Backtracking Search Method for the Optimal Restoration of Distribution System during Cold Load Pickup

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Abstract: - Restoration of distribution system in cold weather and after long interruptions creates cold load pickup problem due to loss of diversity among the loads in residential area. Under such conditions the distribution system load may have to be restored step by step, using sectionalizing switches to prevent overheating of substation transformer. The order in which the sections are restored has a significant impact on the total time of restoration. In this paper, an order of sections will be selected either to minimize the total restoration time or to minimize customer interruption duration. Results obtained using Backtracking Search Method (BTSM) is compared with Adjacent Pairwise Interchange Method (APIM) and global search for a test system.

Key-Words: - Distribution system restoration, cold load pickup, step by step restoration.

1 Introduction

Cold Load Pickup (CLPU) appeared first in literature as a problem due to high inrush currents which last a few seconds and prevent the circuit from being re-energized after extended outages [1]. During normal operation diversity among the loads persists and aggregated load on the substation transformers would be less than the connected load. If a distribution system experiences an extended outage, the diversity among these loads would be lost and during restoration undiversified load demand may be much higher than the distribution substation capacity. This condition is known as cold load pickup. The CLPU has four stages. These four stages are inrush current, motor starting current, motor running current and enduring demand. The first three stages are transient and generally last for about 15 seconds but the enduring load may vary from 2 to 5 times the normal load and it may last for several hours [2]. The magnitude and duration of CLPU depend on several factors including outside temperature, duration of outage, the type and rating of devices and customer habits [3].

The issue of CLPU has been dealt with over the years. For example, researchers studied and analyzed CLPU situations and further developed models to characterize it [4-5]. Others investigated the effects of CLPU on the distribution substation transformer [6]. Some researchers have attempted to include CLPU in distribution system design. Specifically Ucak and Pahwa [1] investigated loading of power transformer and its hot-spot and top oil temperatures during CLPU. Wakileh and Pahwa [7] expanded this work by discussing an optimization problem to select power transformer capacity and number of sectionalizing switches for a service area. Later Gupta and Pahwa [8] have proposed a voltage drop based approach to include CLPU in distribution systems design which could predict the most optimal transformer size, feeder sizes, location and number of sectionalizing switches. Adjacent Pairwise Interchange Method (APIM) to optimize the restoration order has been used in [1]. However this method does not guarantee a global minimum solution. The method may get stuck in local minima depending on initial sequence used. Two approaches including Ant Colony and genetic algorithm for optimal restoration of distribution feeders during CLPU were proposed in [2] and [9]. This paper proposed a Backtracking Search Method (BTSM) that doesn't need an initial guess and is simpler and faster than genetic and Ant Colony algorithms.

2 Modeling CLPU

Several models ranging from very simple piece-wise linear model to more complicated physically based models have been proposed for cold load pickup. A comprehensive list is available in [10].

This paper uses a delayed exponential model shown in Figure 1 [1-3], [7-10]. A delayed exponential model is a good analytical model for representation of aggregated load in distribution system during CLPU. Physically based models can predict the CLPU behavior of thermostatically controlled loads quite accurately, but it is difficult to use them to model manually controlled loads. However based on engineering judgment, the aggregate load of manually controlled loads upon restoration is also expected to be higher than normal and after a time delay it will gradually approach a reduced level.

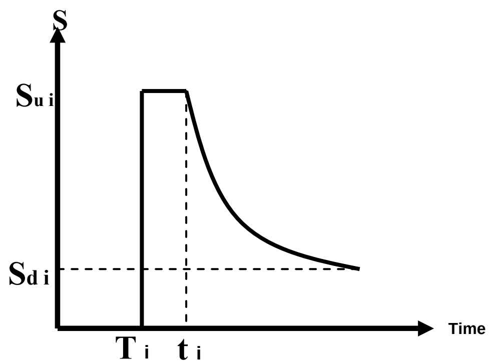

Fig. 1. Delayed exponential model of CLPU

In this model the undiversified load S_U remains constant from restoration time to $t_{[i]}$, the time when load diversity starts and then load decreases exponentially to the diversified load S_d. A mathematical expression for the total load of a section from the CLPU model shown in Figure1 is

$$S_{[i]}(t) = [S_{d[i]} + (S_{U[i]} - S_{d[i]})e^{-\alpha_{[i]}(t-t_{[i]})}] \\ U(t-t_{[i]}) + S_{U[i]}[1-U(t-t_{[i]})]U(t-T_{[i]}) \quad (1)$$

where α is the rate of load decay, $U(t)$ is the unit step function and $T_{[i]}$ is delay part of the load of i'th section.

