Prediction of electric heating load component of distribution feeder loads using statistical modeling
by Vijay Singh

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

Abstract:
A statistical model has been developed to represent the thermodynamic behavior of buildings. The model uses an analogous electric circuit to represent the thermodynamic characteristics of each building. The building model parameters are gaussian distributed, each with a specific mean and standard deviation. A computer program has been written which uses this model to predict the heating load component of the distribution load via simulation. The program can predict the feeder electric heating load demand under continuous power supply as well as after a power outage. It is specifically useful for predicting the feeder cold load pickup currents on cold winter days. The program has several features including allowing for changes in the ambient temperature during the outage and changes in the service voltage. Simulation results are presented and some experiments towards validating the computer program are 'included.

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APPROVAL

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Vijay Singh

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 8/20/92

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ABSTRACT

A statistical model has been developed to represent the thermodynamic behavior of buildings. The model uses an analogous electric circuit to represent the thermodynamic characteristics of each building. The building model parameters are gaussian distributed, each with a specific mean and standard deviation. A computer program has been written which uses this model to predict the heating load component of the distribution load via simulation. The program can predict the feeder electric heating load demand under continuous power supply as well as after a power outage. It is specifically useful for predicting the feeder cold load pickup currents on cold winter days. The program has several features including allowing for changes in the ambient temperature during the outage and changes in the service voltage. Simulation results are presented and some experiments towards validating the computer program are included.

CHAPTER 1

INTRODUCTION

Restoring power to a circuit after a power outage during cold winter days which is commonly called Cold Load Pickup can result in feeder over currents, which may cause circuit breaker tripping. This is because in cold days a large number of buildings will demand heating power at the same time after the outage, thus making the load undiversified and causing excess currents to flow. It is therefore of interest to predict the magnitude and duration of the overload following an outage.

According to Audlin and Pratt [1] there are four separate time phases of the increased restoral pickup demand on any feeder after an outage.

1) The first phase provides inrush current to cold lamp filaments and to the distribution transformers.
2) The second phase lasts for about 1 second or less and provides the motor starting current.
3) The third phase lasts for about 15 seconds and provides the motor acceleration currents.
4) The fourth phase can last for several hours and is due to an abnormal number of appliances energized. These appliances are mostly the heating furnaces.

The solution to the first three phases is relays with extremely inverse settings.

This thesis makes an analysis of the fourth phase current, which is the heating current during cold ambient temperatures. The duration for which this fourth phase current or the Cold Load Pickup current lasts is dependent on the following factors:

1) Ambient temperature;
2) Length of outage;
3) Number of customers on the feeder;
4) Number and type of connected load like washing machines etc.;
5) Thermal parameters of the affected houses;
6) Type of housing (bungalow, apartment, etc.);
7) Water heater size, set point, consumption, etc.

Analysis of the power required for heating is not a simple problem. It is required to model the thermodynamics of a house and the behavior of the thermostat. House thermodynamics is modeled by using an R-C network connected by a switch to a current source Q. The resistor R represents the house insulation level. The capacitor C represents the thermal mass of the house. The current source represents the heat input from the furnace. The switch is controlled by a thermostat, the setting of which is manually adjustable. When the switch is open the charged capacitor provides the current to the resistor. Charge across the capacitor is analogous to the house temperature and so the discharge of the capacitor would mean cooling of the house.

The parameters which determine the current requirement of a house are the resistor R, the capacitor C, the current source Q and the thermostat setting. To model a large number of unique houses a random number generator is used to select the values of the parameters. A specific mean value is specified for each of these parameters and noise is added to it. The noise is a random number with gaussian distribution, mean of zero, and a specific standard deviation.

If the utility does not have an idea of the value of the Cold Load Pickup current the usual way to overcome the unsuccessful reclosure of the circuit breaker would be to disarm protective relays. There are two drawbacks to this.

1) The relay may allow the fault current to flow along with the Cold Load Pickup current.
2) If the disarmed relay is left in place even after the Cold Load Pickup is completed, it could be a severe danger to the protective system.

This thesis recommends two different ways to restore the electrical service successfully.

1) After an estimate of the Cold Load Pickup the relays can be disarmed to an extent to allow the Cold Load Pickup current and not the fault current.
2) Reducing the Cold Load Pickup current by means of feeder sectionalizing. A simulation program has been developed that provides the option of automatic sectionalizing and manual sectionalizing. In

automatic sectionalizing the computer program calculates the time when there is minimum current flowing through the feeder. It then simulates further as if the next load has been connected. In manual sectionalizing the operator has to enter the time for the next section of load to be connected.

