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Demand Limiting Algorithms for Energy Management and Control Systems

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
Building Equipment Division
Washington, DC 20234

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Demand limiting control is one of popular control strategies for electrical energy management in Energy Management and Control Systems (EMCS) in commercial/office buildings. The purpose of demand limiting is to maintain the peak demand level below a predetermined limit by shedding nonessential loads in a building during the peak demand period. In this present report, description of fixed interval metering and sliding window metering for electrical demands are included. Demand limiting calculation procedures discussed are the ideal rate, the predictive, and the instantaneous rate methods. Demand limiting algorithms, which were developed based on available information, are presented. Computer program listings of demand limiting control algorithms in Fortran 77 and an open-loop computer simulation result are included in the appendices.

Key words: electrical demand; electrical energy management; electric power; energy management and control systems; fixed interval metering; ideal rate method; instantaneous rate method; load control; predictive method; sliding window metering.

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1. INTRODUCTION

Electrical energy management has an important role in energy management and control systems (EMCS) in buildings. The purpose of electrical energy management is to lower the charges imposed by electric utilities. Although popular strategies for electrical energy management include demand limiting, duty cycling, time-of-day control, scheduled start/stop control, and optimum start/stop control, only demand limiting is discussed in this report.

Electric utility charges are typically based on some combination of electric energy consumption, fuel adjustment, electric demand, ratchet adjustment, and power factor [1,2]. Electric energy consumption is defined as the electric energy usage read by a watt-hour meter in kWh, while the fuel adjustment charge is based on the kind and cost of fuel used by the utility. The electric demand charge is the portion of the service charge which is based upon a customer's demand, and will be explained later. A ratchet adjustment is made on the basis of energy use or demand. Finally, the power factor is the relationship between the phase of the current and the phase of the voltage in alternating current distribution systems. (A low power factor can overload generating and distribution networks.) Currently, residential customers are not charged for electric demand and power factor, while industrial and commercial customers may be billed for all or some charges discussed.

Electric demand is defined as the load integrated over a specified time interval [3]. In other words, electric demand is the energy consumption over a specific time interval of 15, 30, or 60 minutes. The time interval is determined by a utility and is called demand interval. The maximum demand is the maximum value of demand measures during a billing period in kW. Charges based on maximum demand allow a utility to recover its capital investment in generating and distributing equipment used to meet the maximum demand for electrical power. When the maximum demand of many customers occurs simultaneously, the peak load of the power system will be high, therefore the utility's capital investment will be large. During the off-peak period, a part of the equipment capacity is idle. Because demand charges are high (as much as 30 percent of some customers' bills [4]) and because a demand charge is usually based upon the highest demand that has occurred during a billing period, controlling demand is very important. A high peak demand for just a few minutes can raise the demand charge for the entire billing period.

An electrical demand limiting strategy is outlined by Shih [5]. The purpose of demand limiting is to maintain the peak demand level below a predetermined limit by shedding (disconnecting) nonessential loads in a building during the peak demand period. In conjunction with demand meter pulse signals, Shih presented two demand limiting methods. These are the predictive method (forecasting method), and the ideal rate method. The ideal rate method was used with analog demand limiting meters many decades ago. The concept of demand control was also explored with comprehensive analyses by Militello [6]. On-peak or off-peak metering, automatic load control, and demand billing control are extensively discussed in his paper in addition to the concepts of demand and demand control. The instantaneous rate principle is mentioned as a load shedding technique by Pannkoke [7]. In this technique, the rate of electric energy use is measured at short time intervals and compared with a limiting value. Good examples of the demand computation can be found in Pannkoke's article. Currently, there exist, as discussed above, three calculation methods; i.e., ideal rate, predictive (forecasting) and instantaneous methods. These methods are related to the metering technique employed.

Two metering techniques, associated with impulse signals from the demand meter, are known. They are the fixed interval metering and the sliding window metering. The most widely used one is the fixed interval metering in which shedding of loads is generally performed sequentially or rotationally. The loads that have been shed are restored when the demand is lower than a predetermined level. Novak [8] considered on and off times of loads during shedding and restoring activities, keeping the number of on and off actions to a minimum. A new concept for load shedding, called "comfort fairness," was briefly introduced in an article by Spethmann [9]. The comfort fairness concept is not currently involved in the demand limiting algorithm of this report. The use of this concept can be found in the report of time-of-day control and duty cycling algorithms by May [17].

Although many publications relating to demand limiting are available in the public domain, no detailed information that is suitable for implementation utilizing computers has been found. Software on the market, for practical purposes, is proprietary so that general public has limited access to detailed information. The present report is intended to describe the concept of demand limiting, and the possible implementation of the algorithms to digital control hardware. Metering techniques, calculation principles, and load control algorithms are discussed, and computer programs written in Fortran 77 are provided. With presumed data, the open-loop computer simulations were carried out, and the results are appended for illustration purposes. It should be noted that demand limit control is a closed loop control in practice.

2. ELECTRIC DEMAND METERINGS

Electrical energy consumption and maximum demand are measured by meters and serve as the basis of billing for industrial and commercial customers. A utility and a customer make a contract for the electric charge. Discussion of the contents of such contracts is beyond the scope of this report. Some ideas about the rate structure for these charges may be obtained from papers by Teed [10] and Carpenter [11]. In this chapter, demand meters, fixed interval metering, and sliding window metering will be described.

2.1 DEMAND METERS

Ordinarily a utility must provide electric power to any customer in any quantity required. Since alternating-current (AC) power cannot be stored practically, the utility must increase its generating and distributing capacities to meet an increased maximum load condition. This results in larger generators, larger transformers, heavier switches, heavier wires, and so on. Consequently, fixed investment must be increased to meet increased customers' requirements. Such a situation was being investigated as far back as 1892, and as a result, a dual rate of metering was developed [12]. In this scheme, energy use measured by a watt-hour meter and electric power demand measured by a demand meter determine the charge for billing period.

The demand meter is a device to register the integrated energy used for a specific time interval, namely electric power. There are two different sizes of meters available. One is a small demand meter which is housed in the same case of a watt-hour meter. An internal timer with fixed time interval resets the demand reading at the end of each demand measurement interval. The maximum value of the demand reading is indicated by a sweephand maximum demand pointer during the demand period. The pointer can go upward but not downward until reset is made manually when the meter is read. Thus the maximum demand during a billing period is determined. Internal mechanical connections are made between the demand meter and the watt-hour meter. Figure 1 shows a sketch of a small meter.

Another type of meter is a large demand meter which is a type of recording instrument separate from the integrating watt-hour meter. Recording can be done on a chart or a magnetic tape. Chart recording demand meters have become obsolete and they are being replaced by newer magnetic tape recording device. For large commercial and industrial users who require more than 500 kW peak load, large demand meters are installed [13]. The demand meters are linked to the watt-hour meters electrically. Pulses generated by a signal pickup device in the watt-hour meter are fed into the demand meter in which the pulses are totalized for a short time period, and the totalized value is recorded at each sampling instance for recording. A description of the totalization technique can be found in a report by Hurley, Kelly, and Kopetka [14]. More detailed information on demand meters is described elsewhere [12].

For demand control, sampled data from the pulse counter (totalizer) are required for digital processing by a microprocessor or a computer. The sampling rate, T_s, may depend upon the system of interest. By installing an optical or mechanical device, electric pulses can be generated in small demand meters like those discussed earlier. Figure 2 shows a possible arrangement

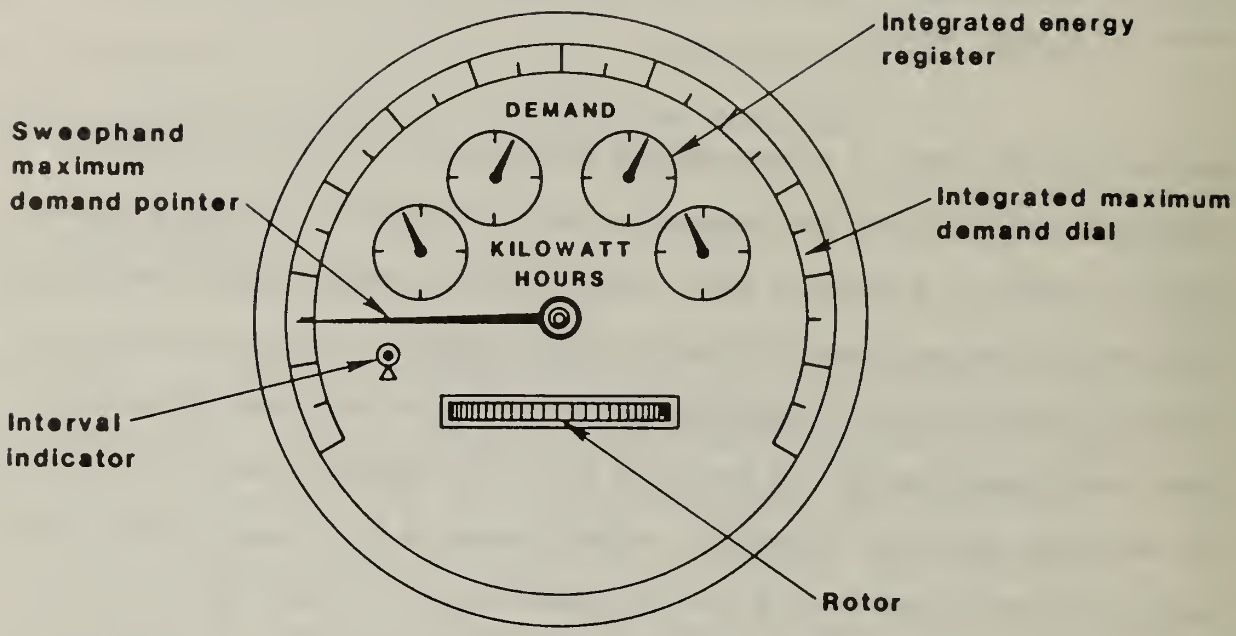

Figure 1. A sketch of a small demand meter

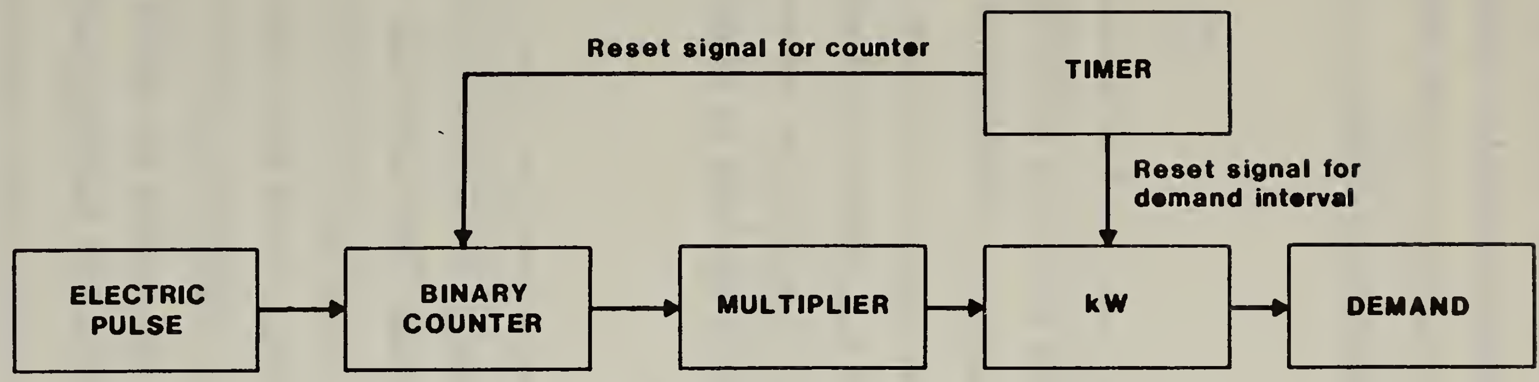

Figure 2. Demand metering set-up for high power users

for demand metering for a customer using large amounts of electric power. This illustration provides a general view of demand metering. Besides the pulses from the watt-hour meter, it is sometimes possible to obtain (from the utility) a second pulse signal which indicates the end of one demand period and the start of the next period; a demand interval signal.

2.2 FIXED INTERVAL METERING

Fixed interval metering is the most widely used method in the measurement of electric demand. For a fixed time interval (15, 30, or 60 minutes set by the utility), the average power use is computed to be the demand for that period. At the end of each billing period, the peak demand is then taken by the power company, and billing is made based on the peak demand in conjunction with the rate schedule. Since billing methods differ depending on the contract between the utility and its customers, no attempt is made here to discuss a customer's payment to a utility in terms of dollars.

A requirement of the fixed interval metering technique is that a reset signal must be available at the end of every demand interval so that the demand meter can again accumulate the energy use from zero. The reset signal can be originated from an internal clock of the demand meter, or from an external clock. The reset signal may also come directly from the utility to the demand meters. Should the reset signal fail once, measured demand will be doubled if the required electric power remains the same for two consecutive demand periods. Thus, special attention must be paid to detecting the reset signal when fixed interval metering is used to control demand, especially if the reset signal is not continuously synchronized with the power company.

When the demand interval is D, and the sampling period is T_s, the number of samples in the demand interval, n, will be D/T_s. If the total number of pulses during the i-th sampling period is given by N_i, the average power, $\overline{P}$, which is the demand during the whole demand interval, is expressed by:

$$\overline{P} = \frac{1}{n} \sum_{i=1}^{n} \frac{CN_i}{T_s} \tag{1}$$

where C is the conversion factor in kWh per pulse. Since C and T_s are usually constant, equation (1) yields:

$$\overline{P} = \frac{C}{T_s n} \sum_{i=1}^{n} N_i \tag{2}$$

The instantaneous power at the i-th sampling instant may be given by:

$$P_i = \frac{CN_i}{T_s} \tag{3}$$

It should be noted that, since the unit of C is kWh per pulse, both D and T_s must be in hours. The term "instantaneous power" means the average power during a sample period when the pulse counting technique with a watt-hour meter is used for power measurement. However, if continuous direct power measurement is available, for example, by means of using analog devices (voltmeter and ammeter), the sampled data at an instant can be considered the instantaneous value of power at that instant.

As an example, if D is 30 min, T_s is 60 sec, N_i is 10 pulses for i-th period, and C is 0.72 kWh per pulse, the instantaneous power at the i-th period can be computed from equation (3), resulting in:

$$P_i = \frac{(.72)(10)}{\frac{60}{3600}} = 432 \text{ kW}$$

If the measured number of pulses for all sampling intervals is the same, the average power in the demand interval is from equation (2):

$$\bar{P} = \frac{0.72}{\left(\frac{60}{3600}\right)(30)} \sum_{i=1}^{30} (10) = (1.44)(300) = 432 \text{ kW}$$

This result coincides with the previous result as expected.

Furthermore, suppose pulse counts of 100 and 200 pulses during the first and second sampling periods, respectively, were obtained during the demand period, then the integrated demand becomes

$$\bar{P} = (1.44)\ (100 + 200) = 432 \text{ kW}.$$

We arrive at the same answer as before. This indicates that high peak power for a short time period does not really increase the demand because the demand is an integrated quantity over the demand interval. Figure 3 illustrates fixed interval metering.

2.3 SLIDING WINDOW METERING

A reset signal, preferably synchronized with the utility's metering system, is a requirement for using the fixed interval method. When reset signal is not available or is missing due to equipment failure, fixed interval metering is

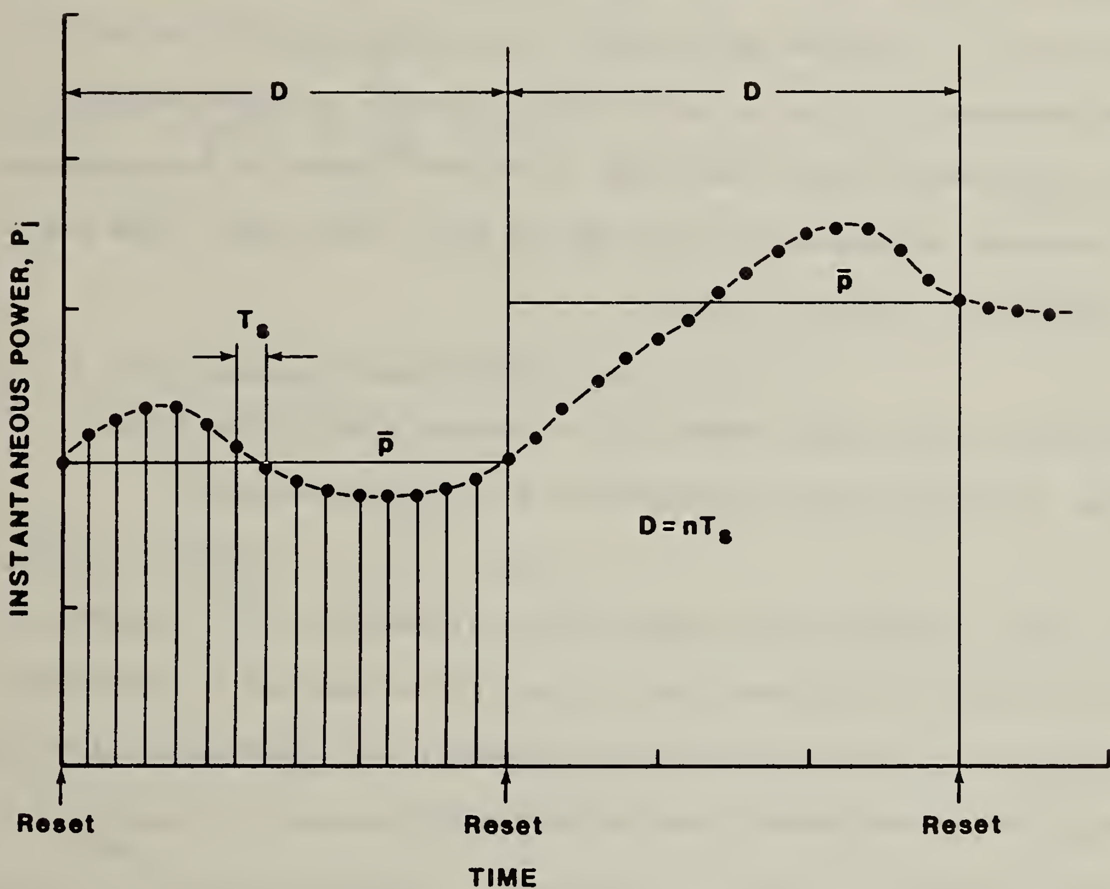

Figure 3. Fixed interval metering

not desirable. Sliding window metering is the method that is usually used when there is no synchronized reset pulse. In this technique, the demand interval is still fixed. If the current sampling instant is moved to the next sampling period and it becomes the upper limit of the integration, then the lower limit moves ahead by one sampling period. In this way, the total number of observations remains unchanged as time progresses so the demand during a demand period is calculated at the end of each sampling period and one of those measurements will be the peak demand. Unlike the fixed interval method, this method requires knowledge of the past history of instantaneous power measurements between the lower and the upper time limits. This means that dynamic data storage is needed.