Depending on the circumstances, utilities can adopt one of the many ways to restore power successfully. Reduced voltage at the time of restoration, adaptive protection, manual sectionalizing and automatic sectionalizing are some of the ways of restoring power [11]. In cold climates and where CLPU condition is happened, restoration is staged after prolonged outage to keep the load demand below the substation transformer rating. Thus sectionalizing switches can be used on distribution system feeders to restore the load in steps in case total load can not be restored in one step [1-2], [9-10].

3 Step by step restoration

The limitations on transformer loading may not allow restoration of the whole system in one step. If the total undiversified load is represented by S_U and loading limit by S_{MT}, then step by step restoration of sections is necessary when $S_U > S_{MT}$.

Let there be n sections to be supplied from the substation transformer. Each section is supplied with the maximum transformer capacity constraint given by:

$$\sum_{i=1}^{n} S_{[i]}(t_i) = S_{MT} \qquad t_i \geq 0 \quad (2)$$

There will be m sections which could be restored in the first step of restoration without violating Eq.(2). Factor m will change depending on undiversified load of sections, loading capacity S_{MT} and priority and precedence constraints. The switching is minimized by maximizing the m, number of sections that are restored in first step.

The sequence in which sectionalizing switches are closed is important since different sequences would result into different restoration times, as undiversified loads of sections are not the same. In this paper, an order of sections will be selected either to minimize the total restoration time or to minimize customer interruption duration. To find the best sequence, Backtracking search algorithm is used which is discussed below:

3.1 Backtracking Search Method (BTSM)

Many problems, which deal with searching for a set of solution satisfying some constraints, can be solved using the Backtracking formulation. In order to apply the Backtrack method, the desired solution must be expressible as a vector $(S_1, S_2, ..., S_n)$ where S_i is chosen from some finite set X_i. Often the problem to be solved calls for finding a vector which maximizes (or minimizes or satisfies) a criterion function $P(S_1, S_2, ..., S_n)$. This method has a major advantage: if it is realized that the partial vector $(S_1, S_2, ..., S_i)$ can in no way lead to an optimal solution, then other possible test vectors may be ignored entirely [12-13].

Backtracking algorithms determine problem solution by systematically searching the solution space for the given problem. This search is facilitated by using a tree organization for the solution space. All paths from the root to other nodes define the state space of the problem. Solution state S_i is the state space X_i for which the path from the root to S_i has the best estimation for criterion function of problem. Once a state space tree has been conceived of for any problem, the problem may be solved by systematically generating other solution states, estimating the criterion function for each state space and finally determining which of these state spaces is solution state. Figure 2 shows a typical solution space.

Figure 3 shows the used backtracking search method.

3.2. Objective functions

3.2.1 Minimization of restoration time

If α_i 's are the same for all the sections, an analytical expression for restoration time $T[i]$ can be derived [1-2], [9].

$$T[k] = -\frac{1}{\alpha} \ln \frac{\prod_{i=m+1}^{k} S_\eta[i]}{\sum_{i=1}^{m} S_\mu[i] \prod_{i=m+1}^{k-1} (S_\eta[i] + S_\mu[i])} \tag{3}$$

where $S_\eta[i]$ *and* $S_\mu[i]$ are defined as

$$S_\eta[i] = S_{MT} - S_{U\,i} - \sum_{j=1}^{i-1} S_{D\,j}$$
$$S_\mu[i] = (S_{U\,i} - S_{D\,i}) e^{\alpha T_i} \tag{4}$$

In restoration process the feeder is needed to be restoring as fast as possible.

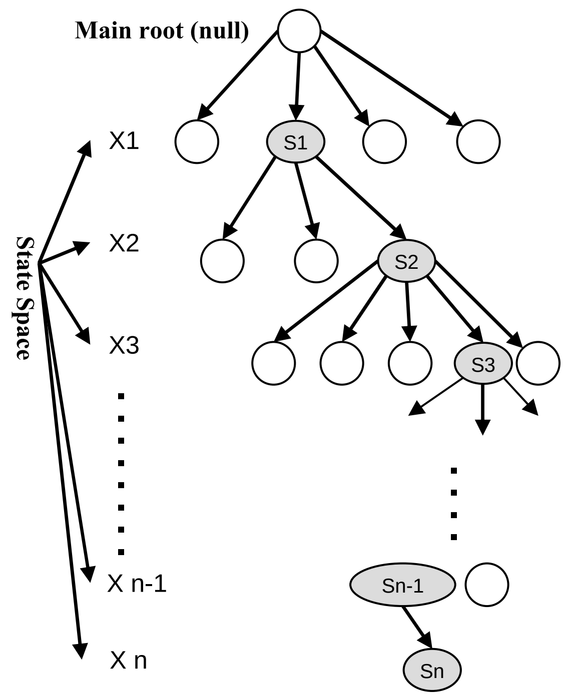

Fig. 2. Solution Space

3.2.2. Minimization of customer interruption duration

Minimization of the customer interruption duration is important because it affects on the system reliability levels. Customer interruption duration (CID) for i'th section is given by the following equation:

