DISTRIBUTION SYSTEM RESTORATION WITH MULTIPLE SUPPLIES AFTER EXTENDED OUTAGES

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Abstract

Restoration of a distribution system following extended outages may cause problems if the supply cannot pick up the initial load. If the initial load is high, either the transformer capacity is increased or step-by-step restoration of sections may be necessary to supply the customers. During step-by-step restoration, a fast procedure is very important because it will reduce the interruption duration of customers and increase the reliability of the system. In this paper, restoration of sections with multiple supplies has been investigated. An algorithm that will minimize the overall restoration time is developed. Restoration capabilities of the system and procedures to return the distribution system to normal operation as fast as possible will benefit not only the operation engineers but also the design engineers.

Keywords: Distribution System Restoration, Cold Load Pickup, Excessive Loads.

I. Introduction

Distribution systems occupy the largest physical region in power systems and therefore, they are highly susceptible to environmental conditions. Bad weather, trees and animals, as well as human errors and equipment failures are responsible for most of the outages. An outage may or may not result in an interruption of service to the customers. Most of the distribution systems do not have built-in redundancy because of their radial nature. So, failure of a distribution component usually results in interruption to the customers. Most of the interruptions are the result of failures occurring in distribution systems. The outages that cause interruptions are important because of unsupplied customers. Thus, the main goal is to supply power to the interrupted customers in minimum time. There are many literatures dealing with distribution system restoration. Some of these papers have presented computer-aided search techniques [1-3], heuristic methods [4-5], knowledge-based approaches [5], and a network flow approach [6]. Mainly, these papers address the issue of searching for the best switching strategy to maximize the number of sections restored and to minimize the time to supply power to the unfaulted areas. This problem is combinatorial in nature; therefore computer analysis becomes difficult and time consuming for large distribution systems.

Advances in computers and communications technology has made it possible to automate several functions in distribution systems. Such automation will make delivery of electricity more efficient, enhance reliability, and lead to more effective utilization and life-extension of existing electricity distribution infrastructure. Moreover, the overall quality of service to the customers can be increased, which will result in more satisfied customers. In addition to operating benefits, other benefits of distribution automation can be realized by using new design concepts. For example, most of existing distribution substations have extra firm capacity to take care of emergencies because very little switching facilities between the substations are available. With distribution automation, the switching between substations becomes possible. Hence, modern substations can be designed with lesser firm transformer capacity because they can depend on extra capacity from a remote substation with the help of switching. Since the switches can be operated remotely, the load transfer between substations can be accomplished very quickly. Integration of such design concepts into distribution automation will provide utilities a modern infrastructure at an optimal cost [7].

In the existing distribution systems, many substation transformers are loaded from 40% to 60% of their rating under normal operation. Hence, the magnitude of initial load during restoration is not a significant problem. However, in the future, due to constraints on capital expenses for system expansion and upgrade, and due to increased reliance on distribution automation, the transformers may be more heavily loaded. Therefore, it is important to investigate impact of initial load in distribution system restoration [8].

Constant load representation of sections during restoration may not be an accurate approach for extended interruptions. The reason is that the diversity among individual loads will exist during normal state whereas it will be lost partially or completely after an extended interruption. Therefore, the load of a section as soon as the section is energized will differ from the load in normal state. Because the undiversified load of the system is larger than the diversified load, restoration problems may occur when there is not enough reserve transformer capacity in the substation. In that case, load behavior of sections and restoration sequence of these sections play an important role in the restoration procedure. Based on the load dynamics of each section, the restoration procedure should be chosen in such a way that some restoration objectives are met.

The rest of the paper has been organized as follows. In Section II, the behavior of thermostatically controlled loads is presented. The previous work about the restoration with one supply is covered in Section III. Section IV is the main contribution of this paper where a restoration algorithm has been proposed. A conclusion is provided at the end of the paper.

II. The Behavior of Thermostatically Controlled Loads

In normal condition, diversity among the thermostatically controlled loads is present. Therefore, the aggregated load is less than the connected load. If an abnormal condition such as an extended outage occurs in a distribution system, some or all thermostatically controlled devices will be on as soon as the power is restored. If an outage involves a large number of customers and has a long duration, it may result in excessive load during restoration. Restoring power to a circuit under such conditions is called cold load pickup (CLPU).

