# Bus Reconfiguration Strategy Based on Local Minimum Tree Search for the Event Processing of Automated Distribution Substations

Yun-Seok Ko †

**Abstract** - This paper proposes an expert system that can enhance the accuracy of real-time bus reconfiguration strategy by adopting the local minimum tree search method and that can minimize the spreading effect of the fault by considering the operating condition when a main transformer fault occurs in an automated substation. The local minimum tree search method is used to expand the best-first search method. This method has the advantage that it can improve the solution performance within the limits of the real-time condition. The inference strategy proposed expert system consists of two stages. The first stage determines the switching candidate set by searching possible switching candidates starting from the main transformer or busbar related to the event. The second stage determines the rational real-time bus reconfiguration strategy based on heuristic rules from the obtained switching candidate set. Also, this paper proposes generalized distribution substation modeling using graph theory, and a substation database based on the study results is designed.

**Keywords:** Bus Reconfiguration, Local Minimum Tree Search, Substation Automation

## 1. Introduction

The distribution substations supply electric customers with power by distribution feeders that are dispersed and disposed widely in their surrounding regions. These substations can prevent the interruption of power supply for customers in the case of power system faults because their 154KV buses are supplied by two transmission lines. However, severe spreading effects for the cases of any main transformer fault and any bus fault can be experienced because their 154KV load sides are operated in a radial structure. Therefore, substation automation has created great interest because it can minimize the spreading effects when any event occurs and further, it can enhance the efficiency and economics of power system operation by introducing unmanned substations based on this automation methodology.

In order to propel the unmanned substation based on substation automation, power companies have installed and operated bus CBs that can be monitored and controlled in their remote side using the SCADA functions between one and two 22.9KV buses. However, because a 22.9KV bus in normal state can be operated under diversity configurations, and because any event can occur under such diversity configurations, realization of the remote control function is necessary for line switches as well as section switches between buses to enhance the safety and efficiency of substation operation. In particular, because under the environment of the unmanned substation based on automation, misjudgments of the system operator result in severe fault spreading effect, a solution for the decision of bus reconfiguration strategy must be incorporated in the substation automation system. Such a solution must be able to furnish the operator with the optimal bus reconfiguration strategy in real-time, considering the bus configuration, facility operation condition and load condition when any event occurs. However, the large-scale combinatorial optimization problem based on such switches must be solved, which must be capable of obtaining the optimal solution satisfying the operational objective[1-3] because the diversity bus configurations are possible by operation of CBs, section switches, and line switches on a 22.9KV bus and maximum eight feeders are allocated to a main transformer (MTr). Therefore, references[4-8] propose the real-time bus configuration strategies that can minimize the search time by minimizing search space using heuristic search strategy. Especially, reference[8] proposes a real-time bus reconfiguration strategy based on best-first search, which determines the first solution among obtained solutions based on heuristics as a real-time solution. This method can satisfy the real-time condition, but has a disadvantage the performance of the solution can be ensured

Accordingly, this paper proposes an expert system that can enhance solution performance by adopting local minimum tree search as a search strategy when a main transformer fault event occurs and can also minimize the spreading effect of the event by considering all substation

The Transactions of the Trans. KIEE, Vol.53A, No.10, pp.565-572, OCT. 2004: A paper recommended and approved by the Editorial Board of the KIEE Power Engineering Society for translation for the KIEE International Transaction on Power Engineering.
† Corresponding Author: Dept. of Electronics and Information Communication Engineering, Namseoul University, Korea. (ysko@nsu.ac.kr.)
Received July 5, 2004 ; Accepted September 7, 2004

operation conditions. The local minimum tree search method, which is used to expand the best-first search method, can enhance the performance of the solution satisfying the real-time condition by adding some search space. The inference strategy consists of two steps. The first step is a switching candidate decision step that determines the possible switching candidates from the event main transformer or bus searching the bus connectivity. The next step is a real-time bus reconfiguration decision step, which determines rational load transferring strategy based on heuristic rules from these candidates. Also, in this paper, a generalized modeling of a distribution substation is obtained by graph theory, and the facility database and the real-time database of the substation are designed based on this model. Also, the inferencing engine, MMI and database are implemented using Visual C++, MFC, and MS database libraries. Finally, database for a typical distribution substation is constructed, and the accuracy and effectiveness for the event processing functions of the proposed expert system are verified by simulation works based on the database.

## 2. Problem Definition

Fig. 1 shows a typical distribution substation diagram. The 22.9KV bus of the substation has a dual bus structure consisting of bus one $B_{1,j}$ and bus two $B_{2,j}$.