$$CID_{[i]} = C_{[i]} (T_{[i]} + T_{OUT}) \tag{5}$$

where $C_{[i]}$ is the number of customers of section i.

Total CID for the distribution system can be written as

$$TCID = \sum_{i=1}^{n} CID_{[i]} = \sum_{i=1}^{n} C_{[i]} T_{[i]} + \sum_{i=1}^{n} C_{[i]} T_{OUT} \tag{6}$$

Last part of equation (6) does not depend on the restoration order and can be dropped out from minimization process [1].

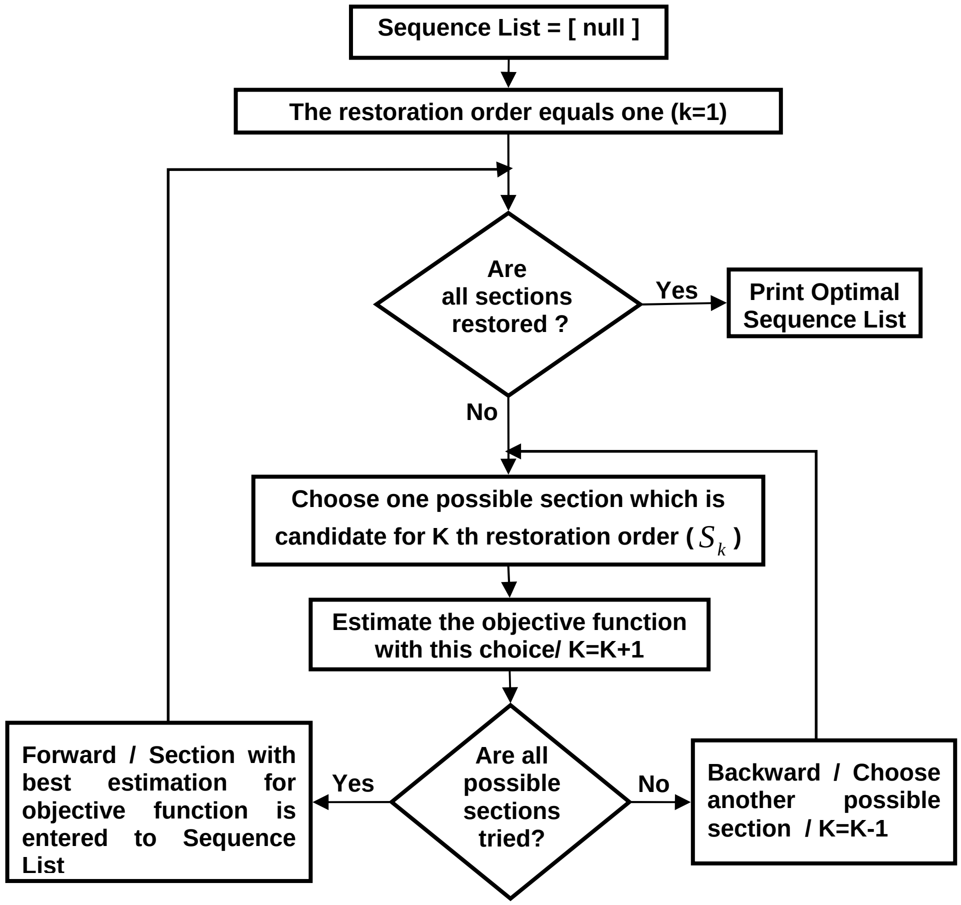

Fig. 3. BTSM algorithm

3.3. Constraints

Temperatures inside a transformer determine its loading capability. Figure 4 shows top oil and hottest-spot temperatures during a typical CLPU [1]. Based on the limitations given by standards [14], maximum undiversified load for different diversified loads and outage durations was determined. In addition to transformer rating limit, the number of switching is another constraint that can be considered.

