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DISTRIBUTION SYSTEM RESTORATION AFTER PROLONGED OUTAGES

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ABSTRACT

Most of the customer outages are the results of some problems related to distribution systems. Prolonged outages may cause cold load pickup problems because of the increased penetration of thermostatically-controlled devices and the loss of diversity among these devices. Since loads higher than normal may be expected after prolonged outages, restoration problems may occur when there is not enough reserve capacity in the substation. Therefore, distribution system restoration becomes an important issue and it directly affects costumer satisfaction and system reliability level. In the near future, with the increase in automation of distribution systems, the reserve margin of substation capacity will decrease. The decreased margin would require an effective restoration procedure following prolonged outages. Algorithms that will reduce the overall restoration time of distribution systems in case of excessive loads has been studied in the literature and it seems that it will be studied further in the next decays. This review paper intends to give a summary of what has been done and outlines the proposed restoration procedures for cold load pickup for single and for multiple distribution system supplies.

Keywords: Distribution system restoration, Cold load pickup, Distribution automation.

UZUN KESİNTİLER SONUNDA DAĞITIM SİSTEM RESTORASYONU

ÖZET

Elektrik kesintilerinin çoğu dağıtım sistemlerinde oluşan problemler sonucu ortaya çıkmaktadır. Dağıtım sistemlerinde termostat kontrollü cihazların artması ve bu cihazlar arasındaki eşzamanlılık katsayısının uzun süreli kesintiler sonunda kaybolması, soğuk-yük sorununa neden olmaktadır. Soğuk-yük uzun kesintiler sonunda sisteme tekrar elektrik enerjisi verilmesi esnasında aşırı yük yaratır ve indirici merkezlerde yeterli transformatör kapasitesinin bulunmaması halinde restorasyon sorunu çıkarabilir. Dağıtım sistem restorasyonu müşteri memnuniyetini ve sistem güvenilirlik seviyesini doğrudan etkiler ve bu nedenle üzerinde önemle durulmalıdır. Yakın gelecekte, dağıtım sistem otomasyonunun yaygınlaşması ile indirici transformatör kapasitesinin azalacağı ve azalan bu farkın, uzun süreli kesintiler sonunda etkili bir restorasyon prosedürü gerektireceği ortaya çıkmaktadır. Aşırı yükler durumunda dağıtım sisteminin toplam restorasyon zamanını azaltacak algoritmalar literatürde bulunmaktadır ve gelecek on yıl içinde daha da artacak gibi görünmektedir. Bu derleme makalesi uzun süreli kesintiler sonunda dağıtım restorasyonu konusunda yapılan çalışmaları özetlemeyi amaçlamakta ve soğuk-yük restorasyonunda yüklerin tek veya birçok kaynaktan beslenme durumunda literatürde önerilen restorasyon prosedürü üzerinde durmaktadır.

Anahtar Sözcükler: Dağıtım sistem restorasyonu, Soğuk-yük restorasyonu, Dağıtım otomasyonu.

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1. INTRODUCTION

Growing demand for electricity, maintaining high service reliability, and a requirement for low environmental impact are some of the challenges currently facing electric utilities. Increased use of computers and advanced technologies for automation may provide answers to meet these challenges. At the distribution level, Distribution Automation (DA), which is an application of advanced computer and communication technology for automation of distribution functions, is increasingly becoming an important research and application area among utilities.

During the past decade, gradually more and more functions in the distribution systems have been automated [1-14]. Although such automation has not yet received a wide-spread acceptance, it is very likely that in the near future most of the distribution systems will be automated. Feeder deployment, substation transformer load balancing, voltage/var control, automatic sectionalizing, and load control are some of the functions that can be implemented in an automated distribution system. Automation will result in economic savings and improved system reliability indices. For example, the faulted parts of the power distribution system can be identified with the aid of computers using the methods suggested by several authors [15-19]. Quick identification of the faulted parts will increase the system reliability. Also, automatic load transfer capability will allow distribution systems to work with less margin between supply and load during normal operation. In general, distribution automation will reduce the need for redundancy, defer construction of new facilities and maintain reliability with lesser resources [9].