The computer program has the provision of simulating for:

1) Change of ambient temperature during and after power outage;

2) Step change in voltage at which power is supplied.

Since the utilities are reluctant to intentionally disrupt electric service, not much validation of the cold load pickup current has been done. In this thesis data was collected from three different experiments towards the validation of the model.

Content of this thesis is contained within seven chapters described below.

Chapter 1 is a general introduction to the Cold Load Pickup problem.

Chapter 2 discusses the work done in the field of Cold Load Pickup so far.

Chapter 3 deals with the thermodynamic model of a house.

Chapter 4 deals with the aggregate load demand of the feeder.

Chapter 5 deals with the simulated results.

Chapter 6 deals with the results of the experiment performed to validate Cold Load Pickup model.

Chapter 7 is the summery and conclusions of the study of Cold Load Pickup. Also suggestions for further research are presented.

CHAPTER 2

COLD LOAD PICKUP LITERATURE REVIEW

An analysis of the overload after a power outage is important for the utilities in order to prevent damage to their equipment. It is required to efficiently model the thermal characteristics of the house on the feeder in order to determine the magnitude and duration of this overload. In this chapter literature pertaining to Cold Load Pickup current and thermodynamics of a house is reviewed.

Survey

In 1949 Audlin et al. [1] performed a 15 minute outage on a feeder serving 3500 customers. Four time phases of the Pickup current was recognized. McDonald and Bruning [2] did experimentation to determine the value of the parameters of a house. House temperature was monitored for 24 hours. The conductance was determined by the steady state test which requires the house temperature to remain constant over a certain period of time. The heat input to the house, the house temperature and the ambient temperature need to be recorded to determine the conductance of the house. The time constant which is the product of the thermal resistance and the thermal mass is determined by a cool down test. In this test power is shut off for a certain period of time. The temperature of the house after the test period, the initial temperature of the house and the outside temperature are required for the calculation of the time constant. The thermal mass of the house is then calculated by multiplying the conductance to the time constant. He then comes up with the average and standard deviation values of the parameters by conducting the individual tests in six electrically heated homes. His results include showing the average steady state power demand per house at different ambient temperatures and the effect of change in ambient temperature on the Cold Load Pickup demand and the duration of its peak.

Ihara and Schweppe [3] developed a thermodynamic model for a house and derived the equation for house on-time (T_{on}) and house off-time (T_{off}). They point out that the heater is either on with a probability $T_{on}/(T_{on}+T_{off})$ or off with a probability $T_{off}/(T_{on}+T_{off})$. An experiment was conducted to verify the results. House temperature was monitored for 80 and 140 minutes. Model and test results have been compared. The effect of change in ambient temperature, change in outage duration and change in the standard deviation of the thermal parameters of the house on the aggregate power demand is shown.

Lang and Anderson come up with the following values, for the model parameters of a house [4].

Thermal Conductance = .318 kw/°C (.177 kw/°F)

Thermal Mass = 3.21 kwh/°C (1.783 kwh/°F)

Reference [5] models an R-C circuit and derives the equation for house on-time and house off-time. Random numbers are generated for the five parameters which affect the current demand of the house. The effect of change in furnace size, ambient temperature, outage duration and service voltage on the Cold Load Pickup current is shown.

Mortensen and Haggerty [6] modeled an R-C circuit using the same basic equation as Ihara and Schweppe [3]. Time is discretized by using a sampling period h. It is assumed that the thermostat always switches exactly at a sampling instant. An equation to find the temperature of a house after each sampling interval is developed. A discrete white noise term was added to the equation to include the effect of the random influences in the environment.

Mortensen [7] has discussed five models to estimate heating and cooling loads. The models are:

1) Deterministic differential equation;
2) Stochastic difference equation;
3) Markov Chain matrix equation;
4) Hybrid partial differential equation;
5) Alternating renewal process.

According to N.W.P.P.C. [8] the following are the typical values for the house parameters in the northwest United States.

Thermal Mass = 3223.0 wh/°F

Thermal conductance = 180 w/°F

Overview

Little work has been done towards validating the results of Cold Load Pickup current. Also the difference in the Cold Load Pickup current due to the type of construction of the houses has not been recognized.

This thesis uses the actual values of the house parameters best suited for the northwest United States. Three different experiments were performed towards validation of the Cold Load Pickup model.

CHAPTER 3

MODELING

A house model has been represented in the past by a multi node network. Lang and Anderson [4] have represented the thermodynamic model of a house by the following circuit.