4. Case study

A numerical example to illustrate restoration procedure for the distribution system shown in Figure 5 is presented in this section. Table 1 gives values of undiversified and diversified load of each section in per unit for an outage duration of one hour. T=30 min and α=0.5 1/hr are considered for all sections. For the example under consideration the value of S_{MT} is 1.45 pu. It is assumed that there are no priority loads.

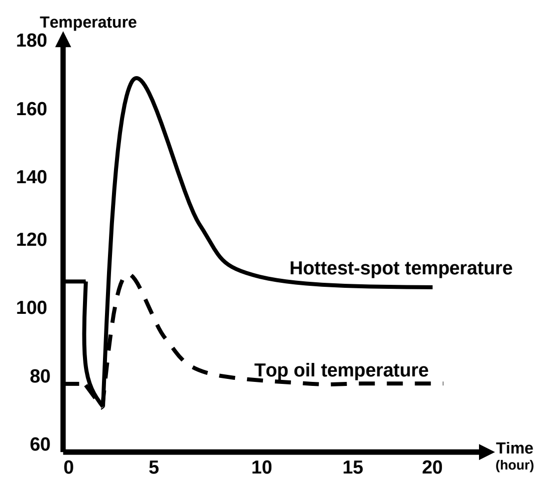

Fig. 4. The top oil and hottest-spot temperature during CLPU

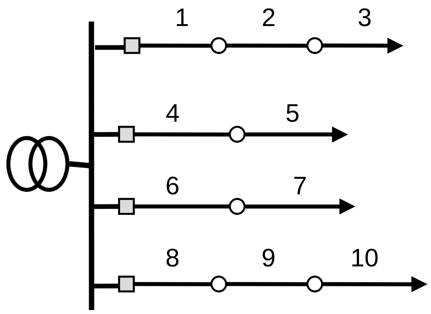

Fig. 5. One-line diagam of a distribution system

Tables 2 to 5 show results of step by step restoration using APIM and BTSM. Table 6 shows results of global search method.

The global search basically searches for all permutation and finds the minimum. So, global search is very time consuming and nearly after 22500 iterations reaches to the goal, while BTSM after 100 iterations reached to the same result. Obviously, with growth of search space, the iterations increase drastically. Number of iterations for APIM is only 20 but this method needs a good initial guess. If this sequence is not chosen appropriately, the algorithm will not reach to an acceptable restoration order.

Table 1 Undiversified and diversified loads of the sections for one hour outage

Sec.No	Su(pu)	Sd(pu)	Ri
1	0.3	0.1	3
2	0.1833	0.1	1.833
3	0.2	0.0833	2.4
4	0.1667	0.05	3.333
5	0.1667	0.1	1.6667
6	0.3167	0.2	1.5833
7	0.2	0.0833	2.4
8	0.2167	0.1167	1.8571
9	0.3667	0.15	2.444
10	0.2667	0.1167	2.2857

Table 2 APIM (Min. Res. Tim.)

Step	Time (min)	Section number which is restored in each step
۱	٠	1 8 6 9 4
۲	63.6	10
۳	109.8	7
۴	157	2
۵	218.6	3
۶	282.6	5

Table 3 BTSM (Min. Res. Tim.)

Step	Time (min)	Section number which is restored in each step
1	0	8 1 2 4 3 9
2	72.8	10
3	147.4	6
4	210.8	7
5	274.7	5

Table 4 APIM (Min. CIDI)

Step	Time (min)	Section number which is restored in each step
1	0	8 1 4 6 9
2	63.6	10
3	109.8	7
۴	157	2
۵	218.6	3
۶	282.6	5

Table 5 BTSM (Min. CIDI)

Step	Time (min)	Section number which is restored in each step
۱	0	8 9 10 4 1
۲	37.9	2
۳	75	3
۴	148.2	6
۵	211.5	7
۶	275.5	5

Table 6 Global search

Step	Time (min)	Section number which is restored in each step
1	0	1 2 3 4 8 9
2	72.8	10
3	147.4	6
4	210.8	7
5	274.7	5

5. Conclusion

Cold load pickup problem (CLPU) is one of the most severe situations that the distribution system experiences when thermal limits are considered. A delayed exponential model is used to model the load during CLPU. It is shown that the model is a good analytical model for representation of aggregated load in distribution system in this situation. This paper proposed a Backtracking Search Method (BTSM) for optimal restoration of distribution system which experiences CLPU problem. BTSM is very suitable for problems which deal with searching for a set of solution satisfying some constraints such as restoration sequence of distribution system's sections during

CLPU. Results obtained using this method for a test system are compared with global search and APIM which highlights the success of the developed method. BTSM is simpler and faster than genetic and Ant Colony algorithms and it doesn't need initial guess.

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