Individual thermostatically controlled devices can be modelled with a simple first-order differential equation. Therefore, the temperature of a house having air-conditioner is given by the equation below;

$$\frac{d\theta(t)}{dt} = -\frac{1}{CR}\left[\theta(t) - \theta_a + w(t)RP\right]. \quad (1)$$

Where, $\theta(t)$ is the inside temperature of the house (°C), θ_a is the ambient temperature (°C), R is the thermal resistance of the house (°C/kW), P is the rating of the air-conditioner (kW), C is the thermal capacity of the house (kWh/°C). The time constant of the house is given by $\tau = CR$ and the heat gain of air-conditioner is given by $\theta_g = RP$.

During steady state condition, one could define the duty cycle, D, of an air-conditioner as

$$D = \frac{d_1}{d_1 + d_0}. \quad (2)$$

Here, d_1 is the On duration and d_0 is the Off duration of the air-conditioner during one period. Average power demand of an air-conditioner can be calculated as the product of the duty cycle and the rating of the air-conditioner. Both d_1 and d_0 can be written as a function of outside temperature, air-conditioner parameters, thermal resistance and capacity of the house, dead band, and thermostat setting of the house [9]. A good approximation for d_w (d_1 and d_0) is

$$d_w \approx \frac{CR\Delta(2w-1)}{\theta_s - \frac{\Delta}{2} - \theta_a + w(\Delta + RP)}. \quad (3)$$

Here, Δ is the dead band of thermostat and θ_s is the thermostat setting. Substituting this result into Equation 2, we get an expression for the duty cycle as a function of outside temperature, thermal resistance, and air-conditioner parameters as

$$D = \frac{\theta_a - (\theta_s - \frac{\Delta}{2})}{RP + \Delta}. \quad (4)$$

Duty cycle changes between zero and one. If ambient temperature is less then the thermostat lower limit, then the air-conditioner will be Off all the time. An extreme case is when the outside temperature exceeds $\theta_g + \theta_s + \Delta/2$. In this case, the air-conditioner will stay On and average inside temperature of the house will never reach the thermostat lower limit. This case corresponds to a duty cycle of one which means that the size of the air-conditioner is too small to cool the house. The duty cycle of an undersized air-conditioner is closer to one whereas the duty cycle of an oversized air-conditioner is closer to zero when it is compared to a normal-sized air-conditioner.

According to Equation 4, the duty cycle of an air-conditioner will change as a function of the ambient temperature. The parameter θ_s is set by the customer and can be considered as constant during the day. Δ, R, and P are the parameters of the air-conditioner and house and they do not change.

There are two important variables that affect the dynamic of an air-conditioner during planned (i.e. direct load control) or forced (i.e. cold load pickup) interruption; the ambient temperature and the duration of the interruption. The change in house temperature as a function of time during an interruption with duration T_{out} is shown in Fig.1. In this case, payback load duration which is shown by Δt can be calculated based on the house and air-conditioner parameters from first order differential equation, Equation 1. Let us assume that

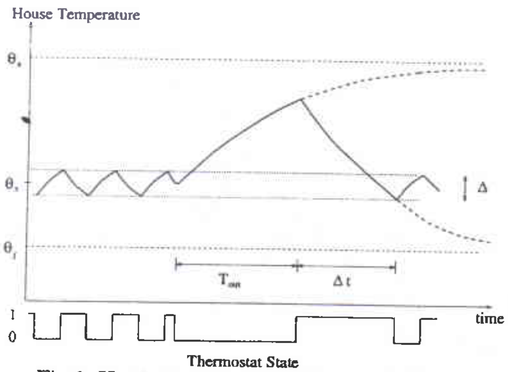

Fig.1. House temperature during an outage [9].

the outage occurred when the house temperature were at θ_s, and at T_{out} the temperature inside the house becomes

$$\theta(T_{out}) = (\theta_a - \theta_s)(1 - e^{\frac{-T_{out}}{\tau}}) + \theta_s . \qquad (5)$$

When the power is restored the house will start to cool down as shown in Fig.1. Thermostat will change its state from one to zero when the temperature reaches $\theta_s - \Delta/2$, that is, the state will change when

$$\theta_s - \Delta/2 = \left[(\theta_a - \theta_s)(1 - e^{\frac{-T_{out}}{\tau}}) + \theta_s - \theta_f \right] e^{\frac{-\Delta t}{\tau}} + \theta_f \qquad (6)$$

is satisfied. Here θ_f is the final temperature value of the house when the air-conditioner is kept on continuously and is given by $\theta_f = \theta_a - \theta_g$. Payback load duration can be solved from Equation 6 to give

$$\Delta t = -\tau \ln \frac{(\theta_s - \Delta/2) - \theta_a + \theta_g}{\theta_g - (\theta_a - \theta_s) e^{\frac{-T_{out}}{\tau}}} \qquad (7)$$

In the payback load duration Δt, the air-conditioner state will be On and the duration will be longer than the steady state On duration of the air-conditioner for the same ambient temperature.

