OPTIMAL RESTORATION OF SUPPLY FOLLOWING A FAULT ON LARGE DISTRIBUTION SYSTEMS

Susheela Devi, D.P. Sen Gupta and Samuel Sargunaraj

1.0 ABSTRACT

A computer aided optimal method has been developed for the restoration of electric supply to areas isolated from the network following a fault in a distribution system. A search technique is used where the search is guided by appropriate heuristics. The optimum solution entails finding the strategy which involves the operation of minimum number of switchgear for rerouting the supply within the constraint of specified loading. This is an essential requirement in countries like India where the circuit breakers are almost always manually operated and a number of transformers and feeders operate close to their rated capacity. It pays therefore to adopt different strategies at peak load and off peak conditions since the number of breaker operations is so critical.

2.0 INTRODUCTION

The restoration of supply to isolated sections involves the opening and closing of switchgear so that the isolated section is fed from an alternative route. In the process, there should be no overloading of buses, transformers and line sections. While finding a series of connections and disconnections of sections to restore supply, there may be many alternative solutions and it is necessary to find the optimal route.

In India, the present practice is for the operating personnel to make the decision on how to restore supply. While making the decision, we have to keep in mind the configuration of the system at the time of the outage and also ensure that there is no overloading on the system. It is evident that experienced personnel are required who are totally familiar with the system. Nowadays with the large size of the distribution systems and with the cables being pushed to their limit due to high demand, this is a formidable task. It can thus be seen that a computer program which displays feasible solutions should be a welcome aid to the operating personnel.

Different approaches have been made and strategies proposed for the restoration following a fault. These include classical optimization techniques, knowledge-based systems and search techniques. The optimization technique has been used in references [1] and [2]. The line capacity constraint and transformer capacity constraint are taken into account. In [2], the constraint of permissible voltage drop has also been added. From the results reported by the authors the solutions obtained seem to require a very large number of switchgear operation to restore power supply. This may not create problems where the switching system is automated and centrally controlled. References [3], [4] and [5] utilize the knowledge-based approach. In [3], a set of 16 rules are used coded in INTERLISP. This program has only been tried for a very small system. The number of rules have to be increased to a large extent to cater to large systems. In [4], an expert system in Prolog has been reported containing 180 rules. This has been enhanced to 382 rules as reported in [5]. The use of expert systems seems to demand the incorporation of a large number of rules when the network considered represents even a section of Metropolitan distribution system.

In [6], a binary tree search is used where every switch is set to 0 or 1. This type of blind search is likely to take a very long time for a large system unless the search is guided by some rules and heuristics.

The criteria for finding an optimum solution is very crucial. Generally the criterion adopted is to transfer the load to be fed to a feeder with a larger margin so that there is a balancing of the load. As has been indicated earlier manual switching is used in India and probably in most of the developing countries. The information on which switchgear are to be operated is communicated to the linemen who have to go physically to the location of the switches to operate them. The restoration of supply becomes more complicated and time consuming if a large number of switching operations are involved. Hence, the strategy of minimum number of switches to be operated without exceeding current limits is the only practical solution to the problem and acceptable to the supply authorities. Several feasible solutions involving minimum operation of switchgear may exist. If more than one solution exists, then the one that offers the largest loading margin is to be preferred unless other intangible yet compelling factors need to be considered.

3.0 METHODOLOGY

The proposed method can be best described as a knowledge based guided search aiming at minimum switching operation and minimum overloading. An overall guiding principle on the search is that the system should be as balanced as possible.

The technique essentially involves searching a tree representing all the solutions possible. Search is a general problem solving strategy suitable for problems which have no direct techniques. In using the search technique certain steps should be followed which necessitate that the problem has to be defined precisely including the initial and final states. The problem has to be analyzed and a set of rules (or operators) have to be specified to act on a state and convert it to another state. A solution is found by moving from the initial to the final state through intermediate states using the operators specified. The order of traversal of the tree is crucial. If the control strategy is right, the search will be more effective end the solution can be obtained faster. Depending on the order of traversal of the tree, breadth-first search, depth-first search and best-first search are possible.