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 interruptions to the customers. More than 90% of the interruptions are result of failures occurring in distribution systems [20]. 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. Many papers dealing with distribution system restoration has appeared in the literature. The authors of these papers have presented computer-aided search techniques [12, 18, 21-28], heuristic methods [29-31], knowledge based approaches [32], and a network flow approach [33]. A selection of papers about distribution restoration can also be found in [34]. All these papers address the issue of cold load pickup, transformer thermal behavior, and search for the best switching strategy to maximize the number of sections restored and to minimize the time to supply power to the unfaulted areas. Reliability evaluation [35] and design aspects of distribution systems [36] have also been studied based on cold load pickup dynamics. Distribution system restoration is combinatoric in nature; therefore computer analysis becomes difficult and time consuming for large distribution systems.

In a restoration procedure, the assumption usually is that the loads in a distribution system are constant throughout the restoration. This assumption does not cause any restoration problem if the total system load is equal to or smaller than the system capacity. Otherwise, some parts of the distribution system must be shedded or if possible, they must be supplied power from neighboring substations via tie switches until the fault is cleared.

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. We will use the term “diversified load” for the load in normal state and “undiversified load” for the load upon restoration. 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 the future, with the increase in automation of distribution systems, the reserve margin of substation capacity will decrease. The decreased margin will require different ways of restoration following extended and widespread outages. Although such occurrences are not common, the effects could be severe and may last for a long time. Therefore, it is important to restore the system as fast as possible to improve reliability and customer satisfaction. For this, transformer capacity for excessive loads becomes an important parameter. Therefore, some of the latest studies investigate improved models to represent the thermal dynamics of power transformers to be able to use the maximum available transformer capacity [37-39].

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. For example, one of these objectives is to minimize customer interruption duration. The customer interruption duration directly affects the reliability of the system. The shorter the customer interruption is, the more reliable the system will be.

This paper is organized as follows. First, an overview of load behavior in a typical residential distribution system is given by emphasizing thermostatically controlled loads. Then, cold load pickup dynamics for an individual air-conditioner and for the aggregated load of many air conditioners are discussed. Restoration procedures for single and for multiple supplies are outlined in the next two sections and a conclusion is given in the last section.

2. RESIDENTIAL LOAD BEHAVIOR AFTER AN INTERRUPTION

Individual loads on a residential feeder can be categorized into two different groups: thermostatically-controlled and manually-controlled. In general, thermostatically-controlled devices such as air-conditioners, heaters, and heat pumps provide the largest contribution to the total load in a typical house. Manually-controlled loads are switched on and off by occupants of the house in undetermined fashion. The life-style of the occupants of the house has a significant influence on the contribution of these loads to the total load of the house. During normal conditions, diversity among loads is present, and therefore, the aggregate load of a number of houses 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. Similarly, the aggregate load of manually-controlled devices will be higher than normal upon restoration because more people may want to use different devices. 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).

CLPU currents can be categorized into four phases according to the current levels and durations. These phases are inrush, motor starting, motor running and enduring current phases. The first three phases last approximately less than 15 seconds and the current may reach 5 to 15 times of the pre-outage current, [40-43]. The enduring current phase follows the third phase and continues until the normal diversity amongst the loads is re-established. The load in this phase may vary from 2 to 5 times of the diversified load level. This phase may last for several hours depending on outage time and outside temperature. The magnitude and duration of load during CLPU will depend on the following factors: outside temperature, duration of outage, the type and ratings of devices. CLPU appeared first in the literature as a problem due to high inrush currents that last a few seconds and prevent the circuit from being re-energized after extended outages. Application of very inverse characteristic relays or sectionalizing the distribution systems were some of the solutions engineers used to overcome the problem. Since then, thermostatically-controlled devices in distribution systems have increased [40, 44]. These types of loads may cause restoration problems during CLPU before they cause serious overload problems in normal operation. Therefore, sustained load after restoration becomes an important issue for thermal and loading limitations of distribution equipment. Utilities do not encounter CLPU problems often. Therefore, an increase in thermostatically-controlled devices in a distribution system may go unnoticed; but during CLPU this type of loads may exceed system capacity. In that case, one of the traditional ways of dealing with the CLPU problem is sectionalizing the system and restoring power to the sections using manual switches. For example, manually-operated sectionalizers have been used successfully to deal with the enduring portion of CLPU [45]. Some utilities have studied application of automated sectionalizing in their distribution systems [46]. In these studies, time of operation of sectionalizers during an actual restoration is based on trial and error. If closing of a sectionalizer results in excessive load, it is opened and reclosed after a time delay. In a manual situation, the operator has to coordinate with field personnel using radio communication. However, in an automated system, the operator can read meters to obtain field data as well as operate the sectionalizers remotely from the control center.