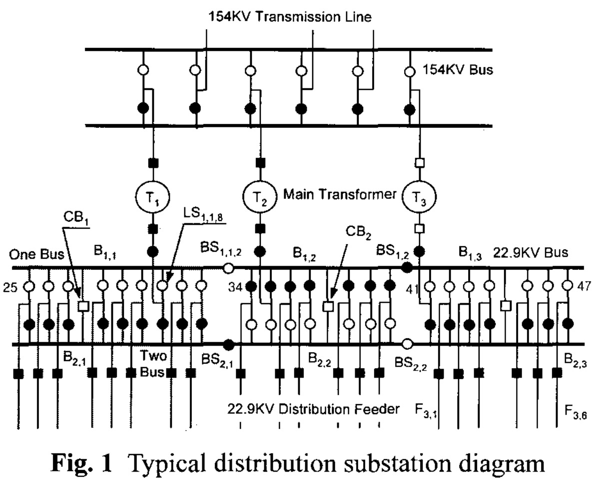



**Fig. 1** Typical distribution substation diagram

Here, line switches $LS_{i,j,k}$ are installed between $B_{1,j}$ and $B_{2,j}$ to transfer the distribution feeders to the crossing bus, and section switches $BS_{i,j,k}$ are installed between neighboring $B_{1,j}$ or $B_{2,j}$ to connect the neighboring $B_{1,j}$ or $B_{2,j}$. Also, bus tie $CB_j$ is installed between bus one and bus two for quick load transfer. Here, $B_{i,j}$ refers to the jth bus section of i bus, and $LS_{i,j,k}$ indicates the line switch for the kth feeder in i bus of the jth bus section. And $BS_{i,j,k}$ is the section switch between the jth bus section and kth of i bus section, while $CB_j$ represents the bus tie circuit breaker between bus one and bus two of the jth bus section. $F_{j,k}$ means the kth distribution feeder belonging to the jth main transformer. ■ and □ represent open, and close status of the circuit breaker. ● and ○ represent open, and close status of switches such as section switch, line switch and disconnecting switch. Fig. 2 shows the configuration of power SCADA system monitoring the substation and an expert system proposed from this study. The power SCADA system only has control capability for CBs when any event occurs in the substation. On the other hand, the substation automation system (SAS) has control capability such as line switch and section switches

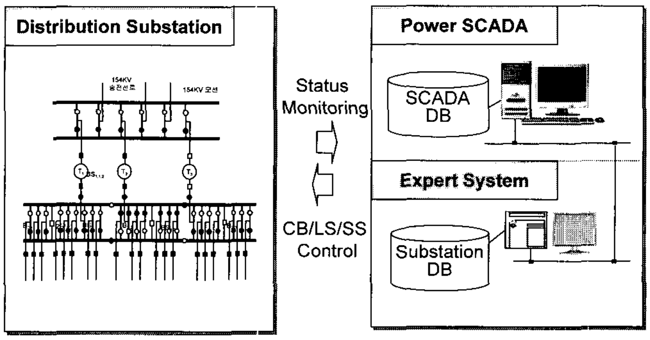



**Fig. 2** Configuration of power SCADA and expert system

Accordingly, to ensure the safety of substation operation under the various environments of the unmanned substation, a remote control function for the bus section switches $BS_{i,j,k}$ and line switches $LS_{i,j,k}$ must be implemented, while at the same time, bus reconfiguration strategy based on this remote control function must be furnished, thereby minimizing the spreading effects of the fault. Suppose that main transformer $T_1$ fault occurs. First, whether the fault is permanent or not is identified by a closing test under no-load. In the case of a permanent fault, the load of the faulted main transformer must be transferred quickly to other banks in the substation to minimize the spreading effect. At this time, the basis operation rule is used to solve the problem quickly by closing the tie CB between bus one and bus two. However, because bus is operated as diversity configuration under normal state, solving the problem with only bus tie CB may be difficult in most cases. Therefore, problem-solving strategy using $LS_{i,j,k}$ and $BS_{i,j,k}$ is obtained, and the operational objective of this case must be the switching number minimization to enhance the reliability of bus operation. Eq. (1) represents the operational objective of switching number minimization.

$$\min(N_{CB} + N_{SS} + N_{LS}) \quad (1)$$

Here

$N_{CB}$ is the number of circuit breakers to be operated

$N_{SS}$ is the number of section switches to be operated
$N_{LS}$ is the number of line switches to be operated

First, transferring the outage feeders of $T_1$ to main transformer $T_2$ is attempted by closing $CB_1$. If the outage feeder load of $T_1$ is in excess of the maximum tolerant capacity of $T_2$, the outage feeders by closing $CB_2$ are allocated to $T_2$ and $T_3$ under parallel operation of two transformers. If the outage feeders of $T_1$ cannot be allocated to two transformers, load separation must be attempted under Eq. (2).

$$\min \sum_{i \in F_R} FAL_i \tag{2}$$

Here
$FAL_i$ : ith distribution feeder load
$F_R$ : outage feeder set not transferred to other banks

Next, after closing the section switch $BS_{2,1,2}$, bus reconfiguration strategy to allocate the outage feeders to two other banks based on the bank maximum capacity operating the line switches must be determined. Here, load balancing is defined, which is represented in Eq. (3)

$$\min(\sum_{i \in T} TIL_i - TAL_i) \tag{3}$$

Here
$T$ : main transformer set in substation
$TIL_i$, $TAL_i$ : ideal, actual load of ith MTr
$TNC_i$, $TMC_i$ : rating, maximum capacity of ith MTr
$TAC_i$ : available capacity of ith MTr
$TIL_i$ : $LF*TNC_i$ or $LF*TMC_i$
$LF$ : $\sum_{i \in T} TAL_i / \sum_{i \in T} TAC_i$

When any event occurs during heavy load time, the outage feeders are divided and allocated to two other banks because these outage feeders cannot be transferred to one unfaulted bank. Because this problem is the combinatorial optimization problem for $CB_j$, $LS_{i,j,k}$ and $BS_{i,j,k}$ under the operational objective (1) or (3), a tremendous time-consuming search procedure is required. In this case best-first search method based on heuristic rules can be applied to reduce the search time, which searches preferentially the path with the highest priority in every depth. Therefore this method has advantage on the side of real-time but disadvantage in that the performance of the obtained solution cannot be ensured. This problem can be solved by adopting the local minimum tree search method, which can enhance the performance of the solution satisfying the real-time condition by adding some search space [9-10].