In a distribution system, there are many air-conditioners with different sizes. Moreover, insulation level of the house, lifestyle and the opening of doors and windows will affect the aggregated load. Analytical models for aggregated load could change from a simple straight line model to a more complicated high order polynomial or a sigmoid type function. But, the simulation result [9] confirms that a delayed exponential model is a good representation of the CLPU load dynamic. Therefore, aggregated load change during a restoration is modeled as a delayed exponential function. This model is mathematically simple and yet it accounts for the behavior of aggregated load.

III. Restoration With One Supply

Restoration of excessive loads has been studied before with only a single supply [8,9]. By considering the transformer loading capacity [10], sections are restored in sequence. The load change of each section is assumed to be a delayed exponential and is given by

$$S_i(t) = \left[S_{D_i} + (S_{U_i} - S_{D_i}) e^{-\alpha_i (t - t_i)} \right] u(t - t_i) + S_{U_i} \left[1 - u(t - t_i) \right] u(t - T_i) \qquad (8)$$

where, T_i is the restoration time of i^{th} section, t_i is the time where diversity starts, S_{D_i} is the diversified load level of i^{th} section, S_{U_i} is the undiversified load level of i^{th} section, α_i is the rate of load decay, and $S_i(t)$ is the load of i^{th} section. $u(t)$ is the unit step function.

The time when a section is restored is called restoration time of that section. Restoration times of the sections will depend on the restoration order. Therefore, it is important to introduce an indexing of the sections so that there will be no confusion when referring to the restoration times. Each section will be represented with a number and its restoration order will be enclosed within brackets. For example, if i^{th} section is restored as the first section in the restoration sequence, then the first element of the index will be i; that is, [1] gives the section number, which is restored first.

The transformer load as a function of time with respect to a restoration order can be expressed using Equation 8 of the cold load pickup model,

$$S(t) = \sum_{i=1}^{n} S_{[i]}(t) . \qquad (9)$$

This is a general equation based on restoration time $T_{[i]}$. An analytical expression for $T_{[i]}$ can be derived from Equation 9 only if $\alpha_{[i]}$'s are the same for all sections. Otherwise a closed form solution for the restoration time is not possible. In the Equation 9, n is the number of sections and the restoration times of sections are shown in closed brackets. Detailed analysis of restoration times of sections can be found in Reference 9. The objective is to minimize the time of the last section restored; that is

$$\min \{ T_{[n]} \} . \qquad (10)$$

The restoration procedure with single supply is similar to a single-machine scheduling problem where scheduling times are sequence dependent [11,12]. To minimize the time of the total restoration, Adjacent Pairwise Interchange Method (APIM) is used.

A restoration procedure, which makes use of maximum transformer capacity in the substation, is given below. Usage of maximum available transformer capacity is important because faster restoration of the distribution system will be possible and also installing new capacity to the system may be postponed.

The five-step restoration procedure is given below. It should be noted that **Step 2** itself is an iterative procedure to find the optimum sequence.

The procedure:

Step 1. Choose a maximum transformer capacity between one and two per unit. If there are some pre-determined maximum loading capacity calculations for CLPU load, then use that value to start the iteration. Loading capacity for step-by-step restoration will be smaller than the value when the load is restored in one step.

Step 2. Use the maximum transformer capacity to find the optimum restoration times. Optimum restoration means that the restoration sequence is optimized for an objective function (such as total restoration time, or customer interruption duration, or energy sold) and for the maximum transformer capacity used in this iteration. The optimum sequence, in general, may not be the same for different values for S_{MT} (maximum transformer capacity).

Step 3. The restoration time will give the transformer total load change for step-by step restoration. Based on these restoration times, find the maximum top-oil temperature, the maximum hottest-spot temperature, and loss of life of the transformer. Maximum loss of life that allowed for an emergency situation is 4%. Usually, if transformer maximum temperatures are within the specified limits for CLPU, loss of life does not exceed 4% emergency loading.