3. CLPU MODEL

In the 1940's, some power companies had problems with re-energizing the feeders after outages occurred [41]. Power companies encountered this difficulty while attempting to reclose the breaker on certain feeders after an outage. The breaker would trip upon reclosure giving the impression of a persistent fault. Commonly, this problem occurred after relatively long interruptions and on residential feeders with no evidence of persistent fault. Continued investigation of the problem eventually led to the main cause of the trouble, loss of diversity in the circuit. Motor starting currents and other household appliance currents were responsible for tripping the breaker upon restoration. Engineers proposed some solutions to deal with these high-magnitude-short-duration currents which they enacted successively. Usage of very inverse characteristic relays and sectionalization of the feeders continue to be the two most popular solutions [42, 43, 47].

The first phase of the CLPU problem, as mentioned earlier, was caused by very high inrush and motor starting currents which interfered with the normal operation of protection equipment. Enduring current, which is the result of loss of diversity, did not capture attention in the 1940's and 1950's. Partially, this was because the current was not as high as inrush and motor starting currents. Also, long duration of enduring current did not force the thermal limits of distribution equipment because of large margins between substation capacity and system load. Large margins were necessary for high system reliability since the distribution systems were in infancy state and load supply from other substations was either very limited or did not exist. Although no problem existed at that time with the enduring component of restoration, Oliver Ramsaur mentioned it in his 1952 paper [43] as a conclusion that enduring current might limit the amount of load that could be picked up at once, and suggested that a sectionalizing scheme should provide a solution to this problem.

Since then, increased penetration of thermostatically-controlled devices such as air-conditioners, water heaters, heat pumps, etc. has resulted in some investigation of enduring currents caused by CLPU. Starting from late 1970's, more literature has appeared to predict and analyze CLPU behavior. In 1979, J.E. McDonald, A.M.Bruning, and W.R. Mahieu [40] studied electrically heated homes to predict the magnitude and the duration of the peak demand following a power outage in cold weather. Their work was experimental and one of the first attempts to predict magnitude and duration of peak demand as a function of outside temperature and outage duration. W.H. Miller, A.S. Serhal, and E. Morris have used the same model with slight modifications in [48]. However, the results could only be applied to the systems with similar type of loads. Therefore, a more general description of the load was needed. C. Y. Chong and A. S. Debs [49] gave a physically based load model for individual loads as a function of weather and human use patterns. Their methodology consists of two basic steps: first, modeling of the individual electrical loads and second, aggregation of these loads to find the total demand.

Following that, physically based load models which make use of stochastic theory have been investigated in detail by many authors. Reference [50] presents and discusses five mathematical models that have been studied in the literature. Aggregated load behavior, when a large number of customers are considered, can be determined based on these models either by use of numerical techniques to solve partial differential equations derived from individual load model or by Monte Carlo simulation based on the stochastic difference equation given in [50]. Lately, uncertainties in aggregated thermostatically-controlled loads using a state queueing model are investigated to study the impact of price responsive demand for competitive power market [51].

On the other hand, instead of stochastic and detailed models, simplified models are used to find the effect of CLPU on substation and distribution transformers. Because thermal response of a transformer to a load is slow, simplified models are sufficient to analyze loading capabilities. Wilde [52] investigated the effects of CLPU on the substation transformer using a model in which post-outage load is constant for some time and then decreases linearly from undiversified load to diversified load. J. Aubin, R. Bergeron, and R. Morin did a similar study using a piece-wise linear CLPU model to find the overloading capability of distribution transformers [53].

3.1. Thermostatically-Controlled Load Dynamics

A discussion based on a simple model for a thermostatically-controlled load developed by Ihara and Schweppe [54] will be presented in this section. According to this model, the temperature of a house having an air-conditioner is given by

$$\frac{d\theta(t)}{dt} = -\frac{1}{\tau}\left[\theta(t) - \theta_a + w(t)\theta_g\right] \tag{1}$$

Heating loads will also have the same type of characteristic. The only difference is the sign of binary variable or thermostat state $w(t)$. The value $\theta(t)$ is the inside temperature of the house, θ_a is the ambient temperature, θ_g is the temperature gain of the air-conditioner, and τ is the time constant of the house. The variable $w(t)$ is a binary variable denoting the state of the air-conditioner (OFF=0 and ON=1.) The state changes when the temperature of the house reaches the thermostat upper or lower limit given by $\theta_S + \Delta/2$ and $\theta_S - \Delta/2$, respectively. Here, θ_S is the thermostat set temperature and Δ is the dead band temperature. Figure 1 shows the state of thermostat and house temperature as a function of time during normal conditions. When the inside temperature of the house reaches the thermostat upper limit, air-conditioner state changes from zero to one, and when the lower limit is reached, the state changes from one to zero.