## 3. Expert System Design

The expert system proposed in this paper consists of database, substation model, inferencing model and MMI. The expert system identifies event type and event location from the event information when any event occurs. The inference engine allows the real-time substation model to represent the electric connectivity of the substation from the substation database using DBMS functions. If any event takes place, the expert system retrieves the load pattern using SCADA function and determines the switching candidates by tracing the electric connectivity of the real-time substation model based on the event information. Furthermore, it permits real-time bus reconfiguration strategy and represents the obtained strategy to MMI in table type. Fig. 3 shows the structure of the expert system.

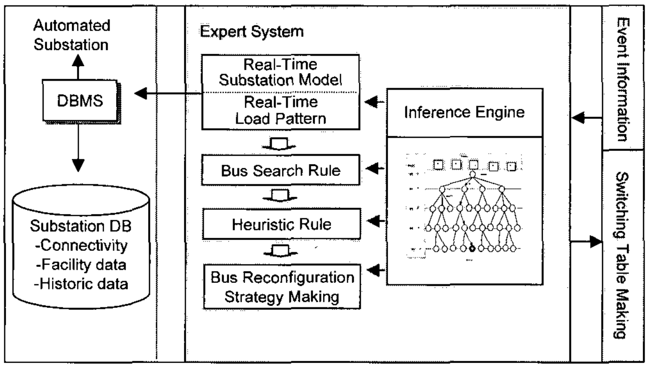



**Fig. 3** The structure of the expert system

### 3.1 Distribution Substation Modeling

The real-time substation model is constructed in memory to trace quickly the electric connectivity of the distribution substation. Fig. 4 shows that the substation model represents substation connectivity using the graph theory. In Fig. 4, the substation model consists of nodes and branches, the nodes represent the electric facilities such as main transformer, busbar, bus, switch, transmission line and distribution line, while the branches represent connectivity among the nodes. Here, ○ represents node and the line among nodes represents branch.

### 3.2 Inference Engine

Inference mechanism of the expert system can be represented as a search tree. In the search tree, the initial node signifies bus configuration at the time when the event occurs. Conversely, the branch means the switching candidate for bus reconfiguration. The general node refers to bus configuration once the switches are opened or closed based on the switching candidate. Fig. 5 shows the search tree for bus reconfiguration, ○ means the search node, and

• means goal node, which represents bus configuration after load transfer.

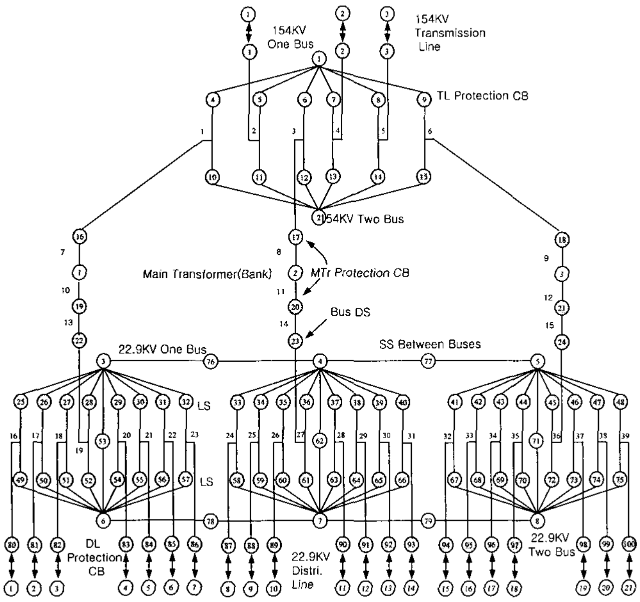


**Fig. 4** Distribution substation modeling

Suppose a main transformer fault event occurs. The expert system starts the search from the initial node. That is, it searches the switching candidate to transfer the load of the faulted main transformer by tracing the connectivity of the substation considering event information from the current bus configuration.

Next, it evaluates heuristic cost @ for all of the obtained switching candidates based on heuristic rules. Here, @ may be switching number minimization (1) or load balancing index (2). In Fig. 5, the expandable offspring nodes from the initial node are four nodes $N_{1,1}$, $N_{1,2}$, $N_{1,3}$ and $N_{1,4}$ in depth one, and heuristic costs @ for these nodes are 3, 1, 2 and 4. Accordingly, node $N_{1,2}$, which shows minimum cost is searched primarily. If any main transformer fault occurs in the substation of Fig. 1, total ten nodes becomes expandable offspring nodes. This proves whether the load transfer is possible or not. If load transfer is possible, it identifies the goal node by proving whether the complete load of the faulted main transformer was transferred or not following load transfer. If load transfer was not finished, the search is expanded to nodes in depth two. In depth two, node $N_{2,4}$ in which @ is 2 is selected primarily.