Breadth-First Search: In this procedure, all nodes on one level of the tree are expanded before examining any of the nodes on the next level. This type of search is guaranteed to find a solution if it exists and also the solution with the shortest path. But this procedure will require a lot of memory and time if the solution lies too deep down in the tree. This is because the number of nodes to be examined increases exponentially with the depth. This strategy was tried first and since the number of operations increases with the ply, this strategy indeed gave the solution with minimum operation of switchgear. But since the system considered is very large, in a few cases the computation time is high. To avoid such cases, the tree has to be pruned so that paths unlikely to offer a solution are not explored at all. For this heuristics have to be used.

Depth-First Search: In this procedure one node is expanded fully before another node is considered. Using this procedure, it is likely that a lot of time is spent exploring unfruitful paths. It is also necessary to limit the depth to which a node is expanded.

Best-First Search: In this procedure, a heuristic function is used at each stage to decide which node to expand. The purpose of the heuristic function is to guide the search process in the most profitable direction by suggesting which path to follow first when more than one is available. Heuristics are formed by using domain-specific knowledge.

The search technique finds a series of connection and disconnection of sections to restore supply. It is first seen which are the normally-open sections which can feed the isolated areas. These form alternatives of path length one. These involve just a single operation. Each alternative is tested for feasibility. A solution is feasible if there is no overloading on any part of the system. If any of the solutions are feasible, the task is done. Otherwise these form partial solutions, and other routes are found to relieve the overload. This can be done in two ways. The first is to split the isolated section and feed them by using two normally-open sections. The second is to relieve the overload on the feeder to which the load has been transferred. These form nodes of path length two. This procedure is repeated till a feasible solution is found. Once a feasible solution is found, it is necessary to backtrack through the tree to find the complete sequence of operations.

In the best-first search, alternatives at path length one are first found. If there is no feasible solutions than one of these is chosen for expansion depending on which feeder has minimum overload. If there is still no feasible solution, then all the unexpanded nodes of path length one and path length two are considered, and a node where minimum load needs to be transferred is chosen for expansion. This process is repeated till a feasible solution is found.

Pruning of the Tree: While breadth-first search seems the obvious strategy to use for the criteria of minimum operation of switchgear, it may be time-consuming, especially for very large systems. One method of reducing the search is to discard paths which are unlikely to offer a solution. A heuristic function has to be used here. These paths are anticipated by using a simple rule. When the loads (CP) in the post-fault region has to be transferred to another feeder X, if the latter (i.e., X) is overloaded by an amount P_o due to the transfer and a Section T from X has to be transferred to a third feeder Y to prevent overloading of X, then ΣP_T (i.e., the sum of the loads of section T) must not be much larger than ΣP . In other words any search that leads to kn excessive accumulation of the loads to be transferred should be anticipated and abandoned. $\Sigma P_T = a \Sigma P_L$ where a is of the order of 2 or 3 is permissible.

In order to ascertain the loading of the transformers, buses and feeders a load flow has to be computed whenever a transfer of load is proposed. A simple dc load flow is found adequate for this purpose, since loading on the system is only being checked. In case voltage drop or system losses need to be calculated a dc load flow is obviously inadequate. Since in our case finer aspects such as obeying voltage constraints and minimizing system losses give way to the prime requirements of minimizing switching operations without overloading, dc load flow serves the necessary purpose.

4.0 LOAD VARIATION

It is evident that the peak load on the system during a day should be considered for the restoration procedure to ensure safety. Overloading may thus be avoided even if the cable may not be repaired in time. But it may not always be expedient to use the peak load if it leads to a large number of switching operations. For example, if the fault occurs late at night when the loading is light mainly due to fans and air-conditioners, it is convenient to restore the supply with minimum operations. It is not always very convenient to carry out manual switching operations in the middle of the night. The study can be carried out based on light load. In case the fault may not be repaired before the advent of peak load, a strategy based on the peak load may be followed during early morning.

Restoration of supply based on the peak load is safe but pessimistic and with continued load growth (often greater than 10% annually) and the surplus capacity of cables being reduced, a feasible solution may not be obtained. If a solution exists the computation may take long and several switchings may be involved. In such cases, it may be more practical to decide the load depending on the time of the day. From the time at which the fault occurs, a time horizon can be considered depending on the time required to detect and repair the fault. The largest load during this time can be considered for the restoration procedure. Once the action has been taken it is essential that the cable should be repaired as early as possible and certainly within the specified time period.