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

$$D = \frac{d_1}{d_1 + d_0} \tag{2}$$

Here, d_1 is the ON duration and d_0 is the OFF duration of thermostat during one period as shown in Figure 1. 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, gain of air-conditioner, dead band, and thermostat setting of the house. A good approximation for d_W (d_1 and d_0) is

$$d_W \approx \frac{\tau\Delta(2w-1)}{\theta_S - \frac{\Delta}{2} - \theta_a + w(\Delta + \theta_g)} \tag{3}$$

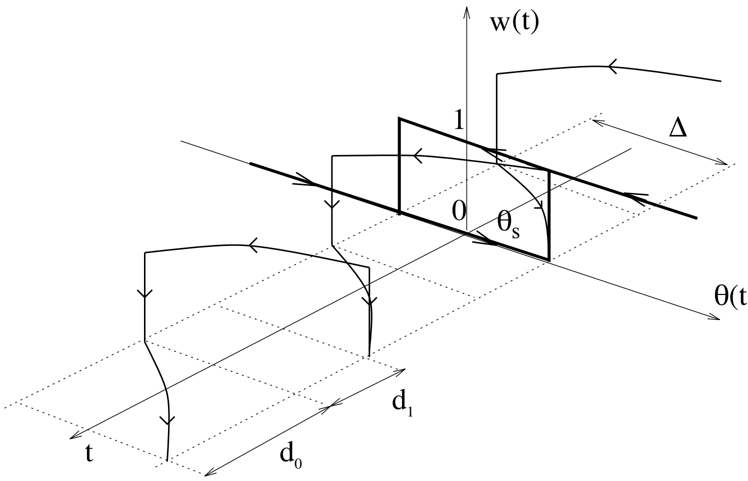

Figure 1. The state of thermostat and house temperature as a function of time.

Substituting this result into Eq. 2, we get an expression for the duty cycle as a function of outside temperature and air-conditioner parameters as

$$D = \frac{\theta_a - (\theta_s - \frac{\Delta}{2})}{\theta_g + \Delta} \tag{4}$$

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 air-conditioner is too small to cool the house.

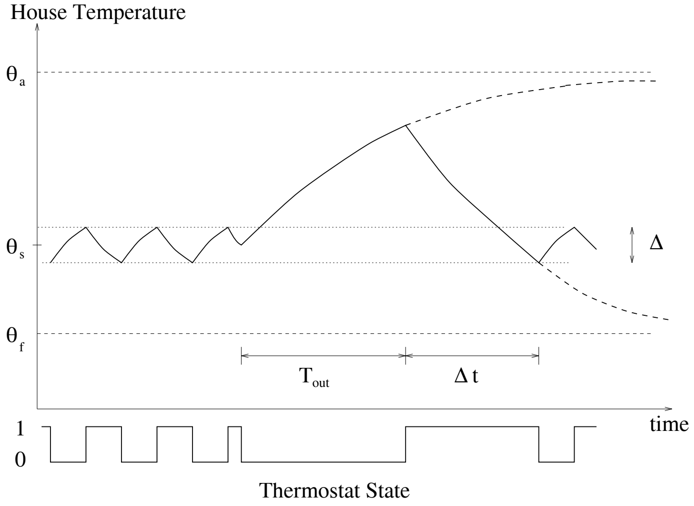

Figure 2. House temperature during an outage

There are two important variables that affect the dynamics of an air-conditioner during planned (i.e. direct load control) or forced (i.e. cold load pickup) interruption of an air-conditioner; 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

Figure 2. 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, Eq. 1. Let us assume that the outage occurred when the house temperature were at θ_s and at T_{out} the temperature inside the house becomes

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

When the power is restored the house will start to cool down as shown in

Figure 2. Thermostat will change its state from one to zero when the temperature reaches $\theta_s - \Delta/2$, that is, the state will change when

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

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 Eq. 6 to give

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

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.