In depth three, node $N_{3,5}$ in which @ is 1 is selected primarily. Such depth expansion process is repeated up to the point when the goal node is searched. Fig. 5 shows the node $N_{4,5}$ in which load transfer is goal node. And, searched path $\{N_{1,2}, N_{2,4}, N_{3,5}, N_{4,5}\}$ to obtain this goal node becomes the solution of best-first search method. The local minimum tree search method applies such a search process to only those nodes in depth 0. That is, it searches the node $N_{4,7}$, which is the switching candidate with the second priority by backtracking from goal node $N_{4,5}$ to depth 0. The searched path $\{N_{1,3}, N_{2,6}, N_{3,7}, N_{4,7}\}$ up to acquisition of the second goal node $N_{4,7}$ becomes the second load transfer strategy. It chooses the load transfer strategy with more improved performance after comparing the second load strategy with the load transfer strategy that was obtained the first time by a new optimal bus reconfiguration strategy. And then, it obtains the third goal node $N_{4,1}$ by backtracking from goal node $N_{4,7}$ to node $N_{1,1}$ in depth one, and selects the better solution after comparing the performance of load transfer strategy made from the goal node with the performance of above optimal solution by the new optimal solution. Next, it searches a new goal node $N_{3,10}$ backtracking to $N_{1,4}$ and obtains the optimal solution by repeating the same procedure. If a main transformer fault occurs in $T_1$ of Fig. 1, as mentioned above, the most thing among ten load transfer strategies is determined in the solution for bus reconfiguration. Thus, the load minimum tree search method can obtain the load strategy with enhanced performance than the existing best-first search method by adding some searched space. Here, the added space can be ignored against the overall search space.

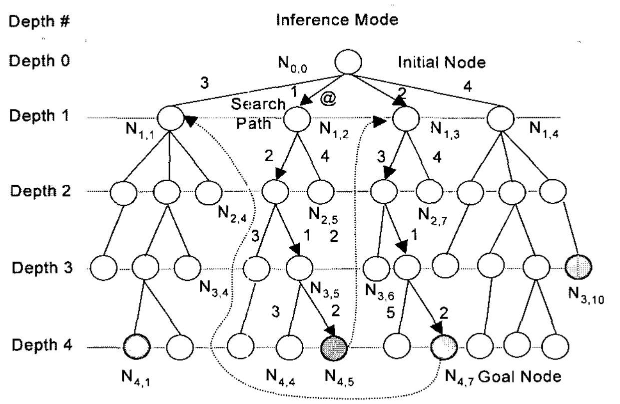


**Fig. 5** Structure of expert system inference engine

### 3.3 Heuristic Rule

Adopting problem-solving strategy based on bus structure in ref [8] makes program design, maintenance and expansion difficult due to the complexity of heuristic rules. Accordingly, in this paper, the method using the generalized switching algorithm is introduced, which is based on the search of the electric connectivity and not on the bus structure. That is, easier program maintenance and program expansion are obtained by excluding the heuristic rules based on bus structure and by adopting generalized heuristic rules such as HR 1-5]. HR 1,2,3] are utilized in heuristic rules under operational objective (1), HR 4] is utilized in a heuristic rule under operational objective (3), and HR 5] is utilized in a heuristic rule under both operational objective (1) and operational objective (3)

- HR 1] $\max\{TL_k : k \in CST_{ij}\}$ is selected primarily. This is the rule to obtain the fault spreading effect by selecting primarily the switching candidate with the highest load priority (LP) among the possible switching candidates set(CSTij) in the jth node of search depth i.
- HR 2] $\min\{LP_k : k \in CST_{ij}\}$ is selected primarily. This is the rule to minimize the fault spreading effect by selecting primarily the switching candidate with the highest load priority (LP) among the possible switching candidates set ($CST_{ij}$).
- HR 3] $\min\{SN_k : k \in CST_{ij}\}$ is selected primarily. This is the rule to protect the safety accident or minimize the delay of restoration by selecting primarily the switching candidate with the minimum switching number (SN) among the possible switching candidates set ($CST_{ij}$).
- HR 4] $\min\{\Delta E_k : k \in CST_{ij}\}$ is selected primarily. This is the rule to enhance the safety of substation operation allocating rationally the outage feeders to two unfaulted banks by selecting primarily the switching candidate with the minimum load balancing index ($\Delta E$) among the possible switching candidates set ($CST_{ij}$). If the transferred load, TL is $\sigma$[KVA], system load balancing index $\Delta E$ is represented as difference of load balancing index between before and after load transfer as shown in eq. (4). In eq. (4), $TE_i = TIL_i - TAL_i$[8].

$$\Delta E_i = TE_i^2 - (TE_i - \sigma)^2 = 2TE_i\sigma - \sigma^2 \qquad (4)$$

- HR 5] $eq\{LS_k : k \in CST_{ij}\}$ is selected primarily. This is the rule to enhance the safety and efficiency of the fault restoration excluding the parallel operation of banks by selecting primarily the switching candidate with the line switch (LS) among the possible switching candidates set ($CST_{ij}$).