Because dynamic data memory capability is required with sliding window metering, a computer must be incorporated with the demand meter.

If the energy consumption rate (power), P(t), is sampled with a sampling period, T_s, and if a zero-order hold filter [15] is employed to reconstruct the sampled data, the integrated energy consumed, E(t), starting at time t_s and ending the current time, t, can be given by:

$$E(t) = \int_{t_s}^{t} P(t)dt \approx \sum_{k=0}^{n-1} P(kT_s)\, T_s \tag{4}$$

where n is the total number of sampled data in the demand period, D. The demand in that period, P(t), is computed by dividing E(t) by D, namely

$$\overline{P}(t) = \frac{E(t)}{D} = \frac{1}{n} \sum_{k=0}^{n-1} P(kT_s) \tag{5}$$

At the next time step, $t + T_s$, retaining the same index k for time t, the demand yields:

$$\overline{P}(t+T_s) = \frac{E(t+T_s)}{D} = \frac{1}{n} \sum_{k=1}^{n} P(kT_s) \tag{6}$$

At $t + 2\,T_s$, the computed demand becomes (see figure 4):

$$\overline{P}(t+2T_s) = \frac{E(t+2T_s)}{D} = \frac{1}{n} \sum_{k=2}^{n+2} P(kT_s) \tag{7}$$

Clearly, one can see that the sliding window method is a moving integration method. Instead of a zero-order hold filter, use of the linear point connector [15] can be considered to minimize errors when the sampling rate is low.

The integration method employed in this report is the simple trapezoidal method. It would not be surprising if the customer's computation of total energy usage during a billing period disagrees with the utility's meter reading because different integration methods may be used. It is obvious that the accuracy of integration will be increased as the sampling rate increases.

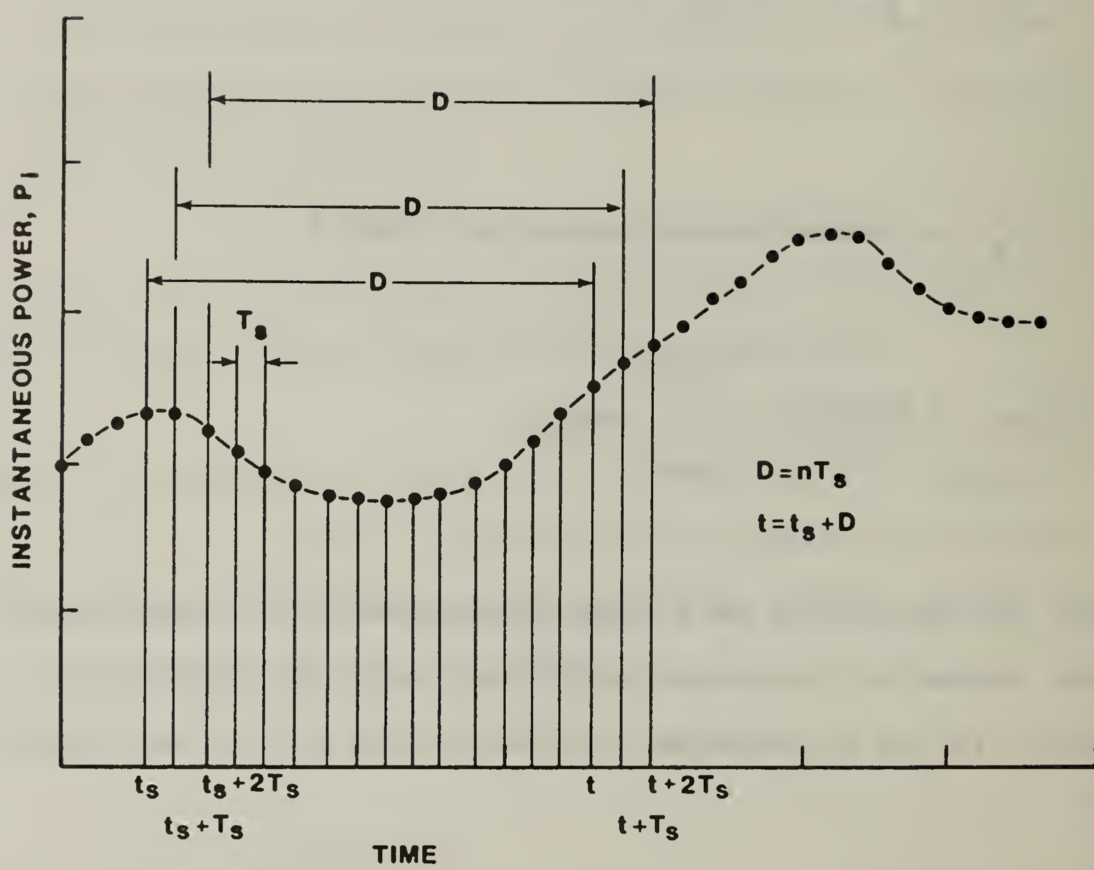

Figure 4. Sliding window metering

3. DEMAND LIMITING CALCULATION METHODS

The highest demand during a billing period is often used as a basis for determining the demand charge for a future billing period. The main purpose of demand limiting is therefore to avoid establishing new higher peaks by maintaining the maximum demand within a preset limit. Non-essential or lower priority loads are usually turned off when load shedding becomes necessary by a demand limiting decision-making process. The load shedding decision is made by a calculation method that is selected as the most appropriate method for a given situation. There exist three well-known calculation methods at the present time [2,5,7,8,9,16]. They are the ideal rate, the predictive (or forecasting), and the instantaneous rate methods.

3.1 IDEAL RATE METHOD

The ideal rate method was first used with analog type demand controllers. In this method, the quantity of energy consumed is measured and accumulated by the demand controller. The integrated value is then compared with a maximum allowable value which varies with respect to time in a predetermined rate. The principle of the ideal rate uses linear prediction to determine the allowable energy at the next sampling instant, and incorporates fixed interval metering. This principle may also be applied on large metering devices that may include computers.

Figure 5 illustrates the ideal rate method. As seen on the figure, an adjustable offset, E_0, is provided to delay required shedding action to a later stage of time in the demand interval instead of having it in the earlier

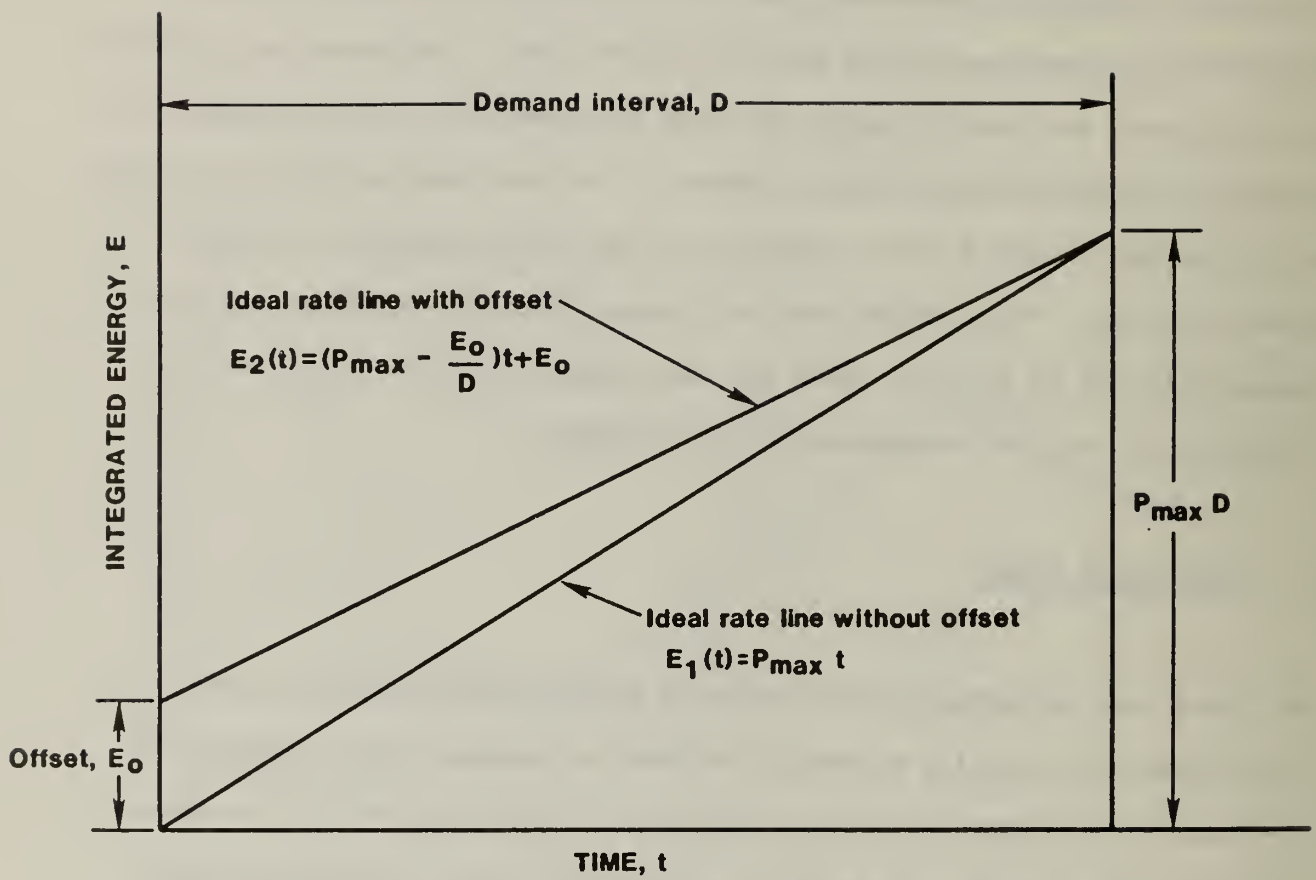

Figure 5. Ideal rate method with offset

time. This offset permits restoring of the shed loads during the previous demand period. If all loads which have been shed are restored at the beginning of the next demand interval, the offset value should be set at a relatively high value.

If the maximum allowable demand power during a demand interval is selected as P_{max}, the integrated energy in that interval will be D times P_{max}. The ideal rate line without the offset, $E_1(t)$, as seen in figure 5, has the slope of P_{max}. When the offset value is other than zero, the integrated energy expression with respect to time, $E_2(t)$, can be given by:

$$E_2(t) = (P_{max} - \frac{E_o}{D})\, t + E_o \qquad (8)$$

where E_o is the offset.

Since E_o and D are positive constants, the rate of change of $E_1(t)$ is always greater than that of $E_2(t)$. The ideal rate of change is thus $(P_{max} - E_o/D)$ instead of P_{max}. Remember that the ideal rate method is used only with fixed interval metering.

$E_2(t)$ may be used as an upper limit for the demand limit control, (see figure 6).

$$E_{max}(t) = E_2(t) \qquad (9)$$

Whenever the measured, integrated energy usage, E(t), exceeds the limit value, $E_{max}(t)$, load shedding takes place. It is also desirable to restore the loads which were shed if the rate of energy use is much lower than the ideal rate.

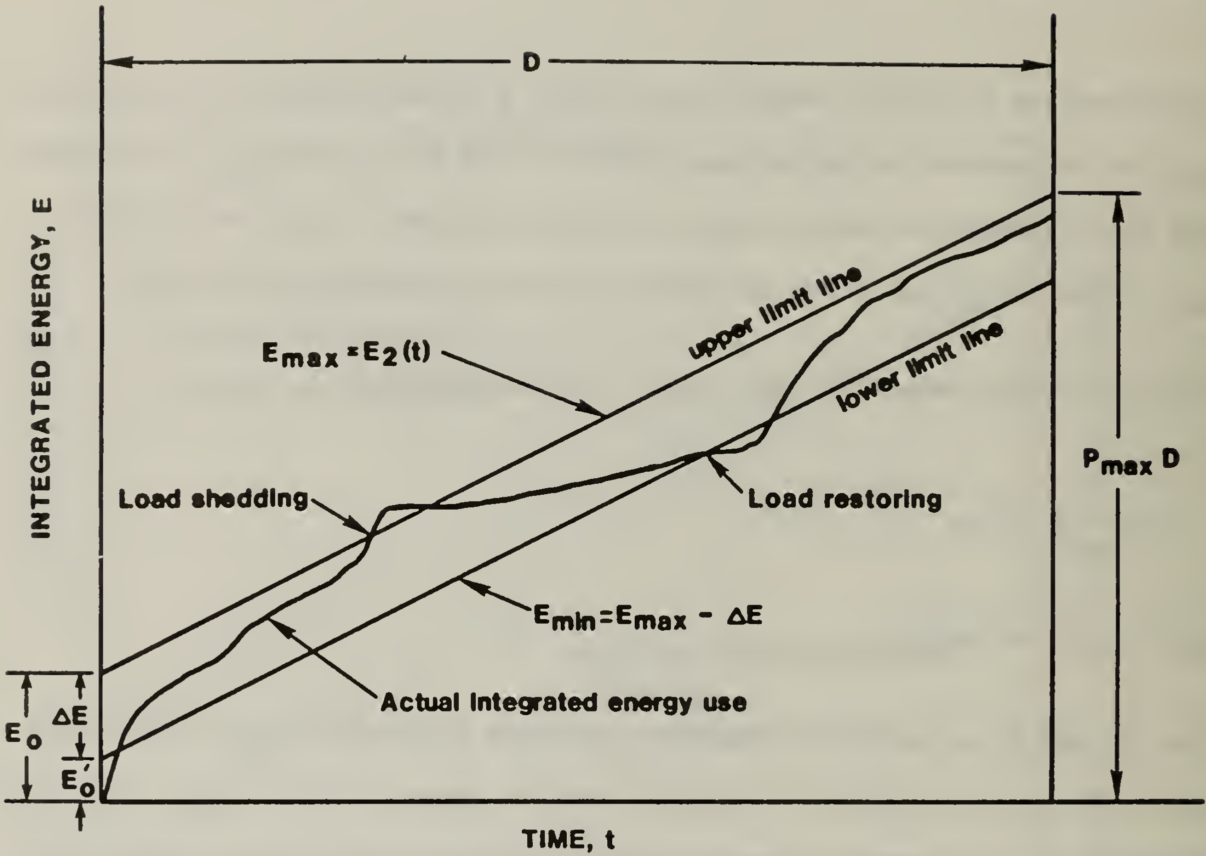

Figure 6. Upper and lower limits for the ideal rate method

A minimum limit value can be assigned so that load restoring may be performed if the energy usage is less than the limit value that is expressed by:

$$E_{min}(t) = \left(P_{max} - \frac{E_o}{D}\right) t + E'_o \tag{10}$$

where E_o' is the intersection that is less than E_o in the amount of ΔE. In terms of the differential, ΔE, equations (9) and (10) give a relationship as:

$$E_{min}(t) = E_{max}(t) - \Delta E \tag{11}$$

Depending upon the value of E at a particular time, the load control actions may be selected. No control action is needed if the E(t) stays in the range as

$$E_{min}(t) \leq E(t) \leq E_{max}(t) \tag{12}$$

3.2 PREDICTIVE METHOD

At each measurement instant in a demand interval, the instantaneous rate of energy consumption is measured and a forecast of the energy consumption at the end of the demand interval is made. This calculation procedure is called the predictive or forecasting method. Either fixed interval or sliding window metering may be used with the predictive method. The predictive principle needs more computational effort than the ideal rate principle. As a result, unlike the ideal rate principle, the predictive method can be employed only with a computer. For simplicity, the predictive method with fixed interval metering will be described in this section.

Assume the desired peak demand is P_{max}. When the peak demand occurs, the accumulated energy use will be $P_{max}D$, in which the demand interval is a constant. Knowing that E(t) is the integrated energy consumption from the beginning of the demand interval to a specific time, t, the total energy consumption at the end of the demand interval can be predicted. A simple linear prediction may be made based on the energy use at the current time and at the previous sampling period. The predicted energy consumption without correction (shedding loads) at the end of the demand interval, $E_p(t)$, is given by:

$$E_p(t) = \left(\frac{D - t}{T_s}\right)\left[E(t) - E(t-T_s)\right] + E(t) \tag{13}$$

The value of $E_p(t)$ is compared with $E_{max}(= P_{max}D)$ at a certain time. Loads are then shed when E_p exceeds the preset value E_{max}. Loads may be restored when E_p is less than a limit given by

$$E_{min} = P_{min}D \tag{14}$$

where P_{min} is the preset value of power selected as the lower limit.

3.3 INSTANTANEOUS RATE METHOD

With the instantaneous rate method, the rate of energy consumption is measured at short time intervals and each measurement is compared with a predetermined limiting value. Whenever this instantaneous rate exceeds the upper limit, P_{max}, load shedding takes place. When the instantaneous rate of energy use is below the limit that is preestablished as the lower limiting value, P_{min}, loads are restored. The control band, which is the difference between the upper and the lower limits, is needed to minimize rapid cycling of the load control action. As long as the measured power at time t, P(t), stays in the range as given by $P_{min} \leq P(t) \leq P_{max}$, loads are neither shed nor restored. The advantage of using this instantaneous rate principle is that synchronization with the utility's demand interval is not necessary. This principle, however, does not involve the demand interval.

4. DEMAND LIMITING ALGORITHMS

In previous sections, the general principles of demand limiting have been reviewed. In this section, the algorithms developed for use with computers will be discussed. The ideal rate and the predictive methods incorporate fixed interval metering. The predictive method may also use sliding window metering, while the instantaneous method does not need specific metering. The load control algorithm is not given with the main algorithms, but is presented in Section 5.

The demand limit algorithms use the trapezoidal integration method in which the average value of the power measured at the current sampling instant and the power measured at the past sampling instant is computed. The average power value is then multiplied by the sampling period to give the instantaneous value of energy consumption at the current time. This approach provides less computational error than the approach using a zero-order holder. Although the accuracy of integration can be improved with a high sampling rate, the system under consideration usually limits the sampling rate.

The algorithms presented here need supporting hardware and software to perform the actual load shedding. With the aid of the supporting software and hardware, the pulse countings can be entered and resulting control action signal can be transmitted to the device of interest. Computer programs are written in FORTRAN 77 and given in the appendices.