Now consider that, 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. Therefore, payback duration of each air-conditioner will be different. Then, the problem becomes how to find an aggregated load model for distribution restoration. This model needs to be mathematically simple and yet it should account for the behavior of aggregated load as closely as possible.

3.2. Aggregated Load Model

The difficult aspect of the work is the selection of a suitable model to represent dynamics of aggregated load for the enduring portion of CLPU. The model should be mathematically simple and yet it must account for the behavior of aggregated load as closely as possible. Analytical models could change from a simple straight line model to a more complicated high order polynomial or a sigmoid type function. High order polynomial and sigmoid type functions have the potential to make the problem very complicated and intractable. At the same time, simple straight line models do not accurately represent the load behavior.

Only extended outages will be considered here because they are the most severe case in distribution systems. In extended outages, diversity is completely lost and the load is the highest immediately upon restoration. Generally, it is considered that the diversity is completely lost if the outage lasts more than half an hour. Higher than normal load may be expected for shorter outages but their effect on distribution system may not be as important as extended outages. Therefore, the aggregated load model does not need to account for the behavior of the partial loss of load diversity in the system.

Actual restoration data adequate to justify the models used for CLPU are extremely rare. Generally utilities record 15 minutes average demand and this resolution is very low to verify CLPU models. In [52], two sets of high resolution current readings in the same circuit during CLPU restoration are given. In this, load change from undiversified to diversified level in the circuit may be closely represented by an exponential function. However, an exponential function model does not take into account the duration of undiversified load. It assumes that the diversity starts just after restoration. Therefore, to include the duration of undiversified load in an analytical model, a delayed exponential function is used to model CLPU behavior of aggregated loads in distribution system as shown in Figure 3 [55]. Also, a delayed exponential model for cold load pickup of thermostatically-controlled devices has been suggested by Lang *et. al*. [44]. The simulation results using physically based load models confirm that a delayed exponential model is a good representation of the CLPU load dynamic [59]. In the delayed exponential model, there is a sharp cut-off between the horizontal part and the exponential part which is not observed in the results obtained using simulation. But the error due to this sharp cut-off is not excessive. The delayed exponential model offers accuracy and simplicity and thus is very attractive for representing cold load pickup of thermostatically-controlled loads, particularly, if a large number of houses are considered to determine the aggregate load.

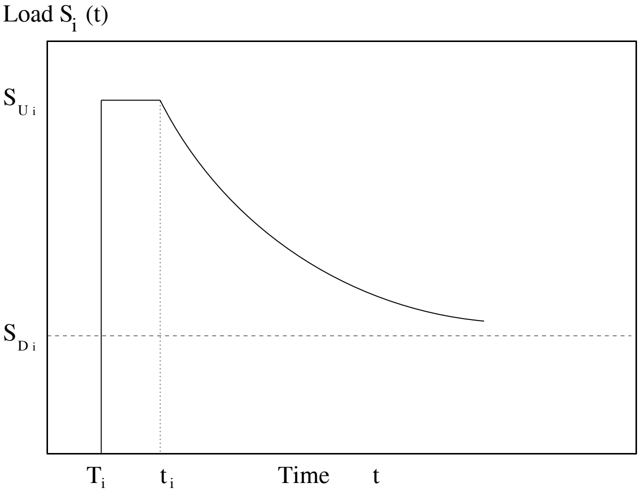

Figure 3. CLPU model of aggregated load of i^{th} section in distribution system

In the delayed exponential model, undiversified load S_{U_i} remains constant from restoration time T_i to t_i where diversity starts and after t_i load decreases exponentially to diversified load level S_{D_i} for i^{th} section of the distribution system as shown in Figure 3. A mathematical expression for this model can be written as

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

where α_i is the rate of decay of load on i^{th} section, and $S_i(t)$ is load of i^{th} section. $u(t)$ is a unit step function given by

$$u(t) = \begin{cases} 1 & for \quad t \geq 0, \\ 0 & for \quad t < 0. \end{cases} \tag{9}$$

For $T_i < t < t_i$, diversity is completely lost and all thermostatically-controlled devices are in the ON state. After t_i, devices start entering the cyclic state and the load in that section will decrease until full diversity is restored.