### 3.4 Database Design

The distribution substation database is designed as the rational model that can be represented easily in a logical manner. The database includes main transformer table (MTr), busbar table (BUSBAR), bus table (BUSLINE), distribution table (DL), switch table (SW) and transmission line table (TL).

From each table, the substation is identified using the substation number (S/S#), which is in the common field, and the connection relationship with other facilities is traced using switch number (SW#). The main transformer is connected to the bus, distribution line and transmission line using switch number (SW#), which is also in the common field. In the main transformer database table, availability capacity means the capacity determined considering the status and the durable period of the main transformer. Bus, busbar and switch represent the connectivity among them by designing bus number (bus#) as part of the common field. The bus position refers to bus one or bus two. The type of bus represents the voltage level Here, voltage level may be 154KV or 22.9KV. In switch database table (SW), the type is classified as CB, section switch (SS), and line switch (LS), the type may be manual or automatic. Moreover, load priority of DL is designed to determine effective load transfer strategy.

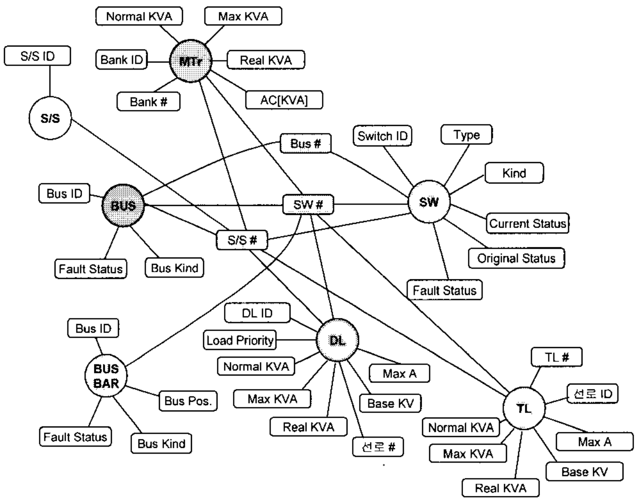



**Fig. 6** Substation database design

## 4. Problem-Solving Strategy

The problem-solving strategy of the expert system based on the local minimum tree search method proposed in this paper can be explained in step 1] to step 8] as shown in Fig. 7.

- Step 1] First, set the inference mode of the expert system to basic mode and construct a real-time substation model in the expert system memory after retrieving the substation data from the substation database.
- Step 2] Monitor the operation status of the substation from the alarm information. If any event occurs, identify the faulted bank from the alarm information, set inference depth i and inference path j, and proceed to step 3].
- Step 3] Determine the switching candidate set ($CST_{i,j}$) to transfer the load of the faulted bank to unfaulted banks, and obtain the rearranged switching candidate set ($CST_{i,j}^*$) based on heuristic rules HR 1-4]. Next, set k to 0 and proceed to step 4].