4.1 IDEAL RATE METHOD WITH FIXED INTERVAL

The computer algorithm of the ideal rate method is quite simple. Because of using fixed interval metering with this method, a demand interval reset signal must be provided. The important input data is the instantaneous power, $P(t)$, determined by measuring the number of pulses from a watt-hour meter for a sampling period. An expression of the instantaneous power at a sampling instant is given by equation (3). The calculation procedure of power using equation (3) is not included in the algorithm given in this report, because the power can also be determined from direct measurements of the electric current and the voltage at an instant.

For a given demand period, D, and sampling interval, T_s, the average energy consumption rate is calculated, and then is compared with the preset ideal rate as described in the section 3.1. The ideal rate is a function of the maximum allowable power, P_{max}, the offset, E_o, and the demand interval. The actual energy usage, $E(t)$, is compared with the maximum energy use up to the point of time from the beginning of the interval. Load shedding occurs if $E(t) > E_{max}(t)$ and loads are restored if $E(t) < E_{min}(t)$, in which $E_{max}(t)$ and $E_{min}(t)$ are the upper and lower limiting quantities at time t. The amount of load to be shed or restored is calculated by:

$$\Delta P = (P_{max} - E_o/D) - \tilde{P}(t) \tag{15}$$

where $$\tilde{P}(t) = (P(t) + P(t - T_s))/2 \tag{16}$$

For simplicity, P_{max} is a constant, but if the rate schedule contains different rates for different times-of-day, P_{max} needs to be varied according to a predetermined schedule.

A flow chart of the ideal rate method in conjunction with fixed interval metering is depicted in figure 7. No load shedding or restoring is performed if the reset signal at the end of the demand interval is missed. Load control is resumed when the next reset signal is received.

A computer program (DLRF) for this algorithm appears in Appendix A.

4.2 PREDICTIVE METHOD WITH FIXED INTERVAL

The predictive method using fixed interval metering has been described in Section 3.2. The algorithm for this metering will be explained briefly here. With this algorithm, the ultimate value of energy consumption at the end of the demand period is forecasted. At every sampling time, the forecasting is made and load shedding is performed if the predicted value exceeds the preset value.

To avoid exceeding the preset limit, the amount of power subject to shedding, ΔP, is determined from equation (13) and the demand limit value of P_{max}.

$$\Delta P = \frac{E_{max} - E_p(t)}{D - t} = \frac{P_{max}D - E_p(t)}{D - t} \tag{17}$$

By differentiating equation (17) with respect to time, using the assumption that the predicted energy usage at each time during the remaining time in the

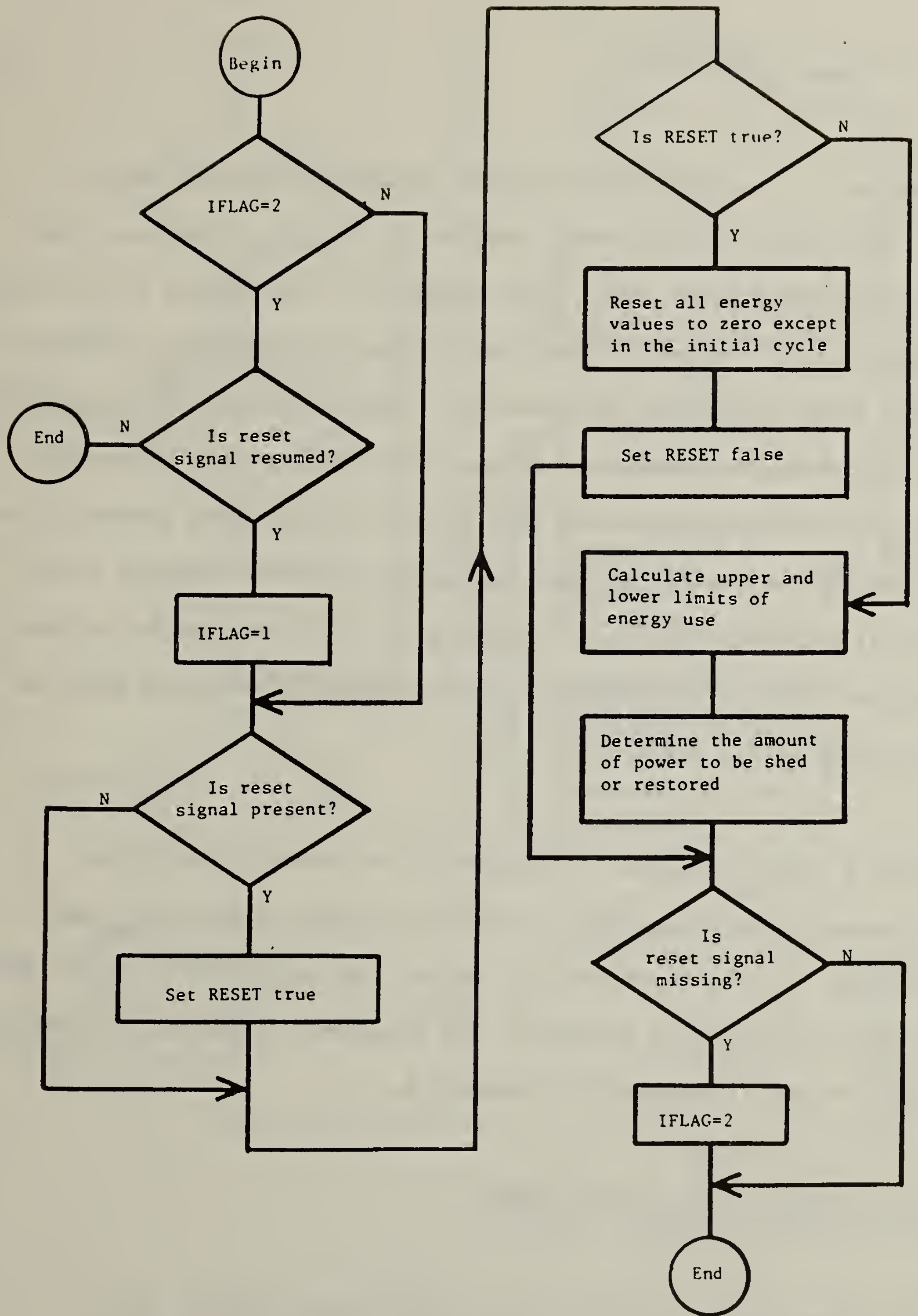

Figure 7. Logic flow diagram of the subroutine DLRF for the ideal rate method

demand period remains unchanged, i.e. $E_p(t) = E_p$, the following result is obtained:

$$\frac{d(\Delta P)}{dt} = -(P_{max}D - E_p)/(D-t)^2 \tag{18}$$

As time approaches D, the denominator becomes smaller, resulting in an increment of the rate of change in ΔP, provided $E_p > P_{max}D$. This means that for the same forecasted value of E_p, load shedding is less likely to be needed at the beginning of the demand interval but the need progressively increases as time passes until the end of the interval. Because of this effect, demand limiting control using the predictive method with fixed interval metering allows an electricity customer to use high power at first, then gradually cut down as the end of the demand interval approaches to prevent setting a new peak demand. As a result, utility load curves show a roller-coaster effect with an overload state at the beginning and an underload condition near the end of each demand period [16].

Figure 8 shows a logic flow chart of the predictive method using fixed interval metering. Given P_{max}, P_{min} and D, this method predicts the load shedding required. If the reset pulse is missed, no load control action takes place until the reset pulse is restored. The computer program DLPF is based on this algorithm and is provided in Appendix B.

4.3 PREDICTIVE METHOD WITH SLIDING WINDOW

As mentioned in the previous section, the roller-coaster effect can be observed in the utility's load curves when customers employ demand limit

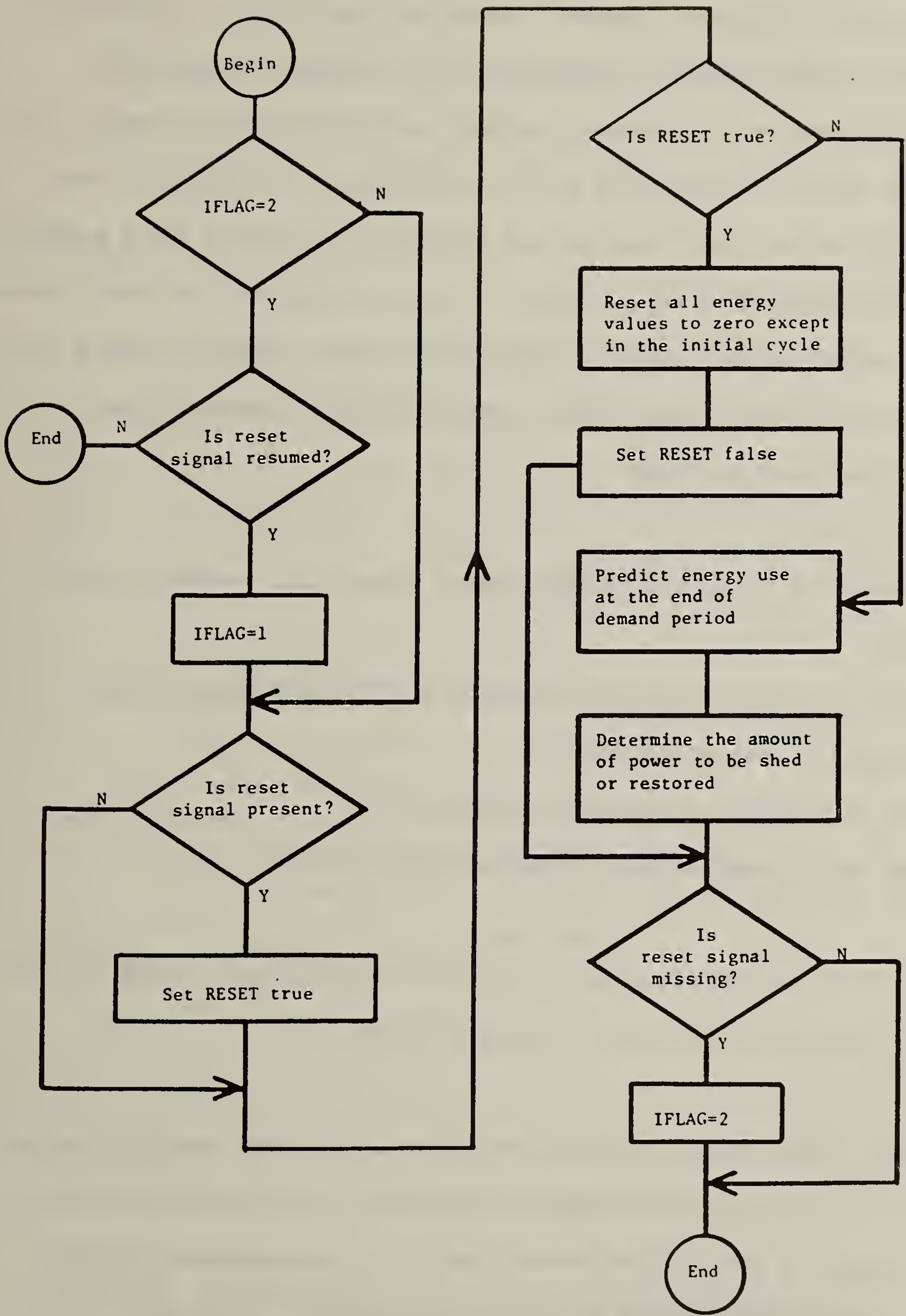

Figure 8. Logic flow diagram of the subroutine DLPFA for the predictive method with fixed interval metering

controls based on fixed interval metering. Peaks and valleys appear in the load distribution, resulting in short-time overloading and underloading. Although short-time high power places a burden on the utility, the charge for the short-period demand cannot be imposed on the consumers because the integrated energy use for the demand interval is still below the preset value. Various billing methods are devised by some utilities. For instance, one utility company charges its industrial and commercial customers for a maximum demand that is calculated by the addition of any two adjacent 15-minute energy consumptions, while another utility computes the demand charge by adding six adjacent 5-minute energy usages. These cases of sliding window billing methods are illustrated in figure 9.

The predictive method using the sliding window metering is needed for the following cases:

(1) When the reset signal at the end of each demand period is not provided by the utilities.

(2) When the reset pulse misses temporarily.

(3) When the sliding window billing method is used.

For the third case, the sampling period for the instantaneous energy use rate must be less than the period of the sliding billing.

In the algorithm under consideration, the demand at the next sampling instant is predicted on the basis of the demands computed at the current time and at the previous sampling period. The demand period, D, the maximum allowable demand, P_{max}, the minimum demand for restoring loads, P_{min}, and the sampling period, T_s, are required input data.

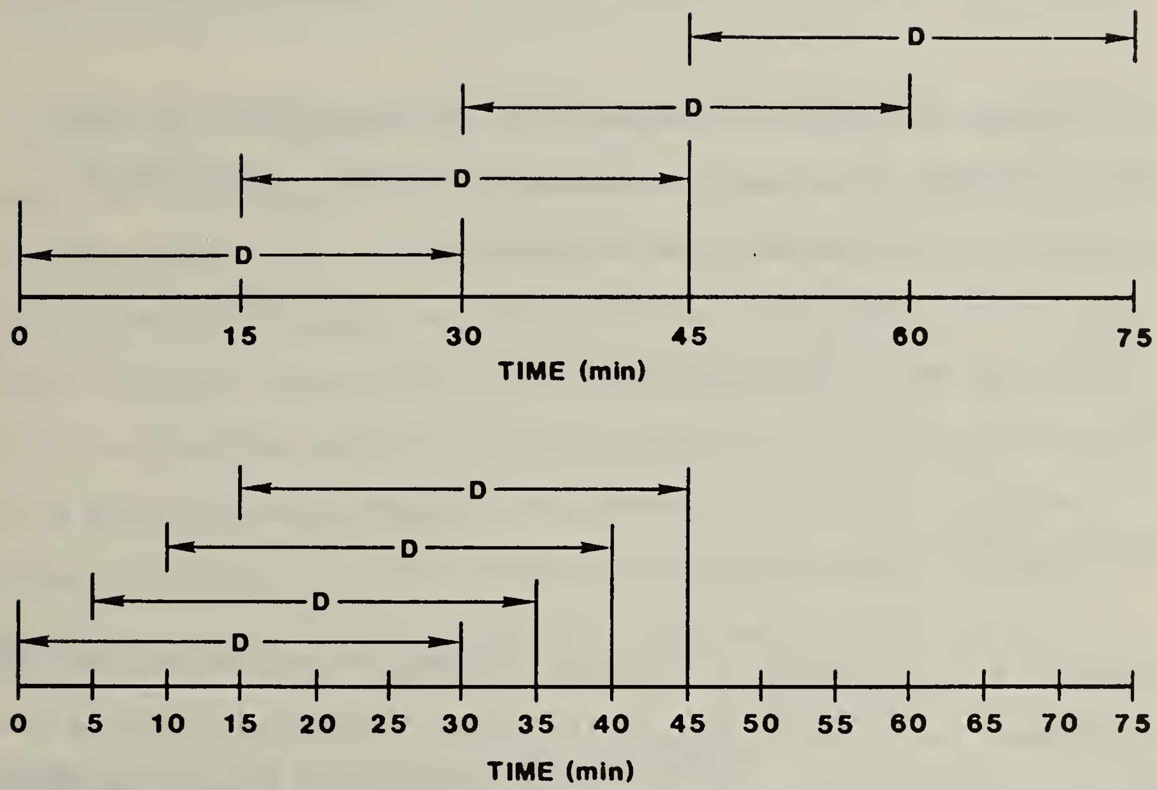

Figure 9. An illustration of sliding window billing method

With this algorithm, the demand at the next time step is unknown and thus must be forecasted from known values. Since the present and past energy consumptions are known, the energy consumption for a given demand period at time $t + T_s$ can be expressed using a linear extrapolation as:

$$E(t + T_s) = 2\,E(t) - E(t - T_s) \tag{19}$$

where $E(t)$ and $E(t+T_s)$ may be obtained from equations (4) and (6) after substituting $\widetilde{P}(t)$ as defined in equation (16) for $P(t)$. The value of $E(t - T_s)$ can be calculated using the equation:

$$E(t - T_s) = \frac{D}{n} \sum_{k=-1}^{n-2} \widetilde{P}(kT_s) \tag{20}$$

where $n = D/T_s$.

By letting $E(t + T_s)$ be $E_p(t)$, a predicted energy consumption one sampling period ahead, and by letting E_{max} be the the maximum allowable demand times the demand interval ($=P_{max}\,D$), the amount of electrical power to be shed when $E_p(t)$ exceeds E_{max} yields:

$$\Delta P = \frac{E_{max} - E_p(t)}{T_s} \tag{21}$$

When $E_p(t)$ is lower than E_{min}, which is the product of P_{min} and D, loads can be restored by:

$$\Delta P = \frac{E_{min} - E_p(t)}{T_s} \tag{22}$$

Figure 10 shows the logic flow of the predictive method with the sliding window metering. The computer program, DLPS is given in Appendix C.

4.4 INSTANTANEOUS RATE METHOD

The instantaneous rate method uses a very simple algorithm. The required input data are P(t), P_{max} and P_{min}. The instantaneous energy consumption rate is the average value of the measured power at the present and the past. Load shedding occurs if $\tilde{P}(t) > P_{max}$, and load restoring takes place if $\tilde{P}(t) < P_{min}$. The demand interval is not needed and the sampling period is not specifically involved. The sampling period is needed in equation (3) if the measurement of pulses is made in order to determine the power at an instant. Since the algorithm is so simple, the logic diagram is not provided here. However, Appendix D provides the computer program listing, DLIS.