Since the actual load at every point is not known, it has to be estimated. Since accurate estimation of the load at every load point is not possible and is not necessary either, a simple method of load estimation is recommended. Given below are three methods to estimate load.

1. Use of three types of load: The restoration procedure can be run using three types of load depending on the time of the day. These are the morning peak, the evening peak and the off peak. These values for every load point have to be available.

2. Use of daily load curves: This method requires the loads to be classed into various categories like commercial load, residential load, heavy industrial load, light industrial load, etc. The number of categories will depend on the region being considered. For instance, in some region, it may be possible to club together the commercial and residential load. The typical daily load curves for the various categories need to be stored. The load as a percent of the peak load is stored for the 24 hours of the day for the various categories. Every load in the system has to be classified. At any time of the day, knowing the peak load at any point, the actual load can be estimated. This method is just an approximation but very simple and fast to implement.

3. Forecasting the total system load: Past data on the total system load has to be used for forecasting the present system load. Any of the available forecasting techniques can be used. This total system load which is estimated has to be allocated to the various categories. It is therefore required to have typical graphs on the percent of total load for the various categories at different times of the day. This will enable one to allocate the estimated system load at any time to the various categories. At any point in time, the load at a load point will be

$$L_p = P_c * S * C_p / C_c$$

where L_p is the estimated load at load point p
P_c is the per unit load of category c to which point p belongs
S is the estimated total system load
C_p is the connected load at point p
C_c is the total connected load of category c.

5. RESULTS

A program for restoration of supply has been written in PASCAL running on the IBM-PC. A very large metropolitan distribution system has been used for testing the program. This system consists of over 2500 nodes and 120 feeders. The use of such a large system led to problems of memory space and convergence. To tackle the convergence problem, appropriate heuristics had to be used as explained earlier.

Figure 1 shows a small part of this system. 8 feeders have been shown. For a fault in section 6288-7149 of feeder 7149, Fig. 2 shows the search tree that has been formed. In Fig. 2, level 1 corresponds to solutions with a single operation. If all these solutions show overloading, these have to be expanded to form level 2. If still no solution is found, level 2 is expanded to give level 3. Whenever a feasible solution is found, backtracking to the root node yields the total solution. As one goes deeper into the tree, the number of operations of switchgear increases. So by expanding one level at a time, it is possible to achieve the objective of finding a solution with the minimum possible operation of switchgear.

Figure 3 shows the solution obtained at peak load. A feasible solution was obtained at the 21st trial at level 3. The solutions are printed out one level at a time. At each level, the node with minimum overloading is expanded first. This principle is followed at every step so that the first feasible solution displayed is the optimal solution. The figures in brackets in Fig. 2 shows the order of expansion of the tree. All solutions are printed out, stopping after every three solutions so that the solutions can be viewed on the VDU. All feasible solutions are boxed in and highlighted using a different colour. Since the operating personnel may not find it possible to implement the optimal solution due to some practical consideration, he selects the next best out of the possible strategies displayed. Trial 21 gives the optimal solution but the search can be continued if more solutions are required.

Figure 4 shows the results we obtained at 30% of the peak load. It may be more practical to implement a solution such as this during the night. If the cable is not repaired before the advent of the peak the next day, it is a simple matter to implement the solution as shown in Fig. 3. The solution at 30% peak load can also be obtained very fast.