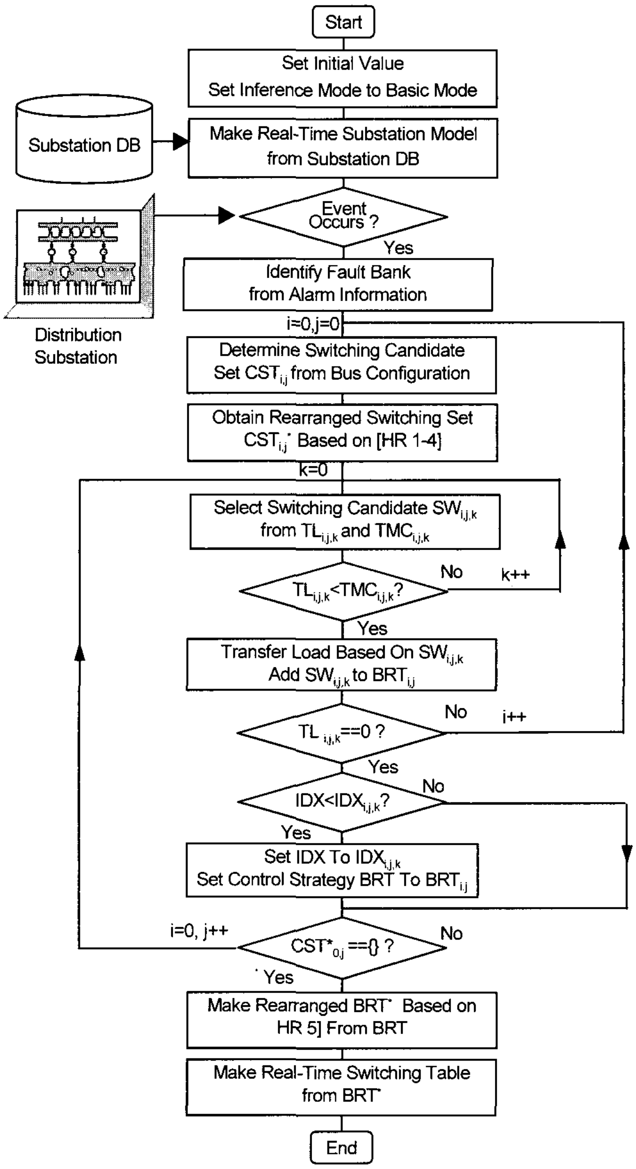



**Fig. 7** Problem-solving strategy of expert system

- Step 4] Select $SW_{i,j,k}$ by the switching candidate. And, check whether load transfer is possible or not by comparing the size of transferred load $TL_{i,j,k}$ by the selected $SW_{i,j,k}$ and margin capacity $TMC_{i,j,k}$ of allocated bank check. That is, check condition $TL_{i,j,k} < TMC_{i,j,k}$. If the condition is satisfied, proceed to step 5], otherwise, proceed to step 4] after incrementing k and choose $SW_{i,j,k+1}$ as the switching candidate.
- Step 5] Attempt the load transfer based on switching candidate $SW_{i,j,k}$ and add the $SW_{i,j,k}$ to bus reconfiguration strategy $BRT_{i,j}$. And, check whether load transfer is completed or not, that is, the size of the load $TL_{i,j,k}$ to be transferred is 0. If the condition is satisfied, proceed to step 6], otherwise, proceed to step 3] after incrementing i and determine $CST_{i+1,j}$ as a new switching candidate.
- Step 6] Compute system index $IDX_{i,j,k}$ by eq. (1) or eq (3) and compare the $IDX_{i,j,k}$ with minimum system index IDX already set. If $IDX>IDX_{i,j,k}$, set $IDX_{i,j,k}$ to IDX and bus reconfiguration strategy BRT to the new strategy $BRT_{i,j}$ because performance of the new bus reconfiguration strategy is better than the existing performance. On the other hand, if $IDX<IDX_{i,j,k}$, just proceed to step 7] because the performance of the existing load transfer strategy is better than the new strategy.
- Step 7] Return to depth 0 by backtracking to lower depths and restore bus configuration obtained by load transfer in the searched path to the original bus configuration at every depth backtracked. And then, check whether $CST_{0,j}^*$ is {} or not. If the condition is satisfied, proceed to step 8], otherwise, after setting i to 0 and incrementing j, proceed to step 4] and repeat the same inference procedures for switching candidate $SW_{0,j+1,k+1}$ with the next priority. At this time, search path j and priority k are equal in the initial node.
- Step 8] Rearrange BRT obtained during inference based on HR 5], formulate a switching table from the BRT and display it in the MMI.

## 5. Simulation Results

This paper proposes an expert system based on local minimum tree search for service restoration in automated distribution substations. In order to prove the effectiveness of the proposed expert system, the performance for solutions obtained from the local minimum tree search method must be compared with the performance for solutions obtained from the existing search method under identical load conditions. Accordingly, this study attempts problem-solving applying both the best-first search method and the local minimum tree search method for the fault cases of main transformer $T_1$ under equivalent load conditions with the typical distribution substation model shown in Fig. 8.

The distribution substation consists of three main transformers $T_1$, $T_2$ and $T_3$, which have seven feeders. Table 1 presents the rating capacity, the maximum capacity, and the peak and minimum load obtained from historic data recorded for the given period, which are related to the main transformers. In this study, the event cases to prove the effectiveness of the proposed expert system are simulated for the diversity load conditions that can be generated from four levels such as peak load, heavy load, light load and minimum load.

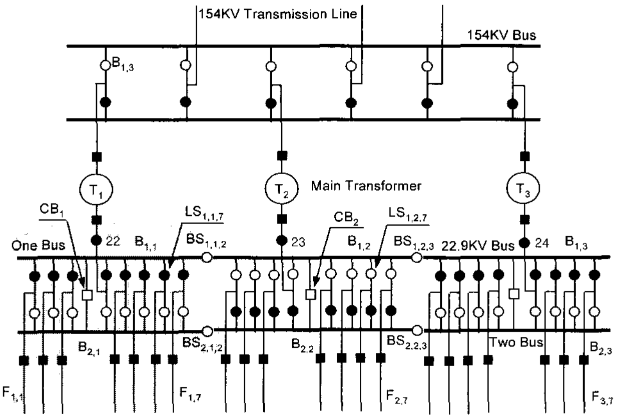



**Fig. 8** Substation model for performance evaluation

**Table 1** The capacity and load of main transformers

| MTr[KVA] | $T_1$ | $T_2$ | $T_3$ |
|---|---|---|---|
| Rating Capacity | 30,000 | 45,000 | 30,000 |
| Maximum Capacity | 40,000 | 60,000 | 40,000 |
| Peak Load | 30,000 | 45,000 | 30,000 |
| Minimum Load | 10,000 | 15,000 | 10,000 |

Table 2 shows the rating capacity, the maximum capacity, and the peak and minimum load obtained from historic data recorded for the given period, which are related to distribution feeders belonging to the main transformer $T_1$. Where, $F_{i,j}$ represents jth distribution feeder belonging to main transformer $T_i$.