In addition to air-conditioning and heating loads, the houses have other loads. Of these loads, refrigerator, freezer, and water heater are thermostatically-controlled whereas some loads turn on or off depending on the actions taken by the occupants of the houses. Few works on models of water heater loads are available [49, 56, 57], although it is not as comprehensive as that of space conditioning loads. However, it appears that the cold load pickup characteristics of water heaters are very similar to the space conditioning loads. The main difference is that the delay part following the restoration of power will be smaller than space conditioning and also the drop off to normal load will be faster. No specific information is available on refrigerator and freezer loads; but it can be assumed that they will also have similar characteristics. Thus, when all of the loads are added to determine the aggregate load during cold load pickup, the shape of the load should be similar to that of the space conditioning load because it is the dominant part of the total load. Water heaters, refrigerators, and freezers will have an influence on the delay part and the rate of decay of the load. Aggregated load of manually-controlled devices may have a higher value than normal upon restoration following an extended outage. This load will also reduce to normal value with time. Manually-controlled loads may also appear as noise and distort the load shape. However, since the total load will be an aggregate load over a large number of houses, the distortion will be averaged out. Thus, the delayed exponential model again is a good model for the total load during cold load pickup.

Next two sections discuss methods on how to restore sections of distribution system considering delayed exponential model for single source and multiple sources.

4. RESTORATION WITH SINGLE SUPPLY

Restoration of excessive loads has been studied in the literature by considering the transformer loading capacity [58-60]. Without exceeding the transformer capacity, sections are restored in sequence. The load change of each section is assumed to be a delayed exponential and is given by Eq. 8. 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 total transformer load as a function of time with respect to a restoration order can be expressed using Eq. 8 of the cold load pickup model,

$$S(t) = \sum_{i=1}^{n} S_{[i]}(t) \tag{10}$$

This is a general equation based on restoration time $T_{[i]}$. An analytical expression for $T_{[i]}$ can be derived from Eq. 10, only if $\alpha_{[i]}$'s are the same for all sections. Otherwise a closed form solution for the restoration time is not possible. In Eq. 10, 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 [59]. The objective is to minimize the time of the last section restored; that is

$$\min\{T_{[n]}\}. \tag{11}$$

The restoration procedure with single supply is similar to a single-machine scheduling problem where scheduling times are sequence dependent [61, 62]. In addition to other methods, Adjacent Pairwise Interchange Method (APIM) may be used to minimize the time of the total restoration.

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.

5. RESTORATION WITH MULTIPLE SUPPLIES

Tie switches between substations in the distribution systems allow the loads to be connected to different supplies. Therefore, loads could be supplied from different transformers by the help of tie switches. Restoration of loads with multiple supplies during CLPU is more difficult then the restoration with only one supply. Because in multiple supplies case, one needs to find not only the optimum order of sections but also which section will be picked up by which source [63].

In the distribution region, let's 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. The load of k^{th} transformer during restoration can be written as

$$S_k(t) = \sum_{i=1}^{n_k} S_{k,[i]}(t) \qquad k = 1,2,...,m. \tag{12}$$

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

$$n = \sum_{i=1}^{m} n_k. \tag{13}$$

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

$$\min\{\max_k \{T_{k,[n_k]}\}\}, \tag{14}$$

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. A restoration procedure is described below.

The procedure:

Step 1. Assign n sections to m transformers.

Step 2. Use APIM to minimize the total restoration time of each transformer, $\min_k T_{k,[n_k]}$.

Step 3. Find $\max_k T_{k,[n_k]}$, Find $\min_k T_{k,[n_k]}$.

Step 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.

Step 5. Go to Step 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.

6. CONCLUSION

Fast restoration of electrical energy to consumers is an important issue because the utilities need to decrease the interruption duration of customers and increase the 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.

Since cold load pickup is one of the most severe conditions that a distribution system experiences, 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. However, a good knowledge of load behavior during cold load pickup is important for implementation. In the future, wide availability of high resolution data from the field during an actual restoration can provide validation or improvement of the cold load pickup model used in the literature.

Algorithms that will reduce the overall restoration time of distribution systems in case of excessive loads has been studied in the literature and it seems that it will be studied further in the next decay. This review paper intends to give a summary of what has been done and also it outlines the proposed restoration procedures for cold load pickup for single and for multiple distribution system supplies.

Distribution restoration studies in conjunction with distribution automation will allow the distribution systems to be operated with less spare transformer capacity. Hence, utilities will be able to accrue financial savings by deferring upgrades of existing transformers and installation of new transformers.

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