4.5 PREDICTIVE METHOD WITH FLEXIBILITY IN METERING

The algorithm introduced here is a combined version of the predictive methods with the fixed interval metering which appeared in Section 4.2 and the sliding window metering which was discussed in Section 4.3. With this algorithm, one of two metering schemes can be selected depending upon the user's choice. When the fixed interval method is chosen and the demand interval reset signal is missed unexpectedly, the metering method is automatically switched to the sliding window metering. This automatic

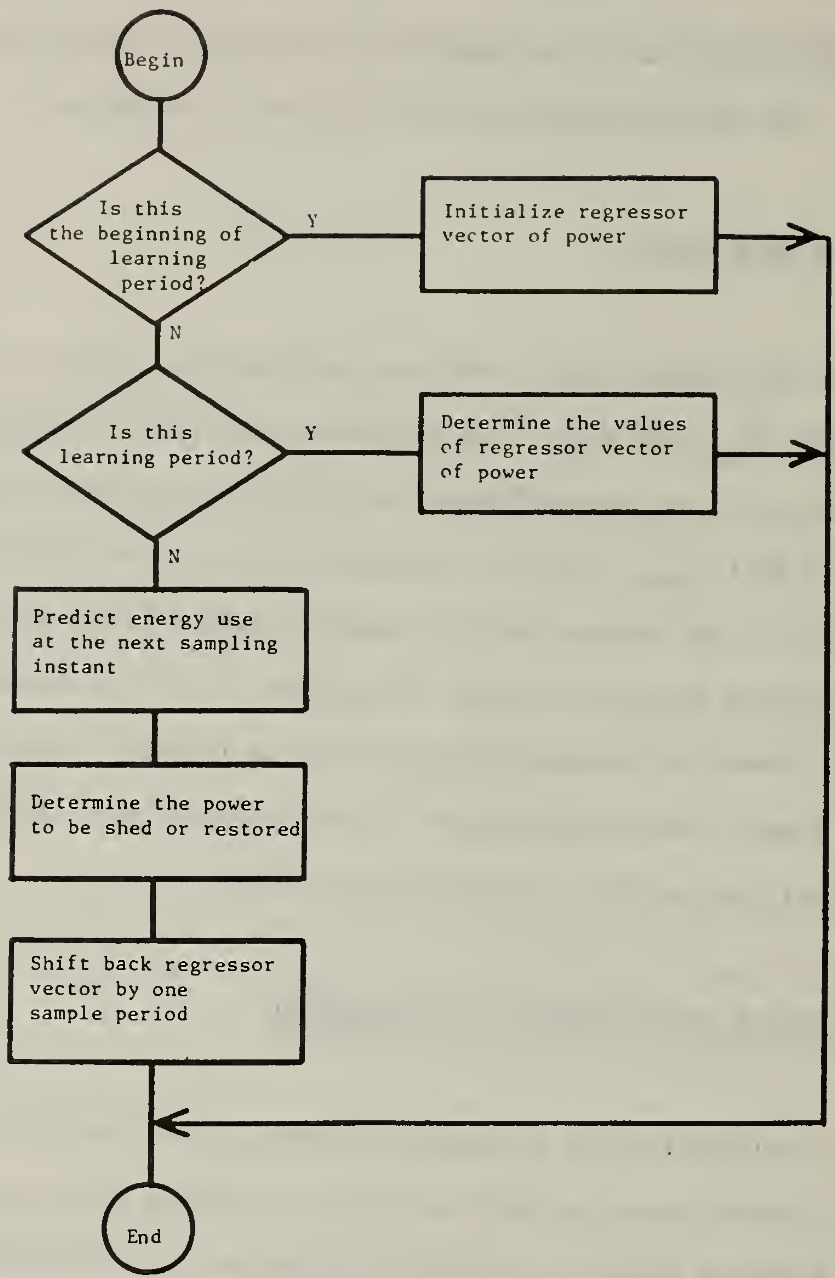

Figure 10. Logic flow diagram of the subroutine DLPSA for the predictive method with sliding window metering

changeover helps to prevent the accidental creation of a new peak demand when an unexpected thing happens such as a broken communication link between the reset signal source and the computer. Fixed interval metering is restored as as soon as the reset pulse is detected again. Variable peak demand distributions based on the time-of-day rate schedule may also be incorporated.

The computer program for this algorithm is lengthier than others in this report, because it allows for flexibility in metering. The logic flow of the linking program is shown in figure 11. Because the flow charts of predictive methods used in this algorithm are similar to the ones which appeared in figures 8 and 10, they are not presented here. The computer program listing, DLPFS, can be found in Appendix E.

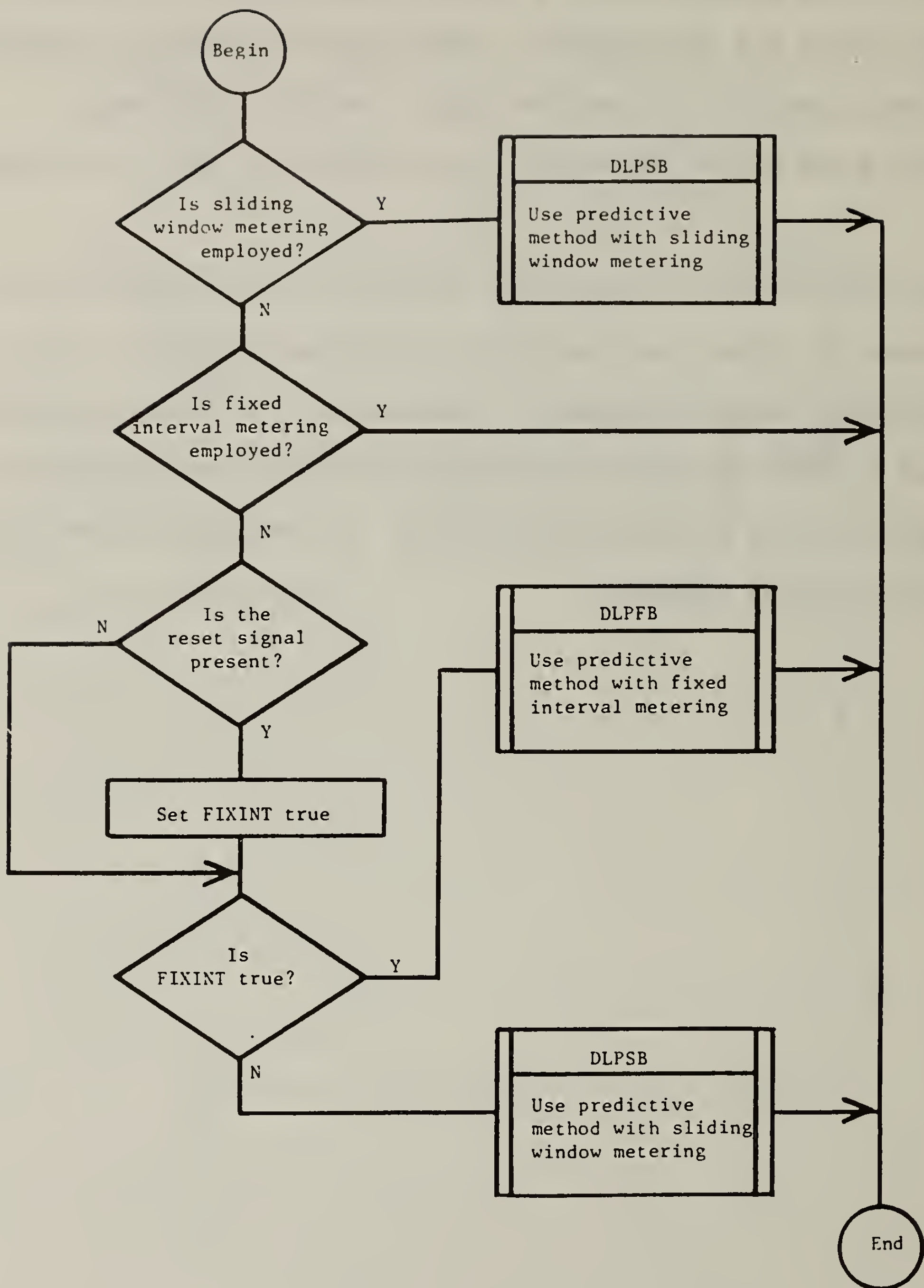

Figure 11. Logic flow diagram of the subroutine DLP for linking

5. LOAD CONTROL ALGORITHM

Controlling loads is part of the job required by demand limiting control. For clarity, the load control algorithm is separately discussed here. Excellent discussions of load control are given in papers by Zilko [2], Spethmann [9], Novak [8], and Shih [5]. Based upon these previous works, the present load control algorithm was developed. This algorithm sheds or restores loads sequentially or rotationally. Provisions for inhibiting short cycling of equipment are made. However, a "comfort fairness" concept [10] is not included but the application of such a concept can be found elsewhere [17].

As pointed out by Pannkoke [7], resistance and motor loads can be shed. Shedable resistance loads include lighting, electric space heaters, boilers, electric furnaces, electric ovens, electric water heaters, battery chargers, de-icers, etc. Motor loads would be fans, pumps, air compressors, refrigeration compressors, etc. Selective loads to be controlled may be anything that can be turned off without harming equipment, significantly impairing comfort, endangering the safety of personnel, or affecting production capability. Elevators, emergency equipment, essential lighting, and computers must be excluded from a list of candidates for shedding. If such loads are included in the list, they must be assigned the highest priority (i.e., not to be shed).

Sequential load shedding is carried out depending upon priority levels of loads. The lowest priority load is shed first and restored last, while the load with the highest priority is cut off last and turned on first. However, when a number of loads are classified with the same priority, the order for shedding is determined on a rotational base (round-robin). With the rotational load shedding, a load shed first will be restored first. Each load has a rating and loads are selected and shed until the accumulated loads being shed satisfy the shedding requirement.

It is possible that loads with low priority might experience rapid cycling which might shorten the life of the equipment. To prevent short cycle operations, time parameters are set for minimum off-time and minimum on-times. The minimum off-time ensures that once a load is shed, it will not be turned back on before a predetermined safe period has elapsed. This is particularly needed for the refrigeration system compressors. On the other hand, the minimum on-time is needed so that once a load is turned on, it will remain on for a reasonable time and is essential to prevent motors from being shut off before reaching full rotational speed.

In addition to these two time parameters, Novak [8] described the maximum off-times of loads. A noticeable change in temperature, humidity, air quality, etc. does not permit a certain type of load to be turned off for more than a specific period. Careful analysis of limiting conditions can determine the length of the maximum off-period of each load. Also, particularly during an initial cycle of load control, delay times for starting loads are necessary to prevent sudden surges of power. Delay times for each load can be set in order to make a smooth start-up during an initial start period of equipment rather than turning on a large number of loads all at once.

The algorithm for controlling loads presented here as the subroutine LDONOF incorporates all the elements mentioned above. To use this algorithm, a table must be prepared prior to the start of program. Load identification number, priority, average required power, delay time, minimum off-time, minimum on-time, and maximum off-time are tabulated and stored as one of the input files for the demand limiting program. The priority listed in the table is referred to as global priority. In contrast to the global priority, local priority levels are generated internally by the algorithm for loads with the same level of global priority.

There are two subroutines, PUSH and POP, that support the main load control routine (LDONOF). One assigns the highest local priority to the load that is most recently shed (PUSH) and the other assigns the lowest local priority to the load most recently restored (POP). Using local priority, the rotational order is created for loads with the same global priority. It is important to point out that even if a load is in the lowest level of priority, it is not shedable if the minimum on-time requirement has not been met. On the other hand, if the minimum off-time for a load has not elapsed, the load cannot be restored. Implementation of these requirements in the algorithm has increased its complexity.

The load controller algorithm is as follows:

(1) Set up local priority levels for each global priority level. Two local priority levels are assigned in a sequential order, one for turn-off and another for turn-on.

(2) Turn on loads during the initial cycle after delay times have passed.

(3) If a power decrease is demanded by a decision-making algorithm as

given in Chapter 4, and only if minimum on-times have passed, start to shed loads with the lowest priority. Then assign the highest local priority to the load which has just shut off.

(4) Restore loads, if a power increase is allowed, and if minimum off-times have passed. A load with the highest priority is restored first. Once a load is back on, assign the lowest local priority to the load.

(5) If the maximum off-time of a load has elapsed, restore the load regardless of its priority.

(6) Increase on and off times by one sample period for the use in next time step.

(7) Go to step (3).

The output values of the load control algorithm are logical values (true or false). If the logical value of a load is true, it is expected that the load is turned on, otherwise the load is turned off. A logical value itself cannot be used to directly to control any device. A command given by a high level language must be transformed into signals that are associated with switching devices. Generally machine language subprograms are involved to speed up the process. Therefore, appropriate software and hardware are needed with the load control algorithm.

Figure 12 shows the logic flow diagram for the subroutine LDONOF, and its computer program appears in Appendix F with the PUSH and POP subroutines. To aid hardware implementation, computer simulations using the open-loop assumption are described in Appendix G.

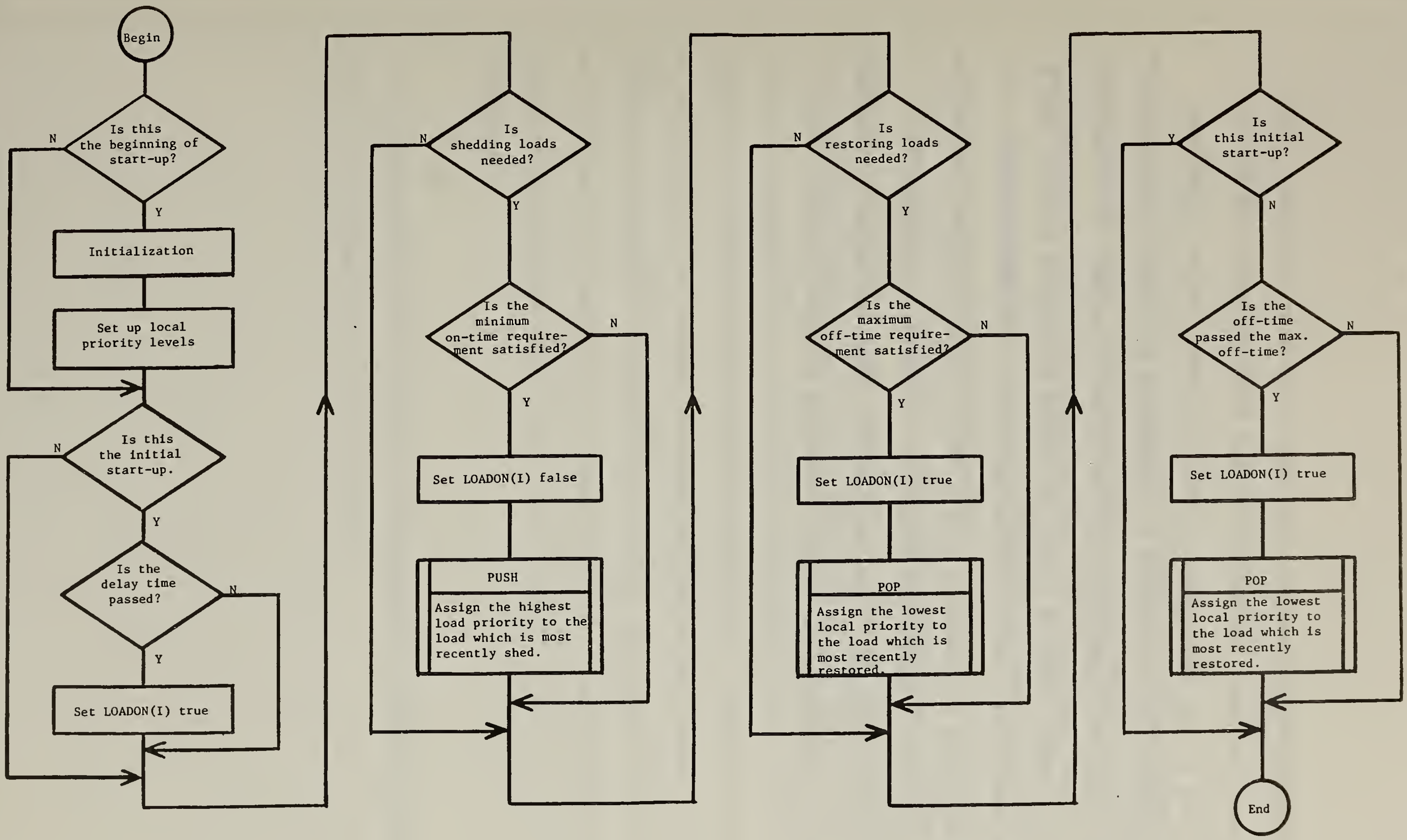

Figure 12. Logic flow diagram of the subrotuine LDONOF for load control

Duty cycle, time-of-day, scheduled start/stop, or optimum start/stop control may be active at the same time that the demand limiting control is in operation. Such a case could cause a conflict between control algorithms. This kind of problem can be resolved by reassigning the level of priority of each control algorithm depending on the conditions to be met. For instance, for shedding, a demand limiting controller should have higher priority than a duty cycling controller. But for restoring activity, the duty cycling controller can ignore a request to turn on by the demand limiting control. As a result, a high level supervisory controller is required to control all control algorithms involved. Since coordination among strategies is discussed by Spethmann [9] and May [17], further discussion will not be made in this report.

6. CONCLUSION

Demand limiting control is an important strategy for energy management and control systems (EMCS). The use of demand limiting control can not only avoid establishment of a new peak demand during a billing period, but it can also reduce energy consumption. Selection of the appropriate demand limit algorithm depends upon the billing method of the utility and the availability of a demand period reset signal. Thus, a demand limiting algorithm should be tailored according to a given situation. In the load control algorithm used with a demand limiting control, the input value determination is the customer's responsibility. The customer must provide sufficient load flexibility to permit adequate shedding capability. Appropriate coordination of the hardware, the computer programs provided in this report, and supporting software are essential for successful controls. When other control strategies are involved simultaneously with demand limiting, a supervisory program must govern the controlling activities to resolve conflicts that may arise between strategies.

It is believed that after necessary modification the algorithms presented here can be implemented on actual hardware.