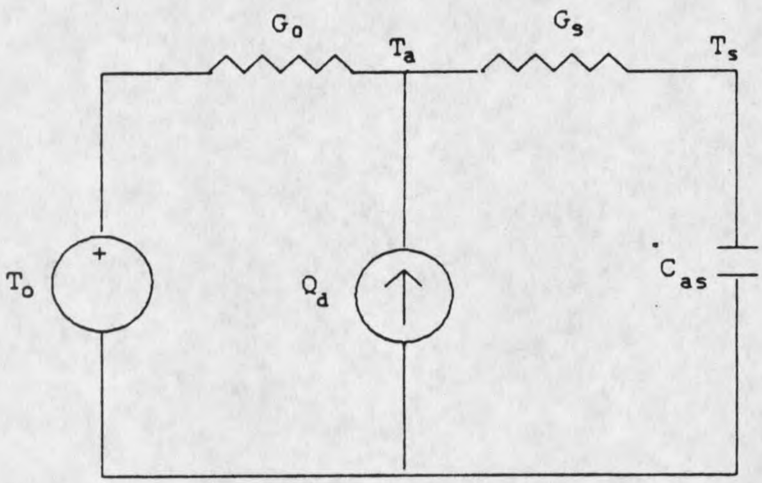

Fig. 1 Heated building electrical equivalent.

Where

T_a is the temperature of the living space air (°C)

T_s is the temperature of the equivalent thermal mass (°C)

T_o is the outdoor temperature (°C)

C_{as} is the equivalent thermal mass representing the entire building (kwh/°C)

G_s is the thermal conductance between the living space and the equivalent thermal mass (kw/°C)

G_o is the thermal conductance between the living space and the outdoors (kw/°C)

Q_d is the total heat injected into the living space (kw)

According to Mortensen and Haggerty [7] only one or two sections are required due to the forgiving nature of highly aggregated configuration. The load on a power system is the aggregation over hundreds or thousands of houses, such that the individual details largely washout, and only consistent trends remain. Most of our references have used a simple RC circuit. Our model of the RC circuit is as follows.

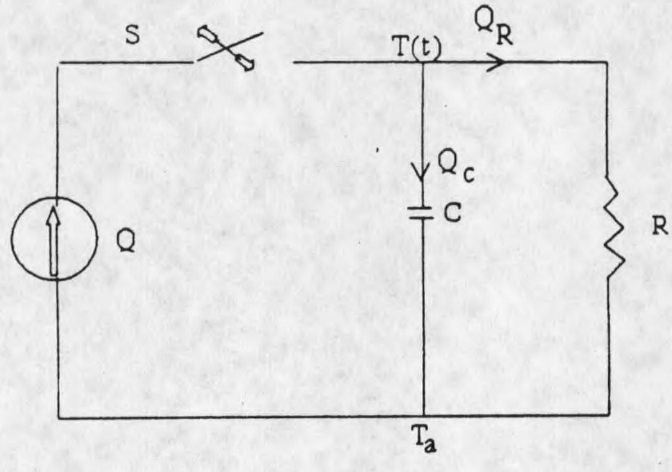

Fig. 2 Analogous electric circuit used for thermodynamic behavior of a house.

In the model

T is the house temperature (°F)

T_a is the ambient temperature (°F)

C is the equivalent thermal mass of the house (kwh/°F)

R is the equivalent thermal resistance of the house (°F/kw)

G is the equivalent thermal conductance of the house (kw/°F)

Q is the total heat injected into the house (kw)

Q_C is the heat flowing into the thermal mass C of the house (kw)

Q_R is the heat loss to the outside environment (kw)

$$Q = Q_C + Q_R$$

The thermal quantities used in this model are analogous to electrical quantities as follows.

Thermal Quantity	Electrical Quantity
Temperature	Voltage
Heat Flow	Current
Thermal Conductance	Electrical Conductance
Thermal Mass	Electrical Capacitance
Time	Time

According to N.W.P.P.C. [8] the following are typical values of the house parameters in the northwest United States.

Thermal Mass C = 3223 wh/°F

Thermal Conductance G = 180 °F/w

A value of heat injected Q = 20.5 kw was found likely in this region.

This thesis uses the above defined value for all plots unless otherwise stated.

