguration Due To the Low-Voltage Problem

Strategy	Closed Switch	Opened Switch	Value*
1	34,35,31	23,27,30	2078
2	34,35,32	23,27,30	2078
3	34,35,36	23,27,33	3450
4	34,35,37	23,27,33	3628
5	34,35,15,31	23,27,25,30	2715
6	34,35,15,32	23,27,25,30	2715
7	34,35,15,36	23,27,25,33	2475
8	34,35,15,37	23,27,25,33	2654

* $\sum_{feeder\ j} (LI_s * NC_j - AL_j)$

Figure 5 shows all the feasible solutions searched by the exhaustive search of expert systems. It takes about 0.93 second to find the optimal solution of the low-voltage problem. Although it does not guarantee the optimal solution of the load balance for all the problems, Fig. 4 and 5 show that the expert systems developed here can obtain at least the near-optimal solution for the MTr overload problem and the low voltage problem of line sections after the first search, respectively.

5. CONCLUSIONS

In this study, an expert system to reconfigure the network in an automated distribution system has been presented. The objective of this expert system is to eliminate the MTr/feeder overload, and the violation of the thermal constraints and the voltage drop limits.

To achieve the load balancing, the strategy of transferring the load is based on the load indices of both the system and each MTr/feeder. In order to remove the voltage violation, the approximate method is adopted, which considers the voltage drop on the direct path from the source with the minimum load margin. Heuristic rules obtained in this study were implemented in AI language Prolog.

Finally, the performance of this expert system was shown with the simulation results for the problems of both MTr overload and the low-voltage violation. By the heuristic-guided best-first search method developed in this study, at least the near-optimal solution for each problem can be found less than 1 second after a single iteration, while the exhaustive search method requires a large number of iterations in order to reach the optimum.

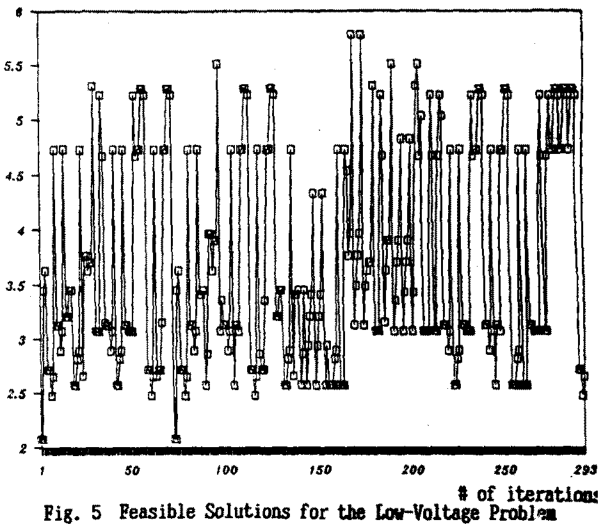

Fig. 5 Feasible Solutions for the Low-Voltage Problem

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