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APPENDIX A. Computer Program Listing of the Ideal Rate Method with Fixed Interval-DLRF

```
Q$Q$Q$*DL(1).DLRF(0)
C ************************************************************************
C
C      DLRFMAIN : Demand limiting main program for the ideal rate method
C                 with fixed interval metering
C
C      January 12, 1984 C.P.
C
C ------------------------------------------------------------------------
C
C     DELAY     Delay time to start                                  (min)
C     DELP      The amount of power to be shed or restored           (kW)
C     DIFF      Difference between maximum and minimum energy levels
C                                                                    (kWh)
C     DMDP      Demand period                                        (min)
C     ID        Identification number of a load
C     INITST    True for initial start
C               False when no initial start is needed
C     IRESET    1 for on-status of the reset signal of demand metering
C               0 for off-status of the reset signal
C     ITIME     Number of samples taken from the beginning of sampling
C     LDNAME    Load name
C     LOADON    True if the load is turned on
C               False if the load is turned off
C     MAXOFF    Maximum off-time of a load                           (min)
C     MINOFF    Minimum off-time of a load                           (min)
C     MINON     Minimum on-time of a load                            (min)
C     NL        Maximum number of loads (=50)
C     NLD       Total number of loads
C     OFFSET    Offset at the beginning of each demand period        (kWh)
C     PDATA     Measured power data                                  (kW)
C     PLOAD     Nominal power of a load                              (kW)
C     PMAX      Maximum power allowed in a demand limit period
C                                                                    (kW)
C     PRILOW    Lowest global priority
C     PRIOR     Global priority of a load
C               The highest priority is 1 and the lowest priority is
C               PRILOW.
C     PRT       True if printing of detailed information of load status
C               is desired.
C               False if short print-out is desired.
C     RESET     True when a reset signal is on.
C               False when the reset signal is off.
C     TSAMPL    Sampling period                                      (min)
C
C ************************************************************************
C
       LOGICAL    RESET,LOADON,INITST,PRT
       REAL       MAXOFF,MINOFF,MINON
       INTEGER    PRIOR,PRILOW
       CHARACTER LDNAME*15
       PARAMETER (NL=50)
       COMMON /BK1/ DMDP,TSAMPL,PMAX,DIFF,OFFSET,PDATA
      &       /BK2/ RESET,IRESET,ENCAL
      &       /BK3/ MAXOFF(NL),MINOFF(NL),MINON(NL),PRIOR(NL),
      &             LDNAME(NL),PLOAD(NL),DELAY(NL),INITST
      &       /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
      &             LPRLOW(NL),LPRION(NL,NL),PRT
```

```
      NAMELIST /INPUT/ DMDP,TSAMPL,PMAX,DIFF,OFFSET,PRILOW,PRT,INITST
     &         /OUTPUT/ ITIME,PDATA,IRESET,DELP
C
C     Read input data files and print them.
C
      OPEN(7,FILE='INPUTRF')
      OPEN(8,FILE='LOADTABL')
      OPEN(9,FILE='INPUTPWR')
      REWIND 7
      REWIND 8
      REWIND 9
C
      READ(7,INPUT)
      PRINT INPUT
      PRINT 4000
      I=1
10    READ(8,1000,END=20) ID(I),LDNAME(I)
      READ(8,*) ID(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      PRINT 2000, ID(I),LDNAME(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      I=I+1
      GOTO 10
20    NLD=I-1
C
C     Read power and reset signals from a meter in real control
C
      ITIME=0
30    READ(9,*,END=999) PDATA,IRESET
      IF(ITIME.EQ.0.AND.IRESET.NE.1) GOTO 30
      IF(ITIME.EQ.1441) ITIME=1
      PRINT 3000
C
C     Ideal rate method using fixed interval metering
C
      CALL DLRF(DELP)
C
C     Control loads based on priorities, minimum on/off-times
C      and maximum on-times of loads.
C
      CALL LDONOF(DELP)
      PRINT OUTPUT
      IF(.NOT.PRT) THEN
        PRINT 5000,(ID(I),I=1,NLD)
        PRINT 6000,(LOADON(I),I=1,NLD)
      ENDIF
      ITIME=ITIME+1
      DELP=0.0
      GOTO 30
C
1000  FORMAT(I3,1X,A15)
2000  FORMAT(I5,1X,A15,I3,5F10.2)
3000  FORMAT(80('-')/)
4000  FORMAT(//T4,'ID',T9,'ITEM',T21,'PRIORITY',T30,'PLOAD',
     & T40,'DELAY',T50,'MINOFF',T60,'MINON',T70,'MAXOFF'/)
5000  FORMAT(20I4)
6000  FORMAT(20L4)
C
```

```
      999   STOP
            END
C ***************************************************************************
C
C       DLRF : Demand limiting using ideal rate method with
C               fixed interval metering
C
C       January 12, 1984 C.P.
C
C ----------------------------------------------------------------------------
C     DELP      The amount of power to be shed or restored           (kW)
C     DIFF      Difference between maximum and minimum energy levels
C                                                                    (kWh)
C     DMDP      Demand period                                        (min)
C     E         The amount of energy used from the beginning of
C               a demand limit period to the current time            (kWh)
C     EMAX      Maximum energy level allowed  at sampling instant
C                                                                    (kWh)
C     EMIN      Minimum energy level allowed at sampling instant
C                                                                    (kWh)
C     ENCAL     Energy used from the beginning of demand period to the
C               sampling instant(i.e., the latest value of E)        (kWh)
C     IRESET    1 for on-status of the reset signal of demand metering
C               0 for off-status of the reset signal
C     N         Number of samples in a demand limit period
C     NINT      Maximum number of samples in a demand limit period(=60)
C     OFFSET    Offset at the beginning of demand period             (kWh)
C     PDATA     Measured power data                                  (kW)
C     PMAX      Maximum power allowed in a demand limit period
C                                                                    (kW)
C     PWR       Average value of power at current and past sampling
C               instants                                             (kW)
C     RESET     True when a reset signal is on.
C               False when the reset signal is off.
C     TSAMPL    Sampling period                                      (min)
C ***************************************************************************
C
       SUBROUTINE DLRF(DELP)
       LOGICAL   RESET
       PARAMETER (NINT=60)
       DIMENSION P(0:NINT),E(0:NINT)
       COMMON /BK1/ DMDP,TSAMPL,PMAX,DIFF,OFFSET,PDATA
     &        /BK2/ RESET,IRESET,ENCAL
       NAMELIST /OUTRFI/ I,PWR,ENCAL,EMAX,EMIN
       DATA ICYCLE,IFLAG/0,1/,E(0)/0.0/
C
C      Bypass  when the reset signal is missed and resume the normal
C      operation when the reset signal appears
C
       IF(IFLAG.EQ.2) THEN
         IF(IRESET.EQ.1) THEN
           IFLAG=1
           ICYCLE=0
         ELSE
           PRINT 3000
           RETURN
         ENDIF
       ENDIF
```

```
C
C     Reset the counting of samples
C
      IF(IRESET.EQ.1 .AND. IFLAG.EQ.1) THEN
        N=DMDP/TSAMPL+0.01
        RESET=.TRUE.
        NN=0
      ENDIF
C
C     Set all energy stock values zero at the end of demand period
C     except the initial cycle
C
      IF(RESET) THEN
        IF(ICYCLE.EQ.0) THEN
          P(0)=PDATA
          ENCAL=0.0
          ICYCLE=1
        ELSE
          P(I)=PDATA
          ENCAL=ENCAL+(P(I)+P(I-1))/2.*TSAMPL/60.
          P(0)=P(I)
        ENDIF
        I=0
        DO 10 K=0,N
10      E(K)=0.0
        RESET=.FALSE.
C
C     Calculate average power and determine the power to be shed
C     or restored.
C
      ELSE
        P(I)=PDATA
        E(I)=(P(I)+P(I-1))/2.*TSAMPL/60.+E(I-1)
        ENCAL=E(I)
        EMAX=(PMAX-60.0*OFFSET/DMDP)*(I*TSAMPL/60.)+OFFSET
        EMIN=EMAX-DIFF
        IF(I.LT.N) THEN
          P(I)=60.*(E(I)-E(I-1))/TSAMPL
          PWR=P(I)
          IF(E(I).GT.EMAX) THEN
            DELP=PMAX-60.*OFFSET/DMDP-P(I)
            PRINT 1000,-DELP
          ELSEIF(E(I).LT.EMIN) THEN
            DELP=PMAX-60.*OFFSET/DMDP-P(I)
            PRINT 2000,DELP
          ENDIF
        ENDIF
      ENDIF
C
      PRINT OUTRFI
      I=I+1
      NN=NN+1
C
C     Set a flag to bypass the calculation when the reset signal misses
C
      IF(NN.GT.N) THEN
        NN=NN-1
        IFLAG=2
```

```
      ENDIF
C
1000  FORMAT(/5X,'----- POWER TO BE SHED',F10.2,'-----')
2000  FORMAT(/5X,'+++++ POWER TO BE RESTORED',F10.2,'+++++')
3000  FORMAT('!!!!!!! MISSING RESET SIGNAL !!!!!'/)
C
      RETURN
      END
```

APPENDIX B. Computer Program Listing of the Predictive Method with Fixed Interval - DLPF

```
QSQSQS*DL(1).DLPF(Ø)
      C *************************************************************************
      C
      C     DLPFMAIN: Demand limiting main program for predictive method
      C               using fixed interval metering
      C
      C     January 12, 1984 C.P.
      C
      C --------------------------------------------------------------------
      C
      C    DELAY    Delay time to start                                  (min)
      C    DELP     The amount of power to be shed or restored           (kW)
      C    DMDP     Demand period                                        (min)
      C    ID       Identification number of a load
      C    INITST   True for initial start
      C             False when no initial start is needed
      C    IRESET   1 for on-status of the reset signal of demand metering
      C             Ø for off-status of the reset signal
      C    ITIME    Number of samples taken from the beginning of sampling
      C    LDNAME   Load name
      C    LOADON   True if the load is turned on
      C             False if the load is turned off
      C    MAXOFF   Maximum off-time of a load                           (min)
      C    MINOFF   Minimum off-time of a load                           (min)
      C    MINON    Minimum on-time of a load                            (min)
      C    NL       Maximum number of loads (=5Ø)
      C    NLD      Total number of loads
      C    PDATA    Measured power data                                  (kW)
      C    PLOAD    Nominal power of a load                              (kW)
      C    PMAX     Maximum power allowed in a demand limit period
      C                                                                  (kW)
      C    PMIN     Minimum power allowed in a demand limit period
      C                                                                  (kW)
      C    PRILOW   Lowest global priority
      C    PRIOR    Global priority of a load
      C             The highest priority is 1 and the lowest priority is
      C             PRILOW.
      C    PRT      True if printing of detailed information of load status
      C             is desired.
      C             False if short print-out is desired.
      C    RESET    True when a reset signal is on.
      C             False when the reset signal is off.
      C
      C *************************************************************************
      C
           LOGICAL    RESET,LOADON,INITST,PRT
           REAL       MAXOFF,MINOFF,MINON
           INTEGER    PRIOR,PRILOW
           CHARACTER LDNAME*15
           PARAMETER (NL=5Ø)
           COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
          &       /BK2/ RESET,IRESET,PPRED,ENCAL
          &       /BK3/ MAXOFF(NL),MINOFF(NL),MINON(NL),PRIOR(NL),
          &             LDNAME(NL),PLOAD(NL),DELAY(NL),INITST
          &       /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
          &             LPRLOW(NL),LPRION(NL,NL),PRT
           NAMELIST /INPUT/ DMDP,TSAMPL,PMAX,PMIN,PRILOW,PRT,INITST
          &          /OUTPUT/ ITIME,PDATA,IRESET,DELP
```

```
C
C      Read input data files and print them.
C
       OPEN(7,FILE='INPUTPF')
       OPEN(8,FILE='LOADTABL')
       OPEN(9,FILE='INPUTPWR')
       REWIND 7
       REWIND 8
       REWIND 9
C
       READ(7,INPUT)
       PRINT INPUT
       PRINT 4000
       I=1
I0     READ(8,1000,END=20) ID(I),LDNAME(I)
       READ(8,*) ID(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
       PRINT 2000, ID(I),LDNAME(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
       I=I+1
       GOTO I0
20     NLD=I-1
C
C      Read power and reset signals from a meter in real control
C
       ITIME=0
30     READ(9,*,END=999) PDATA,IRESET
       IF(ITIME.EQ.0.AND.IRESET.NE.I) GOTO 30
       IF(ITIME.EQ.144I) ITIME=I
       PRINT 3000
C
C      Predictive method  using  fixed interval metering
C
       CALL DLPFA(DELP)
C
C      Control loads based on priorities, minimum on/off-times
C       and maximum on-times of loads.
C      .
       CALL LDONOF(DELP)
       PRINT OUTPUT
       IF(.NOT.PRT) THEN
         PRINT 5000,(ID(I),I=I,NLD)
         PRINT 6000,(LOADON(I),I=I,NLD)
       ENDIF
       ITIME=ITIME+I
       DELP=0.0
       GOTO 30
C
1000   FORMAT(I3,1X,A15)
2000   FORMAT(I5,1X,A15,I3,5FI0.2)
3000   FORMAT(80('-')/)
4000   FORMAT(//T4,'ID',T9,'ITEM',T21,'PRIORITY',T30,'PLOAD',
     & T40,'DELAY',T50,'MINOFF',T60,'MINON',T70,'MAXOFF'/)
5000   FORMAT(20I4)
6000   FORMAT(20L4)
C
999    STOP
       END
```

```
C ***************************************************************************
C
C     DLPFA: Demand limiting using predictive method with
C            fixed interval metering
C
C     January 12, 1984 C.P.
C
C -------------------------------------------------------------------------
C     DELP     The amount of power to be shed or restored         (kW)
C     DMDP     Demand period                                      (min)
C     E        The amount of energy used from the beginning of
C              a demand limit period to the current time          (kWh)
C     EMAX     Maximum energy level allowed in a demand limit period
C                                                                 (kWh)
C     EMIN     Minimum energy level allowed in a demand limit period
C                                                                 (kWh)
C     ENCAL    Energy used during a sampling period               (kWh)
C     EPRED    Predicted value of energy use during a demand period
C                                                                 (kWh)
C     IRESET   1 for on-status of the reset signal of demand metering
C              0 for off-status of the reset signal
C     N        Number of samples in a demand limit period
C     NINT     Maximum number of samples in a demand limit period(=60)
C     P        Power at a sampling instant                        (kW)
C     PDATA    Measured power data                                (kW)
C     PLOAD    Nominal power of a load                            (kW)
C     PMAX     Maximum power allowed in a demand limit period
C                                                                 (kW)
C     PMIN     Minimum power allowed in a demand limit period
C                                                                 (kW)
C     PPRED    Predicted value of average power for a demand limit
C              period                                             (kW)
C     RESET    True when a reset signal is on.
C              False when the reset signal is off.
C     TSAMPL   Sampling period                                    (min)
C ***************************************************************************
C
      SUBROUTINE DLPFA(DELP)
      LOGICAL   RESET
      PARAMETER (NINT=60)
      DIMENSION P(0:NINT),E(0:NINT)
      COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
     &       /BK2/ RESET,IRESET,PPRED,ENCAL
      NAMELIST /OUTPF1/ I,PPRED,EPRED,EMAX,EMIN,ENCAL
      DATA ICYCLE,IFLAG/0,1/
C
C     Bypass when the reset signal is missing and resume the normal
C     operation when the reset signal appears.
C
      IF(IFLAG.EQ.2) THEN
        IF(IRESET.EQ.1) THEN
          ICYCLE=0
          IFLAG=1
        ELSE
          PRINT 3000
          RETURN
        ENDIF
      ENDIF
```

```
C
C     Reset the counting of samples
C
      IF(IRESET.EQ.1 .AND. IFLAG.EQ.1) THEN
        N=DMDP/TSAMPL+0.01
        RESET=.TRUE.
        NN=0
      ENDIF
C
C     Set all energy stock values zero at the end of demand period
C     except the initial cycle.
C
      IF(RESET) THEN
        IF(ICYCLE.EQ.0) THEN
          P(0)=PDATA
          ENCAL=0.0
          ICYCLE=1
        ELSE
          P(I)=PDATA
          ENCAL=ENCAL+(P(I)+P(I-1))/2.*TSAMPL/60.
          P(0)=P(I)
        ENDIF
        I=0
        DO 10 K=0,N
10      E(K)=0.0
        RESET=.FALSE.
C
C     Predict energy use at the end of demand period and
C     determine the power to be shed or restored.
C
      ELSE
        P(I)=PDATA
        E(I)=(P(I)+P(I-1))/2.*TSAMPL/60.+E(I-1)
        ENCAL=E(I)
        EMAX=PMAX*DMDP/60.
        EMIN=PMIN*DMDP/60.
        IF(I.LT.N) THEN
          EPRED=(N-I)*(E(I)-E(I-1))+E(I)
          PPRED=60.*EPRED/DMDP
          IF(EPRED.GT.EMAX) THEN
            DELP=60.*(EMAX-EPRED)/(DMDP-I*TSAMPL)
            PRINT 1000,-DELP
          ELSEIF(EPRED.LT.EMIN) THEN
            DELP=60.*(EMIN-EPRED)/(DMDP-I*TSAMPL)
            PRINT 2000,DELP
          ENDIF
        ENDIF
      ENDIF
      PRINT OUTPFI
      I=I+1
      NN=NN+1
C
C     Set a flag to bypass the prediction when the reset signal misses.
C
      IF(NN.GT.N) THEN
        NN=NN-1
        IFLAG=2
        PRINT 3000
```

```
            PRINT 3000
          ENDIF
C
1000      FORMAT(/5X,'----- POWER TO BE SHED',F10.2,'-----')
2000      FORMAT(/5X,'+++++ POWER TO BE RESTORED',F10.2,'+++++')
3000      FORMAT('!!!!!!! MISSING RESET SIGNAL  !!!!!'/)
C
          RETURN
          END
```