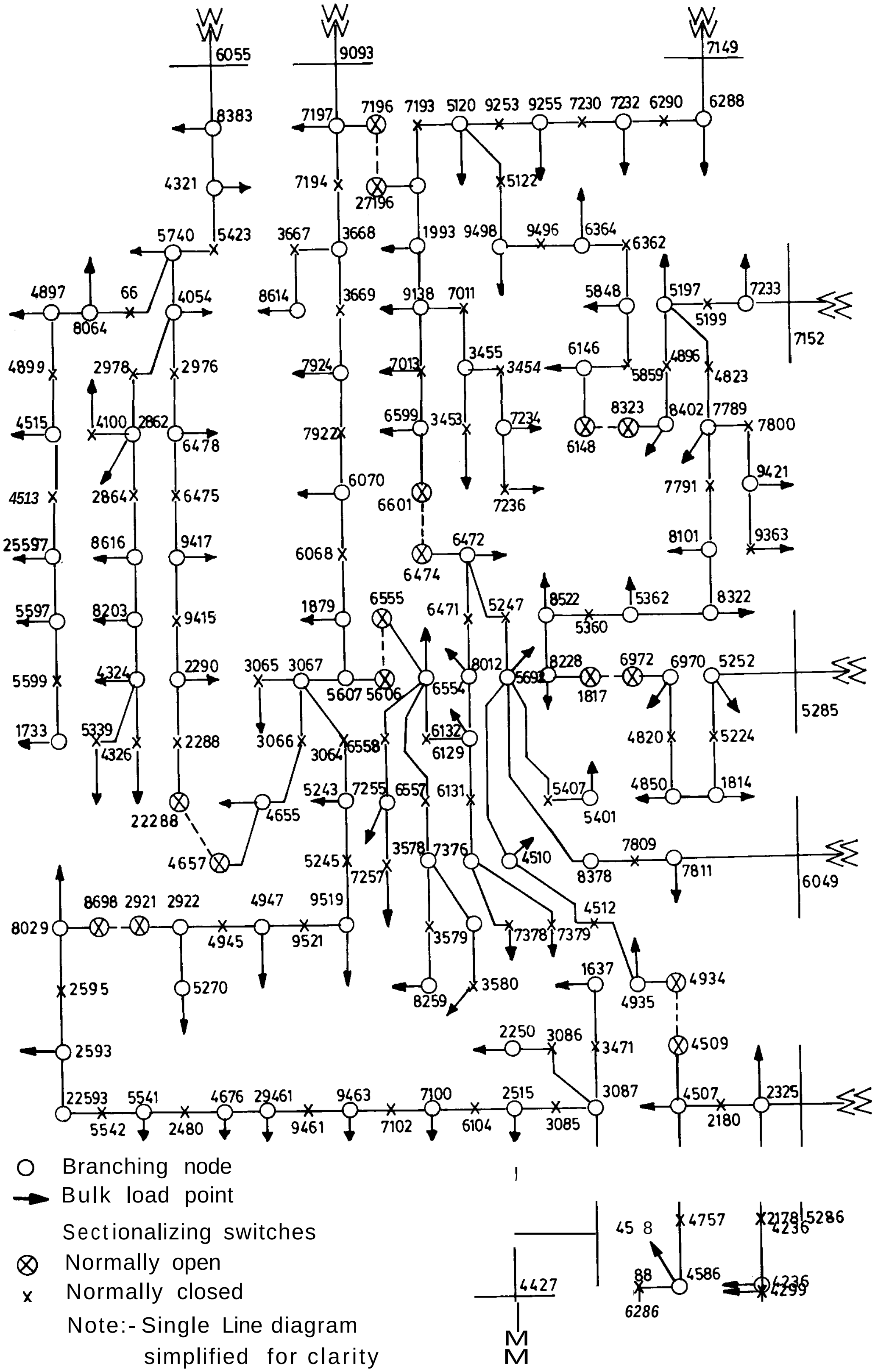
Branching node
Bulk load point
Sectionalizing switches
Normally open
Normally closed
Note:- Single Line diagram
simplified for clarity