Step 4. If one or both of the top-oil and the hottest-spot limits are exceeded, then reduce the maximum transformer capacity S_{MT}. Otherwise, increase S_{MT}. The amount to reduce or increase S_{MT} depends on the accuracy desired by the operation engineer. As a suggestion, in the first iterations, the amount used could be high (0.1 per unit) and could be reduced when the thermal limits are within a small range. Also, some other techniques such as the bisection method could be applied to speed up the procedure. A very accurate result is not necessary because of the approximations made in the use of a first order model for transformer thermal characteristics.

Step 5. Repeat **Step 2**, **Step 3**, and **Step 4** until the top-oil temperature limit, or the hottest-spot limit, or loss of life limit of the transformer is reached.

IV. Restoration With Multiple Supplies

Tie switches between substations in the distribution systems allow the loads to be connected to different supplies. Therefore, a flexible restoration is possible by the help of tie switches. Restoration of loads with multiple supplies during CLPU is more difficult to optimise then the restoration with only one supply. Because in multiple supplies case, not only the optimum order of sections has to be found but also which load will be picked up by which supply has to be determined.

In the distribution region, lets assume that there are *n* sections and *m* substation transformers. The maximum loads for *m* transformers are S_{MT_1}, S_{MT_2} ... S_{MT_m}. The problem is then to restore *n* sections using *m* transformers as fast as possible without violating the constraints. The load of k^{th} transformer during restoration can be written as

$$S_k(t) = \sum_{i=1}^{n_k} S_{k,[i]}(t) \qquad k = 1,2,\ldots m. \tag{11}$$

Where, n_k is the number of sections restored by the k^{th} transformer and $S_{k,[i]}(t)$ is the load of $[i]^{th}$ section restored by the k^{th} transformer. For a feasible solution, all the sections have to be restored; that is

$$n = \sum_{i=1}^{m} n_k \,. \tag{12}$$

Restoration time of a section can be written analytically if the load decays at the same rate in all sections ($\alpha_{[i]} = \alpha$). In general, some or all sections may have a different rate of load decay. Therefore, it is not possible to find a closed form solution for the restoration times. A numerical technique such as Newton-Raphson method can be used to find the restoration time of each section. If the restoration time of i^{th} section in the k^{th} transformer is $T_{k,[i]}$, then the restoration time of the last section for the k^{th} transformer will be $T_{k,[n_k]}$. Based on these assumptions, optimization problem becomes

$$\min\{\max\ \{T_{k,[n_k]}\}\}, \tag{13}$$

subject to transformer loading limits and distribution system topology. The distribution loads are picked up by the substation transformers in such a way that the last load (section) restored gives the minimum time. In this minimization problem, the difficulty arises because of the combinatorial nature of the problem. Furthermore, the restoration times of the sections are sequence dependent and the transformer loading limits are not simple constant constraints. The proposed restoration algorithm for multiple supplies is given below.

The Restoration Algorithm:

1. Split *n* sections to *m* transformers.
2. Use APIM to minimize the total restoration time of each transformer, $\min_k T_{k,[n_k]}$.
3. Find $\max_k T_{k,[n_k]}$, Find $\min_k T_{k,[n_k]}$.
4. From the two restorations, interchange two sections, which will reduce maximum $T_{k,[n_k]}$ most. Check if there is more reduction when only one section is changed.
5. Go to (2) and do until there is no improvement in the overall restoration time.

In this algorithm, second step is the restoration procedure for the single supply. The constraints in this restoration algorithm are the transformer thermal limits and distribution topology.

The algorithm above will not guarantee the global minimum. But, a few different initial sequences can be used to increase the likelihood of obtaining a good solution.

VI. Conclusion

Fast restoration of supply is an important action to be followed because of the interrupted customers and reliability of the system. Especially, in the competitive environment, utilities and distribution companies would not be willing to lose customers, therefore any solution that will reduce interruption duration is a welcomed improvement.

An algorithm that will reduce the overall restoration time of distribution system in case of excessive loads has been proposed for the multiple supplies in this paper. The algorithm is an extension of previous work done for a single supply case. Restoration capabilities of the system and procedures to return the distribution system to normal operation in minimum time will benefit both the operation engineers and the design engineers.

Research to include other constraints such as the thermal and the maximum current limits of feeders, maximum voltage drop at the end of feeders during restoration, and limits of protective equipment to the restoration algorithm above is continuing.

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