APPENDIX C. Computer Program Listing of the Predictive Method with Sliding Window - DLPS

```
Q$Q$Q$*DL(1).DLPS(0)
      C ***********************************************************************
      C
      C     DLPSMAIN: Demand limiting main program for predictive method
      C               using sliding window metering
      C
      C     January 12, 1984 C.P.
      C
      C -----------------------------------------------------------------------
      C
      C    DELAY    Delay time to start                                 (min)
      C    DELP     The amount of power to be shed or restored          (kW)
      C    DMDP     Demand period                                       (min)
      C    ID       Identification number of a load
      C    INITST   True for initial start
      C             False when no initial start is needed
      C    ITIME    Number of samples taken from the beginning of sampling
      C    LDNAME   Load name
      C    LOADON   True if the load is turned on
      C             False if the load is turned off
      C    MAXOFF   Maximum off-time of a load                          (min)
      C    MINOFF   Minimum off-time of a load                          (min)
      C    MINON    Minimum on-time of a load                           (min)
      C    NL       Maximum number of loads (=50)
      C    NLD      Total number of loads
      C    PDATA    Measured power data                                 (kW)
      C    PLOAD    Nominal power of a load                             (kW)
      C    PMAX     Maximum power allowed in a demand limit period
      C                                                                 (kW)
      C    PMIN     Minimum power allowed in a demand limit period
      C                                                                 (kW)
      C    PRILOW   Lowest global priority
      C    PRIOR    Global priority of a load
      C             The highest priority is 1 and the lowest priority is
      C             PRILOW.
      C    PRT      True if printing of detailed information of load status
      C             is desired.
      C             False if short print-out is desired.
      C    TSAMPL   Sampling period                                     (min)
      C
      C ***********************************************************************
      C
            LOGICAL   LOADON,INITST,PRT
            REAL      MAXOFF,MINOFF,MINON
            INTEGER   PRIOR,PRILOW
            CHARACTER LDNAME*15
            PARAMETER (NL=50)
            COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
           &       /BK2/ PPRED,ENCAL
           &       /BK3/ MAXOFF(NL),MINOFF(NL),MINON(NL),PRIOR(NL),
           &             LDNAME(NL),PLOAD(NL),DELAY(NL),INITST
           &       /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
           &             LPRLOW(NL),LPRION(NL,NL),PRT
            NAMELIST /INPUT/ DMDP,TSAMPL,PMAX,PMIN,PRILOW,PRT,INITST
           &         /OUTPUT/ ITIME,PDATA,DELP
      C
      C     Read input data files and print them.
      C
```

```
      OPEN(7,FILE='INPUTPS')
      OPEN(8,FILE='LOADTABL')
      OPEN(9,FILE='INPUTPWR')
      REWIND 7
      REWIND 8
      REWIND 9
C
      READ(7,INPUT)
      PRINT INPUT
      PRINT 4000
      I=1
10    READ(8,1000,END=20) ID(I),LDNAME(I)
      READ(8,*) ID(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      PRINT 2000, ID(I),LDNAME(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      I=I+1
      GOTO 10
20    NLD=I-1
C
C       Read power signal from a meter in real control
C
      ITIME=0
30    READ(9,*,END=999) PDATA
      IF(ITIME.EQ.1441) ITIME=1
      PRINT 3000
C
C     Predictive method  using sliding window metering
C
      CALL DLPSA(DELP)
C
C     Control loads based on priorities, minimum on/off-times
C      and maximum on-times of loads.
C
      CALL LDONOF(DELP)
      PRINT OUTPUT
      IF(.NOT.PRT) THEN
        PRINT 5000,(ID(I),I=1,NLD)
        PRINT 6000,(LOADON(I),I=1,NLD)
      ENDIF
      ITIME=ITIME+1
      DELP=0.0
      GOTO 30
C
1000  FORMAT(I3,1X,A15)
2000  FORMAT(I5,1X,A15,I3,5F10.2)
3000  FORMAT(80('-')/)
4000  FORMAT(//T4,'ID',T9,'ITEM',T21,'PRIORITY',T30,'PLOAD',
     & T40,'DELAY',T50,'MINOFF',T60,'MINON',T70,'MAXOFF'/)
5000  FORMAT(20I4)
6000  FORMAT(20L4)
C
999   STOP
      END
C ***********************************************************************
C
C     DLPSA : Demand limiting using predictive method with
C             sliding window metering
```

```
C
C      January 12, 1984 C.P.
C
C ---------------------------------------------------------------------
C     DELP      The amount of power to be shed or restored          (kW)
C     DMDP      Demand period                                       (min)
C     E         The amount of energy used from the beginning of
C               a demand limit period to the current time           (kWh)
C     EMAX      Maximum energy level allowed in a demand limit period
C                                                                   (kWh)
C     EMIN      Minimum energy level allowed in a demand limit period
C                                                                   (kWh)
C     ENCAL     Energy used during a sampling period                (kWh)
C     EPRED     Predicted value of energy use during a demand period
C                                                                   (kWh)
C     N         Number of samples in a demand limit period
C     NINT      Maximum number of samples in a demand limit period(=60)
C     PDATA     Measured power data                                 (kW)
C     PLAG      Time-lagged power                                   (kW)
C     PMAX      Maximum power allowed in a demand limit period
C                                                                   (kW)
C     PMIN      Minimum power allowed in a demand limit period
C                                                                   (kW)
C     PPRED     Predicted value of average power for a demand limit
C               period                                              (kW)
C     START     True at the beginning of program run
C               False  otherwise
C     TSAMPL    Sampling period                                     (min)
C ***********************************************************************
C
      SUBROUTINE DLPSA(DELP)
      LOGICAL   START
      PARAMETER (NINT=60)
      DIMENSION PLAG(0:NINT),E(0:2)
      COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
     &       /BK2/ PPRED,ENCAL
      NAMELIST /OUTPSW/ I,PPRED,EPRED,EMAX,EMIN,ENCAL
      DATA START/.TRUE./
C
C     Determine the number of samples per  sample period.
C
      N=DMDP/TSAMPL+0.01
C
C     Initialize the regressor vector of power.
C
      IF(START) THEN
        ICYCLE=0
        I=0
        DO 10 K=0,N
 10     PLAG(K)=0.0
        START=.FALSE.
C
C     Determine the regressor vector of power in the learning period.
C
      ELSEIF(ICYCLE.EQ.0) THEN
        PLAG(0)=PDATA
        DO 20 K=N-1,0,-1
 20     PLAG(K+1)=PLAG(K)
```

```
          IF(I.EQ.N-1) ICYCLE=I
          I=I+1
C
C     Predict energy use at the next sampling instance
C     and determine the power to be shed or restored.
C
        ELSE
          PLAG(0)=PDATA
          SUM=0.0
          DO 30 K=1,N-1
30        SUM=SUM+TSAMPL/60.*(PLAG(K)+PLAG(K+1))/2.
          E(0)=SUM
          E(1)=TSAMPL/60.*(PLAG(0)+PLAG(1))/2.+E(0)
          ENCAL=E(1)
          E(2)=2*E(1)-E(0)
          EPRED=E(2)
          PPRED=60.*EPRED/DMDP
          EMAX=PMAX*DMDP/60.
          EMIN=PMIN*DMDP/60.
          IF(EPRED.GT.EMAX) THEN
            DELP=60.*(EMAX-EPRED)/TSAMPL
            PRINT 1000,-DELP
          ELSEIF(EPRED.LT.EMIN) THEN
            DELP=60.*(EMIN-EPRED)/TSAMPL
            PRINT 2000,DELP
          ENDIF
C
          PRINT OUTPSW
C
C     Shift back the  regressor vector by one sample period
C
          DO 40 K=N-1,0,-1
40        PLAG(K+1)=PLAG(K)
        ENDIF
C
1000    FORMAT(/5X,'----- POWER TO BE SHED',F10.2,'-----')
2000    FORMAT(/5X,'+++++ POWER TO BE RESTORED',F10.2,'+++++')
C
        RETURN
        END
```

APPENDIX D. Computer Program Listing of the Instantaneous Rate Method - DLIS

```
Q$Q$Q$*DL(1).DLIS(0)
      C ***********************************************************************
      C
      C     DLISMAIN  : Demand limiting main program for instantaneous
      C                 rate method
      C
      C      January 12, 1984 C.P.
      C
      C -----------------------------------------------------------------
      C
      C     DELAY     Delay time to start                                (min)
      C     DELP      The amount of power to be shed or restored         (kW)
      C     ID        Identification number of a load
      C     INITST    True for initial start
      C               False when no initial start is needed
      C     ITIME     Number of samples taken from the beginning of sampling
      C     LDNAME    Load name
      C     LOADON    True if the load is turned on
      C               False if the load is turned off
      C     MAXOFF    Maximum off-time of a load                         (min)
      C     MINOFF    Minimum off-time of a load                         (min)
      C     MINON     Minimum on-time of a load                          (min)
      C     NL        Maximum number of loads (=50)
      C     NLD       Total number of loads
      C     PDATA     Measured power data                                (kW)
      C     PLOAD     Nominal power of a load                            (kW)
      C     PMAX      Maximum power allowed in a demand limit period
      C                                                                  (kW)
      C     PMIN      Minimum power allowed in a demand limit period
      C                                                                  (kW)
      C     PRILOW    Lowest global priority
      C     PRIOR     Global priority of a load
      C               The highest priority is 1 and the lowest priority is
      C               PRILOW.
      C     PRT       True if printing of detailed information of load status
      C               is desired.
      C               False if short print-out is desired.
      C
      C ***********************************************************************
      C
            LOGICAL   LOADON,INITST,PRT
            REAL      MAXOFF,MINOFF,MINON
            INTEGER   PRIOR,PRILOW
            CHARACTER LDNAME*15
            PARAMETER (NL=50)
            COMMON /BK1/ PMAX,PMIN,PDATA
           &       /BK3/ MAXOFF(NL),MINOFF(NL),MINON(NL),PRIOR(NL),
           &             LDNAME(NL),PLOAD(NL),DELAY(NL),INITST
           &       /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
           &             LPRLOW(NL),LPRION(NL,NL),PRT
            NAMELIST /INPUT/ PMAX,PMIN,PRILOW,PRT,INITST
           &         /OUTPUT/ ITIME,PDATA,DELP
      C
      C     Read input data files and print them.
      C
            OPEN(7,FILE='INPUTIS')
            OPEN(8,FILE='LOADTABL')
            OPEN(9,FILE='INPUTPWR')
```

```
      REWIND 7
      REWIND 8
      REWIND 9
C
      READ(7,INPUT)
      PRINT INPUT
      PRINT 4000
      I=1
10    READ(8,1000,END=20) ID(I),LDNAME(I)
      READ(8,*) ID(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      PRINT 2000, ID(I),LDNAME(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      I=I+1
      GOTO 10
20    NLD=I-1
C
C     Read power from a meter in real control
C
      ITIME=0
30    READ(9,*,END=999) PDATA
      IF(ITIME.EQ.1441) ITIME=1
      PRINT 3000
C
C     Instantaneous rate method
C
      CALL DLIS(DELP)
C
C     Control loads based on priorities, minimum on/off-times
C      and maximum on-times of loads.
C
      CALL LDONOF(DELP)
      PRINT OUTPUT
      IF(.NOT.PRT) THEN
        PRINT 5000,(ID(I),I=1,NLD)
        PRINT 6000,(LOADON(I),I=1,NLD)
      ENDIF
      ITIME=ITIME+1
      DELP=0.0
      GOTO 30
C
1000  FORMAT(I3,1X,A15)
2000  FORMAT(I5,1X,A15,I3,5F10.2)
3000  FORMAT(80('-')/)
4000  FORMAT(//T4,'ID',T9,'ITEM',T21,'PRIORITY',T30,'PLOAD',
     & T40,'DELAY',T50,'MINOFF',T60,'MINON',T70,'MAXOFF'/)
5000  FORMAT(20I4)
6000  FORMAT(20L4)
C
999   STOP
      END
C *************************************************************************
C
C     DLIS : Demand limiting using instantaneous rate method
C
C     January 12, 1984  C.P.
C
C ------------------------------------------------------------------
```

```
C     DELP      The amount of power to be shed or restored          (kW)
C     PAVG      Average value of current and past powers
C     PDATA     Measured power data                                 (kW)
C     PLAG      Time-lagged power                                   (kW)
C     PMAX      Maximum power allowed in a demand limit period
C                                                                   (kW)
C     PMIN      Minimum power allowed in a demand limit period
C                                                                   (kW)
C     RESET     True when a reset signal is on.
C               False when the reset signal is off.
C ******************************************************************************
C
      SUBROUTINE DLIS(DELP)
      LOGICAL   RESET
      DIMENSION PLAG(0:1)
      COMMON /BK1/ PMAX,PMIN,PDATA
      NAMELIST /OUTISW/ PAVG,PMAX,PMIN
      DATA RESET/.TRUE./
C
      IF(RESET) THEN
        PLAG(0)=0.0
        PLAG(1)=0.0
        RESET=.FALSE.
C
      ELSE
        PLAG(0)=PDATA
        PAVG=(PLAG(0)+PLAG(1))/2.
        IF(PAVG.GT.PMAX) THEN
          DELP=PMAX-PAVG
          PRINT 1000,-DELP
        ELSEIF(PAVG.LT.PMIN) THEN
          DELP=PMIN-PAVG
          PRINT 2000,DELP
        ENDIF
C
        PRINT OUTISW
C
        PLAG(1)=PLAG(0)
      ENDIF
C
1000   FORMAT(/5X,'----- POWER TO BE SHED',F10.2,'-----')
2000   FORMAT(/5X,'+++++ POWER TO BE RESTORED',F10.2,'+++++')
C
      RETURN
      END
```