**Table 2** The capacity and load of distribution feeders

| Feeder[KVA] | $F_{11}$ | $F_{12}$ | $F_{13}$ | $F_{14}$ | $F_{15}$ | $F_{16}$ | $F_{17}$ |
|---|---|---|---|---|---|---|---|
| Rating Capacity | 7,000 | 7,000 | 7,000 | 7,000 | 7,000 | 7,000 | 7,000 |
| Maximum Cap. | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 | 10,000 |
| Peak Load | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 |
| Minimum Load | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 |

The performance evaluating work for the proposed expert system consists of three steps. In the first step, total $L^{(n+m)}$ load patterns are generated using the load pattern generation function of the expert system to simulate the diversity of load conditions. Here, L means the number of load level, set in 4 levels including peak load level, heavy load level, lighting load level, and minimum load level. As well, n and m are the number of the varied load patterns separately of the main transformers and distribution feeders set in three and four. Accordingly, a total of 16,414 load patterns were generated from the expert system. In the second step, first, bus reconfiguration strategies are obtained for the generated load patterns by setting the operational objective of the expert system to switching number minimizations (1) and the inferencing mode of the expert system to the best-first search method. Next, bus reconfiguration strategies for the generated load patterns are obtained by setting the inferencing mode of the expert system to the local minimum tree search method. The third step obtains real-time bus reconfiguration strategies for the generated load patterns by applying separately both best-first search method and local minimum tree search method under the load balancing operational objective (3). Fig. 9 indicates the performance of the obtained bus reconfiguration strategies by two approaches under equation (1). Here, bus reconfiguration strategies are inferencing results for the fault of main transformer $T_1$.

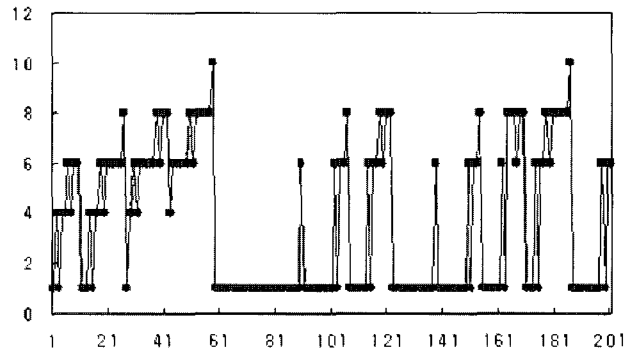



**Fig. 9** The switching number of bus reconfiguration strategies

In Fig. 9, ◆ and ■ represent the switching number of bus reconfiguration strategies obtained from the best-first search method and the local minimum tree search under operational objective of switching number minimization (1). The expert system proposed the strategy allocating to the unfaulted main transformer $T_2$ all feeders of the faulted main transformer $T_1$ by closing $CB_1$ as the first switching strategy. At this time, the switching number is one. Fig. 8 shows switching number for approximately 200 strategies among bus reconfiguration strategies for the continued load patterns. In Fig. 9, difference between switching number of the obtained bus reconfiguration from the best-first search method and the local minimum tree search method is slight, because the feeders of the faulted main transformer are located to one bank among unfaulted main transformers as soon as possible under the operational objective of switching number minimization. However, in case that the feeders of the faulted main transformer van not be allocated to an unfaulted main transformer, the feeders must be divided and allocated to two unfaulted main transformers. This problem is the central topic to be solved in this study, and setting load balancing (3) to operational objective is desired to enhance the safety of substation operation. Fig. 10 indicates load balancing index obtained by adopting separately two approaches for load patterns generated from the load pattern generator. Here, ■ and ◆ are mean the balancing index respectively for bus reconfiguration strategies obtained from the best-first search method and the local minimum tree search method under the operational objective of load balancing (3).

Table 3 presents one case among bus reconfiguration strategies obtained by the local minimum tree search method. Here, DS represents disconnecting switch. In the proposed strategy, first, by operating line switches sequentially, feeders $\{F_{1,4},F_{1,1},F_{1,7},F_{1,2}\}$ among the feeders of the faulted main transformer $T_1$ are connected to bus $B_{2,1}$ Conversely, the remaining feeders $\{F_{1,3},F_{1,5},F_{1,6}\}$ are connected to bus $B_{1,1}$. Next, by closing the section switch $BS_{2,1,2}$, electric power is supplied from main transformer $T_2$ to the feeders $\{F_{1,4},F_{1,1},F_{1,7},F_{1,2}\}$ and by closing the section switch $\{BS_{1,1,2}, BS_{1,2,3}\}$, electric power is supplied from main transformer $T_3$ to the feeders $\{F_{1,3},F_{1,5},F_{1,6}\}$.

**Table 3** The bus reconfiguration strategy

| # | Switch ID | Type | Kind | Auto/Manu | Control |
|---|---|---|---|---|---|
| 1 | $LS_{1,1,5}$ | LS | DS | M | Open |
| 2 | $LS_{2,1,5}$ | LS | DS | M | Close |
| 3 | $LS_{1,1,1}$ | LS | DS | M | Open |
| 4 | $LS_{2,1,1}$ | LS | DS | M | Close |
| 5 | $LS_{1,1,6}$ | LS | DS | M | Open |
| 6 | $LS_{2,1,6}$ | LS | DS | M | Close |
| 7 | $LS_{1,1,2}$ | LS | DS | M | Open |
| 8 | $LS_{2,1,2}$ | LS | DS | M | Close |
| 9 | $BS_{1,1,1}$ | SS | DS | M | Close |
| 10 | $BS_{1,2,3}$ | SS | DS | M | Close |
| 11 | $BS_{2,1,2}$ | SS | DS | M | Close |

The proposed local minimum tree search method shows more improved performance than the best-first search method in most cases except some cases with identical performance in Fig. 10.