Figure - 1

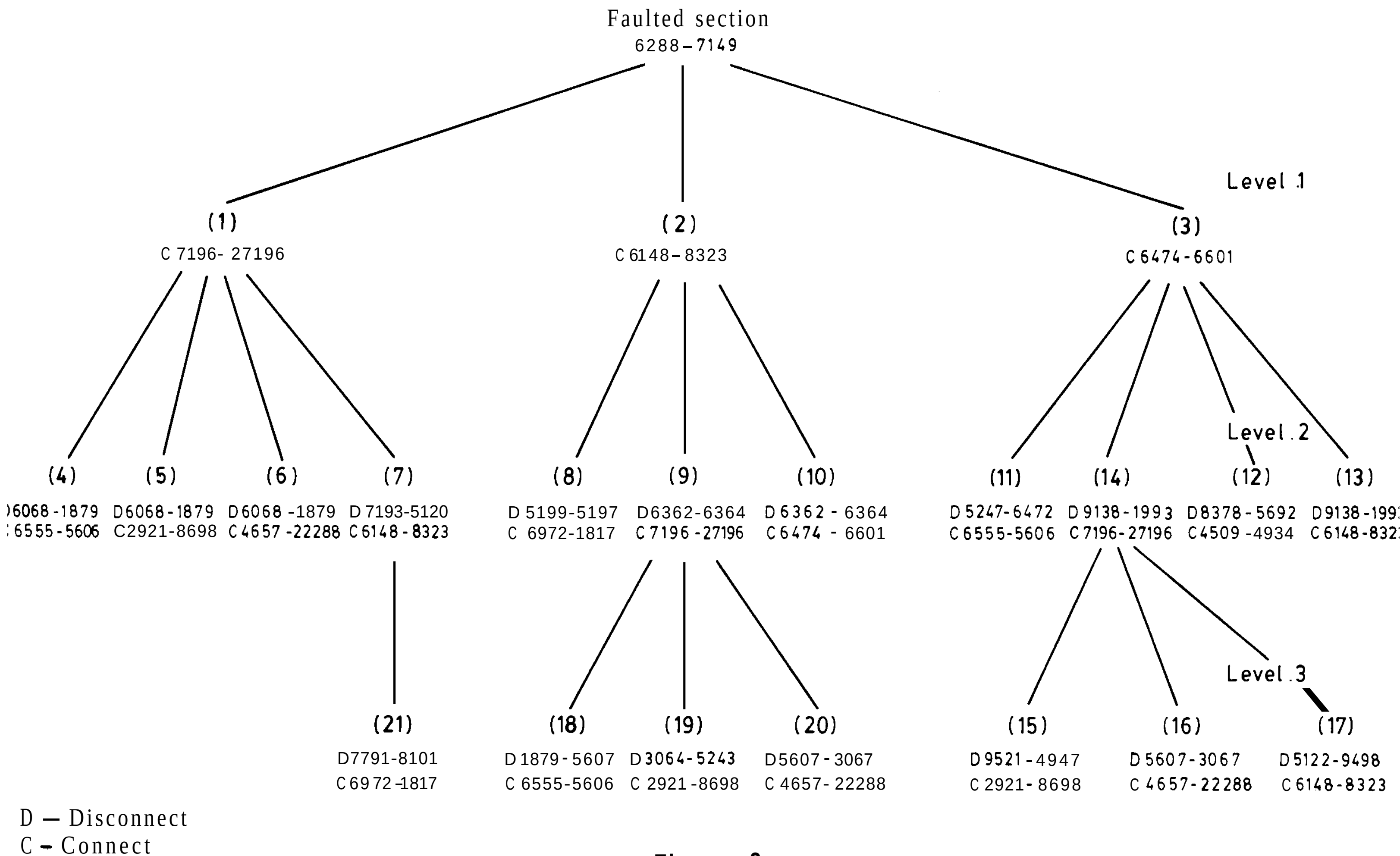
Faulted section
6288–7149
Level .1
(1)
C 7196- 27196
(2)
C 6148–8323
(3)
C 6474-6601
Level .2
(4)
D6068-1879
C6555-5606
(5)
D6068-1879
C2921-8698
(6)
D6068-1879
C4657-22288
(7)
D7193-5120
C6148-8323
(8)
D 5199-5197
C 6972-1817
(9)
D6362-6364
C7196-27196
(10)
D6362-6364
C6474-6601
(11)
D5247-6472
C6555-5606
(14)
D9138-1993
C7196-27196
(12)
D8378-5692
C4509-4934
(13)
D9138-1993
C6148-8323
Level .3
(21)
D7791-8101
C6972-1817
(18)
D1879-5607
C6555-5606
(19)
D3064-5243
C 2921-8698
(20)
D5607-3067
C 4657-22288
(15)
D9521-4947
C2921-8698
(16)
D5607-3067
C4657-22288
(17)
D5122-9498
C6148-8323
D — Disconnect
C – Connect

Figure - 2

FAULT AT 6288-7149

Trial No. 1
Connect 7196 27196
No. of operations: 1.
Overloading of feeder: 50%
Solution unacceptable