APPENDIX E. Computer Program Listing of the Predictive Method with Flexibility in Metering - DLPFS

```
Q$Q$Q$*DL(1).DLPFS(Ø)
      C ***********************************************************************
      C
      C     DLPFSMAIN: Demand limiting main program for predictive method
      C
      C       January 12, 1984 C.P.
      C
      C -----------------------------------------------------------------
      C
      C    DELAY    Delay time to start                              (min)
      C    DELP     The amount of power to be shed or restored       (kW)
      C    DMDP     Demand period                                    (min)
      C    FIXINT   True if fixed interval metering is used
      C             False if sliding window metering is used
      C    ID       Identification number of a load
      C    INITST   True for initial start
      C             False when no initial start is needed
      C    IRESET   1 for on-status of the reset signal of demand metering
      C             Ø for off-status of the reset signal
      C    ITIME    Number of samples taken from the beginning of sampling
      C    LDNAME   Load name
      C    LOADON   True if the load is turned on
      C             False if the load is turned off
      C    MAXOFF   Maximum off-time of a load                       (min)
      C    MINOFF   Minimum off-time of a load                       (min)
      C    MINON    Minimum on-time of a load                        (min)
      C    MODE     = 1 for fixed interval metering
      C             = 2 for sliding window metering
      C    NL       Maximum number of loads (=5Ø)
      C    NLD      Total number of loads
      C    PDATA    Measured power data                              (kW)
      C    PLOAD    Nominal power of a load                          (kW)
      C    PMAX     Maximum power allowed in a demand limit period
      C                                                              (kW)
      C    PMIN     Minimum power allowed in a demand limit period
      C                                                              (kW)
      C    PRILOW   Lowest global priority
      C    PRIOR    Global priority of a load
      C             The highest priority is 1 and the lowest priority is
      C             PRILOW.
      C    PRT      True if printing of detailed information of load status
      C             is desired.
      C             False if short print-out is desired.
      C    TSAMPL   Sampling period                                  (min)
      C
      C ***********************************************************************
      C
          LOGICAL    RESET,FIXINT,LOADON,INITST,PRT
          REAL       MAXOFF,MINOFF,MINON
          INTEGER    PRIOR,PRILOW
          CHARACTER  LDNAME*15
          PARAMETER  (NL=5Ø)
          COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
         &       /BK2/ FIXINT,RESET,IRESET,PPRED,ENCAL
         &       /BK3/ MAXOFF(NL),MINOFF(NL),MINON(NL),PRIOR(NL),
         &             LDNAME(NL),PLOAD(NL),DELAY(NL),INITST
         &       /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
         &             LPRLOW(NL),LPRION(NL,NL),PRT
```

```
      NAMELIST /INPUT/ DMDP,TSAMPL,PMAX,PMIN,PRILOW,PRT,MODE,INITST
     &         /OUTPUT/ ITIME,PDATA,IRESET,DELP,FIXINT
      DATA FIXINT/.FALSE./
C
C     Read input data files and print them.
C
      OPEN(7,FILE='INPUTPFS')
      OPEN(8,FILE='LOADTABL')
      OPEN(9,FILE='INPUTPWR')
      REWIND 7
      REWIND 8
      REWIND 9
C
      READ(7,INPUT)
      PRINT INPUT
      PRINT 4000
      I=1
10    READ(8,1000,END=20) ID(I),LDNAME(I)
      READ(8,*) ID(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      PRINT 2000, ID(I),LDNAME(I),PRIOR(I),PLOAD(I),DELAY(I),MINOFF(I),
     & MINON(I),MAXOFF(I)
      I=I+1
      GOTO 10
20    NLD=I-1
C
C     Read power and reset signals from a meter in real control
C     when fixed interval metering is used(MODE=1).
C     Read power data only from a meter when sliding window
C     metering is used(MODE=2).
C
      ITIME=0
30    READ(9,*,END=999) PDATA,IRESET
      IF(MODE.EQ.1.AND.ITIME.EQ.0.AND.IRESET.NE.1) GOTO 30
      IF(ITIME.EQ.1441) ITIME=1
      PRINT 3000
C
C     Predictive method is called using sliding window or fixed
C      interval metering
C
      CALL DLP(MODE,DELP)
C
C     Control loads based on priorities, minimum on/off-times
C      and maximum on-times of loads.
C
      CALL LDONOF(DELP)
      PRINT OUTPUT
      IF(.NOT.PRT) THEN
        PRINT 5000,(ID(I),I=1,NLD)
        PRINT 6000,(LOADON(I),I=1,NLD)
      ENDIF
      ITIME=ITIME+1
      DELP=0.0
      GOTO 30
C
1000  FORMAT(I3,1X,A15)
2000  FORMAT(I5,1X,A15,I3,5F10.2)
3000  FORMAT(80('-')/)
```

```
      4000  FORMAT(//T4,'ID',T9,'ITEM',T21,'PRIORITY',T30,'PLOAD',
     &  T40,'DELAY',T50,'MINOFF',T60,'MINON',T70,'MAXOFF'/)
      5000  FORMAT(2014)
      6000  FORMAT(20L4)
      C
      999   STOP
            END
      C ***********************************************************************
      C
      C     DLP   : Demand limiting link program for predictive method
      C
      C     January 12, 1984 C.P.
      C
      C ***********************************************************************
      C
            SUBROUTINE DLP(MODE,DELP)
            LOGICAL   RESET,FIXINT
            COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
           &       /BK2/ FIXINT,RESET,IRESET,PPRED,ENCAL
      C
      C     Sliding window metering
      C
            IF(MODE.EQ.2) THEN
              CALL DLPSB(DELP)
      C
      C     Fixed interval metering
      C     If the reset signal is missing at the next sampling
      C     instance, sliding window metering is activated. When
      C     the reset signal is restored, fixed interval metering
      C     is also restored.
      C
            ELSEIF(MODE.EQ.1) THEN
              IF(IRESET.EQ.1) THEN
                FIXINT=.TRUE.
              ENDIF
              IF(FIXINT) THEN
                CALL DLPFB(DELP)
              ELSE
                CALL DLPSB(DELP)
              ENDIF
            ENDIF
      C
            RETURN
            END
      C ***********************************************************************
      C
      C     DLPFB: Demand limiting using predictive method with
      C            fixed interval metering
      C
      C     January 12, 1984 C.P.
      C
      C ---------------------------------------------------------------------
      C    DELP     The amount of power to be shed or restored        (kW)
      C    DMDP     Demand period                                     (min)
      C    E        The amount of energy used from the beginning of
      C             a demand limit period to the current time         (kWh)
      C    EMAX     Maximum energy level allowed in a demand limit period
      C                                                               (kWh)
```

```
C     EMIN     Minimum energy level allowed in a demand limit period
C                                                              (kWh)
C     ENCAL    Energy used during a sampling period            (kWh)
C     EPRED    Predicted value of energy use during a demand period
C                                                              (kWh)
C     EPS      A small positive number (=0.01)
C     FIXINT   True if fixed interval metering is used
C              False if sliding window metering is used
C     IRESET   1 for on-status of the reset signal of demand metering
C              0 for off-status of the reset signal
C     N        Number of samples in a demand limit period
C     NINT     Maximum number of samples in a demand limit period(=60)
C     P        Power at a sampling instant                     (kW)
C     PDATA    Measured power data                             (kW)
C     PMAX     Maximum power allowed in a demand limit period
C                                                              (kW)
C     PMIN     Minimum power allowed in a demand limit period
C                                                              (kW)
C     PPRED    Predicted value of average power for a demand limit
C              period                                          (kW)
C     RESET    True when a reset signal is on.
C              False when the reset signal is off.
C     TSAMPL   Sampling period                                 (min)
C ************************************************************************
C
      SUBROUTINE DLPFB(DELP)
      LOGICAL   RESET,FIXINT
      PARAMETER (NINT=60)
      DIMENSION P(0:NINT),E(0:NINT)
      COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
     &       /BK2/ FIXINT,RESET,IRESET,PPRED,ENCAL
      NAMELIST /OUTPFI/ I,PPRED,EPRED,EMAX,EMIN,ENCAL
      DATA ICYCLE/0/
C
C     Reset the counting of samples
C
      IF(IRESET.EQ.1) THEN
        N=DMDP/TSAMPL+0.01
        RESET=.TRUE.
        NN=0
      ENDIF
C
C     Set all energy stock values zero at the end of demand period
C     except the initial cycle
C
      IF(RESET) THEN
        IF(ICYCLE.EQ.0) THEN
          P(0)=PDATA
          ENCAL=0.0
          ICYCLE=1
        ELSE
          P(I)=PDATA
          ENCAL=ENCAL+(P(I)+P(I-1))/2.*TSAMPL/60.
          P(0)=P(I)
        ENDIF
        I=0
        DO 10 K=0,N
 10     E(K)=0.0
```

```
          RESET=.FALSE.
C
C     Predict energy use at the end of demand period and
C     determine the power to be shed or restored.
C
        ELSE
          P(I)=PDATA
          E(I)=(P(I)+P(I-1))/2.*TSAMPL/60.+E(I-1)
          ENCAL=E(I)
          EMAX=PMAX*DMDP/60.
          EMIN=PMIN*DMDP/60.
          IF(I.LT.N) THEN
            EPRED=(N-I)*(E(I)-E(I-1))+E(I)
            PPRED=60.*EPRED/DMDP
            IF(EPRED.GT.EMAX) THEN
              DELP=60.*(EMAX-EPRED)/(DMDP-I*TSAMPL)
              PRINT 1000,-DELP
            ELSEIF(EPRED.LT.EMIN) THEN
              DELP=60.*(EMIN-EPRED)/(DMDP-I*TSAMPL)
              PRINT 2000,DELP
            ENDIF
          ENDIF
        ENDIF
        PRINT OUTPFI
        I=I+1
        NN=NN+1
C
C     Switch over to sliding window metering when
C     the reset signal is not detected.
C
        IF(NN.GT.N) THEN
          ICYCLE=0
          FIXINT=.FALSE.
          RESET=.TRUE.
          PRINT 3000
        ENDIF
C
1000    FORMAT(/5X,'----- POWER TO BE SHED',F10.2,'-----')
2000    FORMAT(/5X,'+++++ POWER TO BE RESTORED',F10.2,'+++++')
3000    FORMAT('!!!!!!! SWITCHED TO SLIDING WINDOW !!!!!'/)
C
        RETURN
        END
C ***********************************************************************
C
C       DLPSB : Demand limiting using predictive method with
C               sliding window metering
C
C       January 12, 1984 C.P.
C
C ----------------------------------------------------------------------
C      DELP      The amount of power to be shed or restored        (kW)
C      DMDP      Demand period                                     (min)
C      E         The amount of energy used from the beginning of
C                a demand limit period to the current time         (kWh)
C      EMAX      Maximum energy level allowed in a demand limit period
C                                                                  (kWh)
C      EMIN      Minimum energy level allowed in a demand limit period
```

```
C                                                                   (kWh)
C     ENCAL     Energy used during a sampling period                (kWh)
C     EPRED     Predicted value of energy use during a demand period
C                                                                   (kWh)
C     N         Number of samples in a demand limit period
C     NINT      Maximum number of samples in a demand limit period(=60)
C     PDATA     Measured power data                                 (kW)
C     PLAG      Time-lagged power                                   (kW)
C     PMAX      Maximum power allowed in a demand limit period
C                                                                   (kW)
C     PMIN      Minimum power allowed in a demand limit period
C                                                                   (kW)
C     PPRED     Predicted value of average power for a demand limit
C               period                                              (kW)
C     RESET     True when a reset signal is on.
C               False when the reset signal is off.
C     TSAMPL    Sampling period                                     (min)
C ***********************************************************************
C
      SUBROUTINE DLPSB(DELP)
      LOGICAL   RESET
      PARAMETER (NINT=60)
      DIMENSION PLAG(0:NINT),E(0:2)
      COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
     &       /BK2/ FIXINT,RESET,IRESET,PPRED,ENCAL
      NAMELIST /OUTPSW/ I,PPRED,EPRED,EMAX,EMIN,ENCAL
C
C     Determine the number of samples per demand period
C
      N=DMDP/TSAMPL+0.01
C
C     Initialize the regressor vector of power.
C
      IF(RESET) THEN
        ICYCLE=0
        I=0
        DO 10 K=0,N
10      PLAG(K)=0.0
        RESET=.FALSE.
C
C     Determine the regressor vector of power in the learning period.
C
      ELSEIF(ICYCLE.EQ.0) THEN
        PLAG(0)=PDATA
        DO 20 K=N-1,0,-1
20      PLAG(K+1)=PLAG(K)
        IF(I.EQ.N-1) ICYCLE=1
        I=I+1
C
C     Predict energy use at the next sampling instance
C     and determine the power to be shed or restored.
C
      ELSE
        PLAG(0)=PDATA
        SUM=0.0
        DO 30 K=1,N-1
30      SUM=SUM+TSAMPL/60.*(PLAG(K)+PLAG(K+1))/2.
        E(0)=SUM
```

```
        E(1)=TSAMPL/60.*(PLAG(0)+PLAG(1))/2.+E(0)
        ENCAL=E(1)
        E(2)=2*E(1)-E(0)
        EPRED=E(2)
        PPRED=60.*EPRED/DMDP
        EMAX=PMAX*DMDP/60.
        EMIN=PMIN*DMDP/60.
        IF(EPRED.GT.EMAX) THEN
          DELP=60.*(EMAX-EPRED)/TSAMPL
          PRINT 1000,-DELP
        ELSEIF(EPRED.LT.EMIN) THEN
          DELP=60.*(EMIN-EPRED)/TSAMPL
          PRINT 2000,DELP
        ENDIF
C
        PRINT OUTPSW
C
C     Shift back the  regressor vector by one sample period
C
        DO 40 K=N-1,0,-1
40      PLAG(K+1)=PLAG(K)
      ENDIF
C
1000  FORMAT(/5X,'----- POWER TO BE SHED',F10.2,'-----')
2000  FORMAT(/5X,'+++++ POWER TO BE RESTORED',F10.2,'+++++')
C
      RETURN
      END
```

APPENDIX F. Computer Program Listing of the Load Control Algorithm - LDONOF

```
QSQSQS*DL(1).LDONOF(Ø)
C *************************************************************************
C
C      LDONOF :  Turn on or off loads
C
C      April 29, 1983 C.P.
C
C -----------------------------------------------------------------------
C
C     DELAY    Delay time to start                                 (min)
C     DELP     The amount of power to be shed or restored          (kW)
C     EPS      Small positive number for tolerance(=Ø.Ø1)
C     INITST   True for initial start
C              False when no initial start is needed
C     ISTAT    Number of loads which are turned on at an initial stage
C     ISUM     Number of loads turned on during initial cycle
C     LOADON   True if the load is turned on
C              False if the load is turned off
C     LPR      Local priority of a load
C     LPRIOF   Local priority of a load for shedding
C     LPRION   Local priority of a load for restoring
C     LPRLOW   Lowest local priority level
C     MAXOFF   Maximum off-time of a load                          (min)
C     MINOFF   Minimum off-time of a load                          (min)
C     MINON    Minimum on-time of a load                           (min)
C     NL       Maximum number of loads (=5Ø)
C     NLD      Total number of loads
C     PLOAD    Nominal power of a load                             (kW)
C     PRI      Global priority of a load
C     PRILOW   Lowest global priority
C     PRIOR    Global priority of a load
C              The highest priority is 1 and the lowest priority is
C              PRILOW.
C     PRT      True if printing of detailed information of load status
C              is desired.
C              False if short print-out is desired.
C     SUMPINT  Summed nominal power turned on during initial cycle
C     SUMP     Summed nominal power actually shed or restored at an instant
C                                                                  (kW)
C     TOFF     Off-time of a load                                  (min)
C     TON      On-time of a load                                   (min)
C     TSAMPL   Sampling period                                     (min)
C
C *************************************************************************
C
      SUBROUTINE LDONOF(DELP)
C
      REAL      MAXOFF,MINOFF,MINON
      INTEGER   PRIOR,PRI,PRILOW
      LOGICAL   LOADON,INITST,PRT
      CHARACTER LDNAME*15
      PARAMETER (NL=5Ø)
      DIMENSION TON(NL),TOFF(NL),ISTAT(NL)
      COMMON /BK1/ DMDP,TSAMPL,PMAX,PMIN,PDATA
      COMMON /BK3/ MAXOFF(NL),MINOFF(NL),MINON(NL),PRIOR(NL),
     &             LDNAME(NL),PLOAD(NL),DELAY(NL),INITST
     &       /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
     &             LPRLOW(NL),LPRION(NL,NL),PRT
```

```
      NAMELIST /NAM1/ SUMINT,ISUM,INITST
     &         /NAM2/ SUMP
      DATA EPS/0.01/,IFLAG/0/
C
C     Initialization
C
      IF(IFLAG.EQ.0) THEN
        DO 10 I=1,NLD
        TON(I)=0.0
        TOFF(I)=0.0
        LOADON(I)=.FALSE.
        ISTAT(I)=0
10      CONTINUE
C
C     Set up local priority levels for each global priority
C     level, PRIOR(I).  Two local priority levels are assigned
C     in a sequential order, one for turn-off and another for
C     turn-on.
C
        DO 40 PRI=1,PRILOW
        K=0
        DO 20 I=1,NLD
        IF(PRIOR(I).EQ.PRI) THEN
          K=K+1
          LPRIOF(PRI,I)=K
        ENDIF
20      CONTINUE
        LPRLOW(PRI)=K
        KK=LPRLOW(PRI)+1
        DO 30 I=1,NLD
        IF(PRIOR(I).EQ.PRI) THEN
          KK=KK-1
          LPRION(PRI,I)=KK
        ENDIF
30      CONTINUE
40      CONTINUE
        IFLAG=1
      ENDIF
C
C     Turn on loads during the initial cycle after delay times
C     are over.
c
C
      IF(INITST) THEN
        ISUM=0
        SUMINT=0.0
        DO 50 I=1,NLD
        IF(TOFF(I).GE.DELAY(I)) THEN
          LOADON(I)=.TRUE.
          SUMINT=SUMINT+PLOAD(I)
          ISTAT(I)=1
        ENDIF
        ISUM=ISUM+ISTAT(I)
        IF(ISUM.EQ.NLD) INITST=.FALSE.
50      CONTINUE
      PRINT NAM1
      ENDIF
C
```

```
C      Shed loads if power decrease is demanded by the
C      amount of DELP, and if minimum on-times are passed.
C      Start to shed loads with low priority first.
C      Assign the highest local priority to the load most
C      recently shed.
C
       IF(DELP.LT.-EPS) THEN
         SUMP=0.0
         DO 90 PRI=PRILOW,1,-1
 60      DO 80 LPR=LPRLOW(PRI),1,-1
         DO 70 I=1,NLD
         IF(PRIOR(I).GE.PRI.AND.TON(I).GE.MINON(I).AND.MAXOFF(I).GT.
     &     0.0.AND.LOADON(I).AND.LPRIOF(PRI,I).EQ.LPR) THEN
           LOADON(I)=.FALSE.
           TOFF(I)=0.0
           KEY=LPRIOF(PRI,I)
           CALL PUSH(KEY,PRI)
           SUMP=SUMP+PLOAD(I)
           PRINT 1000,I
           GOTO 60
         ENDIF
         IF(SUMP.GE.-DELP) GOTO 100
 70      CONTINUE
 80      CONTINUE
 90      CONTINUE
 100     PRINT NAM2
       ENDIF
C
C      Restore loads if power increase is allowed by the
C      amount of DELP, and if minimum off-times are passed.
C      Start to restore loads with high priority first.
C      Assign the lowest local priority to the load most
C      recently restored.
C
       IF(DELP.GT.EPS) THEN
         SUMP=0.0
         DO 140 PRI=1,PRILOW
 110     DO 130 LPR=1,LPRLOW(PRI)
         DO 120 I=1,NLD
         IF(PRIOR(I).EQ.PRI.AND.TOFF(I).GE.MINOFF(I).AND.
     &     (.NOT.LOADON(I)).AND.LPRION(PRI,I).EQ.LPR) THEN
           LOADON(I)=.TRUE.
           TON(I)=0.0
           ISTAT(I)=1
           KEY=LPRION(PRI,I)
           CALL POP(KEY,PRI)
           SUMP=SUMP+PLOAD(I)
           PRINT 2000,I
           GOTO 110
         ENDIF
         IF(SUMP.GE.DELP) GOTO 150
 120     CONTINUE
 130     CONTINUE
 140     CONTINUE
 150     PRINT NAM2
       ENDIF
C
C      Restore loads regardless of priority level, if maximum
```

```
C      off-times are passed.
C
       IF(.NOT.INITST) THEN
         DO 160 PRI=1,PRILOW
         DO 160 I=1,NLD
         IF(PRIOR(I).EQ.PRI.AND.TOFF(I).GE.MAXOFF(I)
     &     .AND.(.NOT.LOADON(I))) THEN
           LOADON(I)=.TRUE.
           TON(I)=0.0
           KEY=LPRION(PRI,I)
           CALL POP(KEY,PRI)
           PRINT 5000,I
         ENDIF
 160      CONTINUE
       ENDIF
C
C      Print details
C
       IF(PRT) THEN
         PRINT 3000
         DO 170 I=1,NLD
 170     PRINT 4000,I,PLOAD(I),TOFF(I),MINOFF(I),TON(I),MINON(I),
     &   LOADON(I),PRIOR(I),LPRIOF(PRIOR(I),I),LPRION(PRIOR(I),I)
       ENDIF
C
C      Increase on- and off-times by one sample period for
C      the use in the next time step
C
       DO 180 I=1,NLD
       IF(LOADON(I)) THEN
         TON(I)=TON(I)+TSAMPL
         IF(TON(I).GE.2*MINON(I)+24*60) TON(I)=2*MINON(I)
       ELSE
         TOFF(I)=TOFF(I)+TSAMPL
         IF(TOFF(I).GE.2*MAXOFF(I)+24*60) TOFF(I)=2*MAXOFF(I)
       ENDIF
 180   CONTINUE
C
 1000  FORMAT(5X,'------ LOAD #',I5,2X,'SHED-----')
 2000  FORMAT(5X,'++++++ LOAD #',I5,2X,'RESTORED++++++')
 3000  FORMAT(/T5,'I',T10,'PLOAD',T21,'TOFF',T29,'MINOFF',T41,'TON',
     &T50,'MINON',T56,'STATUS',T63,'PRI',T67,'LPRIOF',T74,'LPRION'/)
 4000  FORMAT(I5,5(F9.2,1X),3X,L1,2X,I4,2(3X,I3,1X))
 5000  FORMAT(5X,'++++++ LOAD #',I5,2X,'RESTORED SINCE ',
     & 'THE MAXIMUM OFF-TIME IS PASSED')
C
       RETURN
       END
C ***********************************************************************
C
C      PUSH :  Determine local priority levels for each given
C                global priority .
C
C              Assign the highest local priority to the load
C              which is most recently shed.
C
C      April 27, 1983 C.P.
C
```

```
C ************************************************************************
C
      SUBROUTINE PUSH(KEY,PRI)
      LOGICAL   LOADON,PRT
      INTEGER   PRI,PRILOW
      PARAMETER (NL=50)
      COMMON /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
     &               LPRLOW(NL),LPRION(NL,NL),PRT
      DIMENSION ITEMP(NL,NL)
C
      DO 10 I=1,NLD
        IF(LPRIOF(PRI,I).LT.KEY) THEN
          ITEMP(PRI,I)=LPRIOF(PRI,I)+1
        ELSEIF(LPRIOF(PRI,I).GT.KEY) THEN
          ITEMP(PRI,I)=LPRIOF(PRI,I)
        ELSE
          ITEMP(PRI,I)=1
        ENDIF
10    CONTINUE
C
      DO 20 I=1,NLD
20    LPRIOF(PRI,I)=ITEMP(PRI,I)
C
      RETURN
      END
C ************************************************************************
C
C     POP :  Determine local priority levels for each given
C                global priority .
C
C            Assign the lowest local priority to the load
C            which is most recently restored.
C
C
C     April 27, 1983 C.P.
C
C ************************************************************************
C
      SUBROUTINE POP(KEY,PRI)
      LOGICAL   LOADON,PRT
      INTEGER   PRI,PRILOW
      PARAMETER (NL=50)
      COMMON /BK4/ NLD,ID(NL),LOADON(NL),PRILOW,LPRIOF(NL,NL),
     &               LPRLOW(NL),LPRION(NL,NL),PRT
      DIMENSION ITEMP(NL,NL)
C
      DO 10 I=1,NLD
        IF(LPRION(PRI,I).GT.KEY) THEN
          ITEMP(PRI,I)=LPRION(PRI,I)-1
        ELSEIF(LPRION(PRI,I).LT.KEY) THEN
          ITEMP(PRI,I)=LPRION(PRI,I)
        ELSE
          ITEMP(PRI,I)=LPRLOW(PRI)
        ENDIF
10    CONTINUE
C
      DO 20 I=1,NLD
20    LPRION(PRI,I)=ITEMP(PRI,I)
C
      RETURN
      END
```

APPENDIX G. Open-Loop Computer Simulation

For illustration purposes, a computer simulation was performed under an open-loop condition and is presented in this appendix. The open-loop assumption cannot be applied in actual load control condition, employing demand limiting control algorithms. Without feedback, the effects of load shedding or restoring are not realized in the control action. The selected algorithm for the simulation was the predictive method with flexibility in metering (either fixed interval or sliding window metering) as described in section 4.5. Accordingly, the computer programs given in Appendix E and Appendix F were used. Most numerical values of input data were arbitrarily selected but some of the values for average power requirement were extracted from the work by May.* Some extremely large and small numerical values were specified as input data in order to check the capability of the computer program.