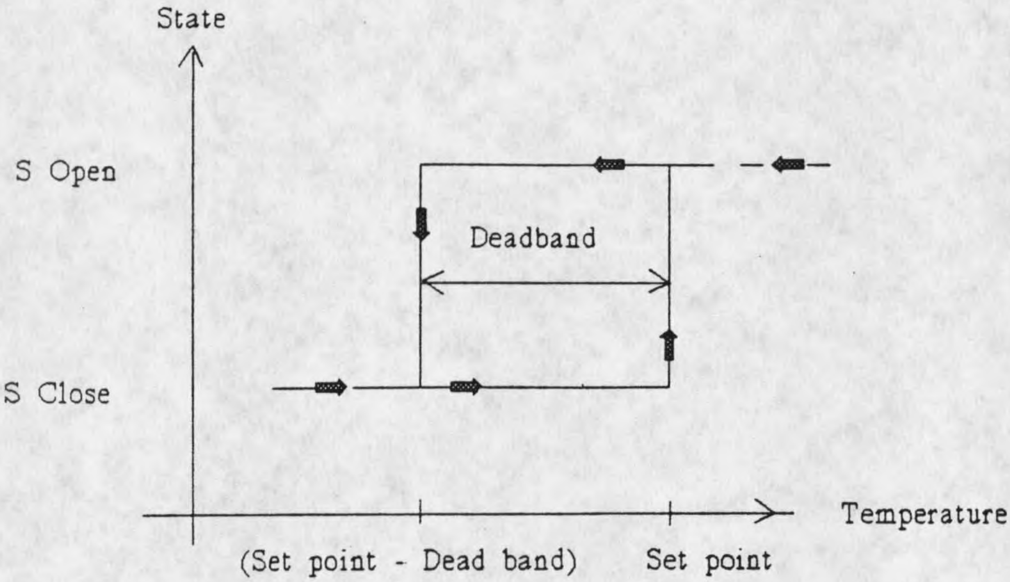

Fig. 3 Hysteresis loop of a thermostat.

Fig. 3 shows the hysteresis characteristics of the thermostat to which the switch S is connected. The upper setting of the thermostat is the setpoint and the lower setting is the setpoint minus the dead band. The switch S closes when the house temperature drops below the lower thermostat setting and opens when the house temperature reaches the upper setting.

It is assumed in this thesis that during power outage people do not add heat to their houses by any other source like wood burning or any gas heating appliance. Also the effect of solar heat is not considered. The following range of values of the thermostat were found most likely.

Set point = 67-70 °F

Dead band = 2 °F

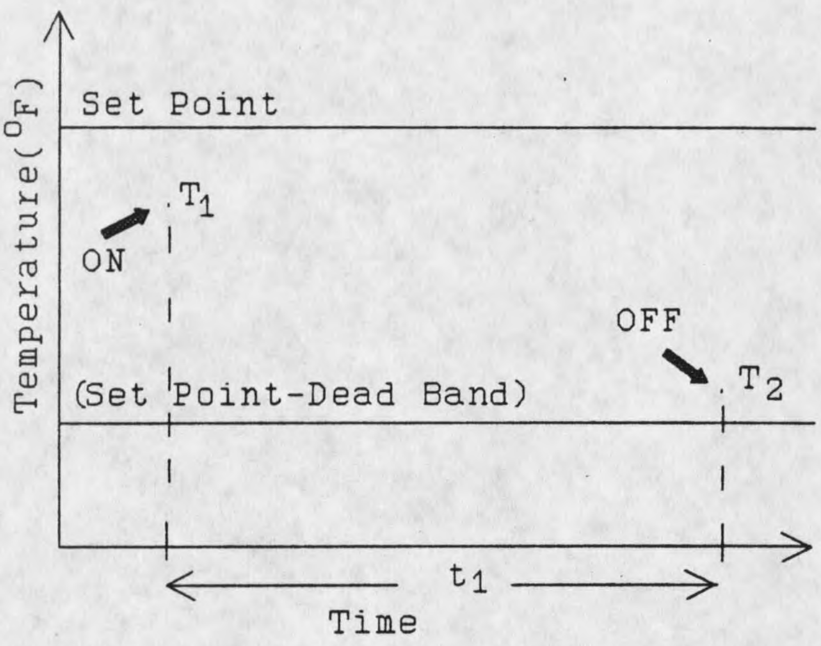

Fig. 4 House ON/OFF state before and after a power outage.

In Fig. 4 house A has a room temperature of T_1 and it is in the on state. There is a power outage for time t_1 after which power is restored. During this time t_1 the house has cooled to a temperature T_2. Since the house temperature is above the lower setting of the thermostat it will be in the cooling state. The house will be switched on once its temperature drops below the lower setting of the thermostat. It is for this reason that for short outages power demand at the instant of power restoration is less than the power demand a short time after power restoration.

From the equivalent circuit of a house given in Fig. 2 the temperature T of a house at any time t is given by the following equation. See Appendix A for details.

$$T(t) = Ta + (T_{ho} - T_a) e^{-t/RC} + wQR (1 - e^{-t/RC}) \qquad (M-1)$$

where

T_{ho} is the initial house temperature

T_a is the ambient temperature

w = 1 when S is closed or

w = 0 when S is open