Therefore, we can identify that proposed local minimum tree search improves the load balancing and enhances the safety of substation operation for the cases in which the feeders of the faulted main transformer are divided and allocated to unfaulted main transformers under the operational objective of load balancing.

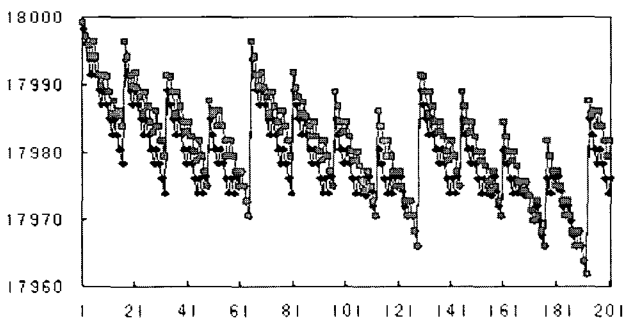



**Fig. 10** Load balancing index of reconfiguration strategies

## 6. Conclusion

This paper proposed an expert system that can enhance the performance of bus reconfiguration strategy by adopting local minimum tree search as a search strategy when any main transformer fault occurs in an unmanned substation. The local minimum tree search method expanding the best-first search method can enhance the performance of the solution satisfying the real-time condition by adding some search space. The inference strategy of the expert system was designed as a switching candidate decision step and a real-time bus reconfiguration decision step. Especially, the expandability of programming and the efficiency of maintenance were improved by excluding the structure rules obtained from the fixed topology of the substation and by applying the generalized switching algorithm based on bus connectivity. Finally, the fault cases of the main transformer under diversity load conditions of the typical distribution substation were simulated. The expert system proposed real-time bus reconfiguration strategies indicating more improved performance than the existing best-first search method in simulation cases when the feeders of the faulted main transformer were allocated to two other unfaulted transformers. Therefore, it is expected that the proposed strategy can be utilized as an effective bus reconfiguration strategy for the processing of real-time events under unmanned substation operating situations based on automation.

## Acknowledgements

This work has been supported by KESRI (R-2003-B-390), which is funded by MOCIE (Ministry of Commerce Industry and Energy). And, This work was supported by Namseoul University by 2005 Namseoul University Grant.

## References

[1] C.S. Chang, T.S.Chung, "An Expert System for On-Line Security-Economic Load Allocation on Distribution Systems", *IEEE Trans. on Power Delivery*, Vol. 5, No. 1, pp. 467- 469, January 1990.

[2] Aoki, K., H. Kuwabara, T. Satoh, and M. Kanezashi, "An Efficient Algorithm for Load Balancing of Transformers and Feeders by Switch Operation in Large Scale Distribution Systems", *IEEE Trans. on Power Delivery*, Vol. 3, No. 4, pp. 1865-1872, October 1988.

[3] Taylor T. and D., Lubkeman, "Implementation of Heuristic Search Strategies for Distribution Feeder Reconfiguration", *IEEE Trans. on Power Delivery*, Vol. 5, No. 2, pp. 239-246, January 1990.

[4] Mori S., I.Hata, T.Usui and K. Morita, "Expert

System Supporting Substation Service Restoration", *ESAP IV*, pp. 131-136, January 1993.

[5] Bernard J. P. and D. Durocher, "An Expert System for Fault Diagnosis Integrated in Existing SCADA Systems", *IEEE Trans. on Power Systems*, Vol. 9, No. 1, pp. 548-554, February 1994.

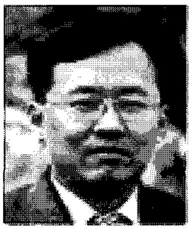
[6] Power System Restoration Working Group, "Special Consideration in Power System Restoration: The Second Working Group Report", *IEEE Trans. on Power Systems*, Vol. 9, No. 1, February 1994.

[7] Yang, Hong-Tzer, Wen-Yeay Chang, Ching-Lien Huang, "On-Line Fault Diagnosis of Power Substation Using Connectionist Expert System," *IEEE Trans on Power Systems*", Vol. 10, No. 1, February 1995.

[8] Kim, H., Y. Ko, and K. H. Jung, "Algorithm of Transferring the Load of the Faulted Substation Transformer using the Best-First Search Method", *IEEE Trans. on PWRD*, Vol. 7 No. 3, pp. 1434-1442, July 1992.

[9] Luger, G.F. and Stubblefield, W.A. *ARTIFICIAL INTELLIGENCE AND THE DESIGN OF EXPERT SYSTEM*, the Beniman/Cummings Publishing Company, Inc.

[10] Patterson, Dan W, *INTRODUCTION TO ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS*, Prentice-Hall International Inc.



**Yun-Seok Ko**

He received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Kwangwoon University, Seoul, Korea, in 1984, 1986, & 1996, respectively. He was with KERI (Korea Electric Research Institute) from 1986 to 1996 and then POSRI (POSCO Research Institute) from 1996 to 1997. Currently, he is an Associate Professor in the Dept. of Electronic and Information Communication Engineering at Namseoul University, Korea. His research interests are distribution automation, substation automation, expert system application to power systems and IED (Intelligent Electric Device).