Trial No. 2
Connect 6148 8323
No. of operations: 1.
Overloading of feeder: 63%
Solution unacceptable

Trial No. 3
Connect 6474 6601
No. of operations: 1.
Overloading of feeder: 50%
Solution unacceptable

Trial No. 4
Disconnect 6068 1879 Connect 6555 5606
Connect 7196 27196
No. of operations: 3.
Overloading of feeder: 29%
Solution unacceptable

Trial No. 5
Disconnect 6068 1879 Connect 2921 8698
Connect 7196 27196
No. of operations: 3.
Overloading of feeder: 38%
Solution unacceptable

Trial No. 20
Disconnect 5607 3067 Connect 4657 22288
Disconnect 6362 6364 Connect 7196 27196
Connect 6148 8323
No. of operations: 5.
Overloading of feeder: 45%
Solution unacceptable

Trial No. 21
Disconnect 7791 8101 Connect 6972 1817
Disconnect 7193 5120 Connect 6148 8323
Connect 7196 27196
No. of operations: 5
Solution feasible.

Fig. 3: Solutions at peak load

FAULT AT 6288 - 7149

Trial No. 1
Connect 7196 27196
No. of operations: 1
Solution feasible

Trial No. 2
Connect 6148 8323
No. of operations: 1
Solution feasible

Trial No. 3
Connect 6474 6601
No. of operations: 1
Solution feasible

Fig. 4: Solutions at 30% peak load

6. CONCLUSION

The paper describes a method for restoration of supply to areas isolated from the supply on the occurrence of a fault. The method is simple and efficient and is suitable for handling very large systems. The criteria used for optimality is the minimum operation of switchgear. In case no feasible solutions are available, load shedding may have to be resorted to. In India and other developing countries, finding the location of the fault takes very long since the personnel have to go to the location of the lines to find the fault. During this time if solutions for several potential fault locations are found and stored, the time taken to find a solution is not so critical.

It is evident that with growing demand it will become increasingly difficult to find solutions to restore supply if peak load is used for the computation. Using peak load obviously gives a safe solution which is valid at all times of the day. However, the large number of manual operations that may be required to effect the restoration of supply may be difficult to carry out within a short time, especially during the night. The strategy of restoring supply immediately, based on off-peak load and reverting to the one based on peak load (if the solution is different) may reduce complaints and ease pressure on the personnel from the affected customers. Use of estimated load for the restoration procedure is permissible provided the cables may be repaired promptly. The estimation of the load can be done as shown in this paper. This will give faster solutions with lesser number of switchgear to be operated.

7. BIBLIOGRAPHY

[1] K. Aoki, H. Kuwabara, T. Satoh, M. Kanezashi, 'Outage State Optimal Load Allocation by Automatic Sectionalizing Switches Operation in Distribution Systems', IEEE Trans. on Power Delivery, Vol.PWRD-2,No.4,October 1987.

[2] K. Aoki, K. Nara, M. Itoh, T. Satoh, H. Kuwabara, 'A New Algorithm for Service Restoration in Distribution Systems', IEEE Trans. on Power Delivery, Vol. 4, No. 3, July 1989.

[3] T. Sakaguchi, K. Matsumoto, 'Development of a Knowledge Based Systems for Power System Restoration', IEEE Trans. PAS, Vol. PAS-22, No. 2, February 1983.

[4] Chen-Ching Liu, Seung Jee Lee, S.S. Venkata, 'An Expert System Operational Aid for Restoration and Loss Reduction of Distribution Systems', IEEE Trans. on Power Systems, Vol.3, No.2,May 1988.

[5] S.J. Lee, C.C. Liu, S.S. Venkata, 'An Extended Expert System for Service Restoration of Distribution Feeders', IFAC Symposium, Power Systems, Modelling and Control Applications, September 1988.

[6] A.L. Morelata, A. Monticelli, 'Heuristic Search Approach to Distribution System Restoration', IEEE Trans. on Power Delivery, Vol. 4, No. 4, October 1989.

[7] Susheela Devi, D.P. Sen Gupta, Samuel Sargunaraj, 'A Search Technique for Restoring Power Supply in Complex Distribution Systems', VI NPSC, Bombay, June 4-7, 1990.