The main program, DLPFSMAIN, in Appendix E calls three input files as follows:

Logical Unit	File Name
7	INPUTPFS
8	LOADTABL
9	INPUTPWR

The format used by the file, INPUTPFS, is an input format for the NAMELIST statement of Fortran 77 in a Sperry 1100/82 computer. Since this format is machine-dependent, a Fortran user's manual should be consulted if other

*W. B. May, "Analysis of Data from the Energy Monitoring and Control System at the Norris Cotton Federal Office Building," Natl. Bur. of Standards, NBSIR 81-2358, 1981.

computers are employed. If desired, the main program, DLPFSMAIN, may be modified to read the information in the INPUTPFS file interactively. The INPUTPFS file contains the following:

DMDP = 5.0 min	:	demand period
TSAMPL = 1.0 min	:	sampling period
PMAX = 75.0 kW	:	maximum power allowed in a demand period above which shedding loads takes place
PMIN = 70.0 kW	:	minimum power allowed in a demand period below which restoring loads takes place
PRILOW = 3	:	integer variable, lowest global priority. The highest priority is 1 and the lowest priority is PRILOW
PRT = F	:	logical variable, set true (=T) if printing of detailed information of load status is desired, set false (=F) otherwise.
MODE = 1	:	integer variable, choice of metering. When fixed interval used, MODE = 1 and when sliding window is used, MODE = 2.
INITST = T	:	logical variable, true (=T) if initial start; otherwise set false (=F).

The file, LOADTABL, is needed for the load control routine, LDONOF, that is listed in Appendix F. The file comprises the following items for each load:

ID = 001	:	integer variable, load identification number
LDNAME = NORMAL LIGHT #1	:	description of a load, up to 15 characters

PRIOR = 2	:	integer variable indicating the global priority of a load. The lower the number the higher the priority, and vice versa.
PLOAD = 5.974 kW	:	nominal average power of a load
DELAY = 0.0 min	:	delay time for starting at the initial period
MINOFF = 0.0 min	:	minimum off-time of a load. Only after this off-time, the load may be restored.
MINON = 0.0 min	:	minimum on-time of a load. Only after the on-time passes the minimum on-time, the load may be shed.
MAXOFF = 1440.0 min	:	maximum off-time of a load. If the load is maintained off more than the time period specified by MAXOFF, restoring the load occurs automatically. Assignment of highest number (=1440) prevents automatic restoring.

The values given above are the values for the first load in the file, LOADTABL, in this appendix. For each load, two lines of data are needed such as shown below:

1st line: ID, LDNAME (I3, 1X, A15)

2nd line: ID, PRIOR, PLOAD, DELAY, MINOFF, MINON, MAXOFF (free format)

The instantaneous power, PDATA, is actually measured at each sampling instant in a real control environment. In this open-loop simulation, the instantaneous power is not measured, but specified arbitrarily. The file, INPUTPWR, contains the instantaneous power, PDATA, and a reset signal, IRESET. PDATA has a unit of kW, and IRESET is an integer, either 0 or 1. Presence of the reset signal from the utility's meter is indicated by IRESET = 1. PDATA and IRESET have a free format in the INPUTPWR file.

Important simulation output data are:

DELP: the amount of power to be shed or restored

LOADON: logical variable. True (=T) if the load is turned on and false (=F) if off. Using a supporting program, this logical value may be translated into a binary code and used as input to actual hardware controls.

Printout of I/O operation for the simulation is included in the following pages.

INPUT DATA FOR SIMULATION

```
QSQSQS*INPUTPFS(1)
        $INPUT DMDP=5.0,TSAMPL=1.0,PMAX=75.0,PMIN=70.0,PRILOW=3,PRT=F,
               MODE=1,INITST=T,$END
```

```
QSQSQS*LOADTABL(1)
     001 NORMAL LIGHT#1
     001 2  5.974  0.0   0.0   0.0   1440.0
     002 NORMAL LIGHT#2
     002 3  3.625  2.0   0.0   0.0   1440.0
     003 ESSENTIAL LIGHT
     003 1  8.516  0.0   0.0   0.0      0.0
     004 HEAT PUMP #1
     004 3 13.753  3.0   5.0  90.0     20.0
     005 HEAT PUMP #2
     005 3  5.597  4.0   3.0   3.0     15.0
     006 FAN COIL
     006 2  0.546  3.0   2.0   2.0     10.0
     007 FAN
     007 3  9.554  4.0   3.0   3.0     10.0
     008 COOLER
     008 3  0.037  5.0   5.0   5.0     20.0
     009 PUMP
     009 2  0.748  4.0   3.0   3.0     20.0
     010 ELEVATOR
     010 1  8.876  0.0   0.0   0.0      0.0
     011 EMERG. SYSTEM
     011 1  8.395  0.0   0.0   0.0      0.0
     012 OTHER
     012 3  2.091  2.0   0.0  90.0   1440.0
```

```
QSQSQS*INPUTPWR(1)
     31.76 0
     31.76 0
     31.76 0
     31.76 0
     31.76 0
     31.76 1
     31.76 0
     37.48 0
     51.78 0
     67.68 0
     67.72 1
     67.72 0
     67.72 0
     67.75 0
     67.00 0
     75.00 1
     60.00 0
     70.00 0
     75.00 0
     60.00 0
     70.00 1
     75.00 0
     80.00 0
     85.00 0
     60.00 0
     50.00 1
     80.00 0
     40.00 0
     50.00 0
     67.00 0
     80.00 1
     40.00 0
```

```
@XQT DL.NAMES
 $INPUT
DMOP = .50000000-001,TSAMPL = .10000000+001,PMAX = .75000000+002,PMIN = .70000000+002,PRILOW =          3,PRT = F,
MODE =          1,INITST = T
$END
```

ID	ITEM	PRIORITY	PLOAD	DELAY	MINOFF	MINON	MAXOFF
1	NORMAL LIGHT#1	2	5.97	.00	.00	.00	1440.00
2	NORMAL LIGHT#2	3	3.63	2.00	.00	.00	1440.00
3	ESSENTIAL LIGHT	1	8.52	.00	.00	.00	.00
4	HEAT PUMP #1	3	13.75	3.00	5.00	90.00	20.00
5	HEAT PUMP #2	3	5.60	4.00	3.00	3.00	15.00
6	FAN COIL	2	.55	3.00	2.00	2.00	10.00
7	FAN	3	9.55	4.00	3.00	3.00	10.00
8	COOLER	3	.04	5.00	5.00	5.00	20.00
9	PUMP	2	.75	4.00	3.00	3.00	20.00
10	ELEVATOR	1	8.88	.00	.00	.00	.00
11	EMERG. SYSTEM	1	8.39	.00	.00	.00	.00
12	OTHER	3	2.09	2.00	.00	90.00	1440.00

```
 $OUTPF1
1 =          0,PPRED = .00000000     ,EPRED = .00000000     ,EMAX = .00000000     ,EMIN = .00000000     ,ENCAL = .00000000
$END
 $NAM1
SUMINT = .31761000+002,ISUM =          4,INITST = T
$END
 $OUTPUT
ITIME =          0,PDATA = .31760000+002,IRESET =          1,DELP = .00000000     ,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   F   T   F   F   F   F   F   F   T   T   F
-------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED      47.80*****
 $OUTPF1
1 =          1,PPRED = .31759999+002,EPRED = .26466666+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .52933333+000
$END
 $NAM1
SUMINT = .31761000+002,ISUM =          4,INITST = T
$END
    ****** LOAD #    12  RESTORED******
    ****** LOAD #     2  RESTORED******
 $NAM2
SUMP = .57160000+001
$END
 $OUTPUT
ITIME =          1,PDATA = .31760000+002,IRESET =          0,DELP = .47800000+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   F   F   F   F   F   F   T   T   T
-------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED      59.92*****
 $OUTPF1
1 =          2,PPRED = .34047999+002,EPRED = .28373333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .11063333+001
$END
 $NAM1
SUMINT = .31761000+002,ISUM =          6,INITST = T
$END
    ****** LOAD #     6  RESTORED******
 $NAM2
SUMP = .54600000+000
$END
 $OUTPUT
ITIME =          2,PDATA = .37480000+002,IRESET =          0,DELP = .59920001+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   F   F   T   F   F   F   T   T   T
-------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED      74.87*****
 $OUTPF1
1 =          3,PPRED = .40053999+002,EPRED = .33378333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .10581666+001
$END
 $NAM1
```

```
SUMINT = .45514ØØØ+ØØ2.ISUM =           8.INITST = T
$END
    ****** LOAD #     9  RESTORED******
    ****** LOAD #     7  RESTORED******
    ****** LOAD #     5  RESTORED******
 $NAM2
SUMP = .15899ØØØ+ØØ2
$END
 $OUTPUT
ITIME =           3.PDATA = .5178ØØØØ+ØØ2.IRESET =           Ø.DELP = .74865ØØ1+ØØ2.FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12
  T   T   T   T   T   T   T   F   T   T   T   T
--------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED    119.53*****
 $OUTPFI
I =          4.PPRED = .46Ø93999+ØØ2.EPRED = .38411666+ØØ1.EMAX = .625ØØØØØ+ØØ1.EMIN = .58333333+ØØ1.ENCAL = .28456666+ØØ1
$END
 $NAM1
SUMINT = .45514ØØØ+ØØ2.ISUM =           11.INITST = T
$END
 $NAM2
SUMP = .ØØØØØØØØ
$END
 $OUTPUT
ITIME =           4.PDATA = .6768ØØØØ+ØØ2.IRESET =           Ø.DELP = .11953ØØØ+ØØ3.FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12
  T   T   T   T   T   T   T   F   T   T   T   T
--------------------------------------------------------------------------------

 $OUTPFI
I =          Ø.PPRED = .46Ø93999+ØØ2.EPRED = .38411666+ØØ1.EMAX = .625ØØØØØ+ØØ1.EMIN = .58333333+ØØ1.ENCAL = .3974ØØØØ+ØØ1
$END
 $NAM1
SUMINT = .45551ØØØ+ØØ2.ISUM =           12.INITST = F
$END
 $OUTPUT
ITIME =           5.PDATA = .6772ØØØØ+ØØ2.IRESET =           1.DELP = .ØØØØØØØØ     .FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
--------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED      2.85*****
 $OUTPFI
I =          1.PPRED = .67719999+ØØ2.EPRED = .56433333+ØØ1.EMAX = .625ØØØØØ+ØØ1.EMIN = .58333333+ØØ1.ENCAL = .11286667+ØØ1
$END
 $NAM2
SUMP = .ØØØØØØØØ
$END
 $OUTPUT
ITIME =           6.PDATA = .6772ØØØØ+ØØ2.IRESET =           Ø.DELP = .285ØØØØØ+ØØ1.FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12

  T   T   T   T   T   T   T   T   T   T   T   T
--------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED      3.8Ø*****
 $OUTPFI
I =          2.PPRED = .67719999+ØØ2.EPRED = .56433333+ØØ1.EMAX = .625ØØØØØ+ØØ1.EMIN = .58333333+ØØ1.ENCAL = .22573333+ØØ1
$END
 $NAM2
SUMP = .ØØØØØØØØ
$END
 $OUTPUT
ITIME =           7.PDATA = .6772ØØØØ+ØØ2.IRESET =           Ø.DELP = .38ØØØØØØ+ØØ1.FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
--------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED  -   5.68*****
 $OUTPFI
I =          3.PPRED = .67728998+ØØ2.EPRED = .5644Ø833+ØØ1.EMAX = .625ØØØØØ+ØØ1.EMIN = .58333333+ØØ1.ENCAL = .338625ØØ+ØØ1
$END
 $NAM2
SUMP = .ØØØØØØØØ
$END
 $OUTPUT
ITIME =           8.PDATA = .6775ØØØØ+ØØ2.IRESET =           Ø.DELP = .56775Ø16+ØØ1.FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
--------------------------------------------------------------------------------

    ***** POWER TO BE RESTORED     12.Ø8*****
 $OUTPFI
I =          4.PPRED = .67584998+ØØ2.EPRED = .5632Ø832+ØØ1.EMAX = .625ØØØØØ+ØØ1.EMIN = .58333333+ØØ1.ENCAL = .45Ø91666+ØØ1
$END
 $NAM2
SUMP = .ØØØØØØØØ
$END
 $OUTPUT
ITIME =           9.PDATA = .67ØØØØØØ+ØØ2.IRESET =           Ø.DELP = .12Ø75ØØ5+ØØ2.FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
--------------------------------------------------------------------------------

 $OUTPFI
I =          Ø.PPRED = .67584998+ØØ2.EPRED = .5632Ø832+ØØ1.EMAX = .625ØØØØØ+ØØ1.EMIN = .58333333+ØØ1.ENCAL = .56924999+ØØ1
$END
 $OUTPUT
ITIME =          1Ø.PDATA = .75ØØØØØØ+ØØ2.IRESET =           1.DELP = .ØØØØØØØØ     .FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  1Ø  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
--------------------------------------------------------------------------------
```

```
    +++++ POWER TO BE RESTORED       3.12+++++
 $OUTPF1
I =            1,PPRED = .67500000+002,EPRED = .56250000+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .11250000+001
$END
 $NAM2
SUMP = .00000000
$END
 $OUTPUT
ITIME =           11,PDATA = .68000000+002,IRESET =           0,DELP = .31249997+001,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED       7.50+++++
 $OUTPF1
I =            2,PPRED = .65499998+002,EPRED = .54583333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .22083333+001
$END
 $NAM2
SUMP = .00000000
$END
 $OUTPUT
ITIME =           12,PDATA = .70000000+002,IRESET =           0,DELP = .75000012+001,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED        .00+++++
 $OUTPF1
I =            3,PPRED = .69999998+002,EPRED = .58333333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .34166666+001
$END
 $OUTPUT
ITIME =           13,PDATA = .75000000+002,IRESET =           0,DELP = .17881393-005,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED      10.00+++++
 $OUTPF1
I =            4,PPRED = .67999999+002,EPRED = .56666666+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .45416666+001
$END
 $NAM2
SUMP = .00000000
$END
 $OUTPUT
ITIME =           14,PDATA = .68000000+002,IRESET =           0,DELP = .10000001+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
------------------------------------------------------------------------------------

 $OUTPF1



I =            0,PPRED = .67999999+002,EPRED = .56666666+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .56249999+001
$END
 $OUTPUT
ITIME =           15,PDATA = .70000000+002,IRESET =           1,DELP = .00000000     ,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
------------------------------------------------------------------------------------

 $OUTPF1
I =            1,PPRED = .72499999+002,EPRED = .60416666+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .12083333+001
$END
 $OUTPUT
ITIME =           16,PDATA = .75000000+002,IRESET =           0,DELP = .00000000     ,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
------------------------------------------------------------------------------------

     ----- POWER TO BE SHED       2.50-----
 $OUTPF1
I =            2,PPRED = .76499999+002,EPRED = .63749999+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .25000000+001
$END
     ------ LOAD #     8  SHED-----
     ------ LOAD #     7  SHED-----
 $NAM2
SUMP = .95910000+001
$END
 $OUTPUT
ITIME =           17,PDATA = .80000000+002,IRESET =           0,DELP =-.24999980+001,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   F   F   T   T   T   T
------------------------------------------------------------------------------------

     ----- POWER TO BE SHED      11.25-----
 $OUTPF1
I =            3,PPRED = .79499999+002,EPRED = .66249999+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .38750000+001
$END
     ------ LOAD #     5  SHED-----
     ------ LOAD #     2  SHED-----
     ------ LOAD #     9  SHED-----
     ------ LOAD #     6  SHED-----
     ------ LOAD #     1  SHED-----
 $NAM2
SUMP = .16490000+002
$END
 $OUTPUT
ITIME =           18,PDATA = .85000000+002,IRESET =           0,DELP =-.11249998+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  F   F   T   T   F   F   F   F   F   T   T   T
------------------------------------------------------------------------------------

     ----- POWER TO BE SHED       2.50-----
```

```
 $OUTPF1
I =           4,PPRED = .75499998+002,EPRED = .62916666+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .50833333+001
$END
 $NAM2
SUMP = .00000000
$END
 $OUTPUT
ITIME =          19,PDATA = .60000000+002,IRESET =           0,DELP =-.24999940+001,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  F   F   T   T   F   F   F   F   F   T   T   T
-------------------------------------------------------------------------------------

 $OUTPF1
I =           0,PPRED = .75499998+002,EPRED = .62916666+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .59999999+001
$END
 $OUTPUT
ITIME =          20,PDATA = .50000000+002,IRESET =           1,DELP = .00000000     ,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  F   F   T   T   F   F   F   F   F   T   T   T
-------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED      6.25+++++
 $OUTPF1
I =           1,PPRED = .64999999+002,EPRED = .54166666+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .10833333+001
$END
    ++++++ LOAD #     1  RESTORED++++++
    ++++++ LOAD #     6  RESTORED++++++
 $NAM2
SUMP = .65199999+001
$END
 $OUTPUT
ITIME =          21,PDATA = .80000000+002,IRESET =           0,DELP = .62500003+001,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   F   T   T   F   T   F   F   F   T   T   T
-------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED     15.00+++++
 $OUTPF1
I =           2,PPRED = .60999999+002,EPRED = .50833333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .20833333+001
$END
    ++++++ LOAD #     9  RESTORED++++++
    ++++++ LOAD #     8  RESTORED++++++
    ++++++ LOAD #     2  RESTORED++++++
    ++++++ LOAD #     7  RESTORED++++++
    ++++++ LOAD #     5  RESTORED++++++
 $NAM2
SUMP = .19561000+002
$END
 $OUTPUT
ITIME =          22,PDATA = .40000000+002,IRESET =           0,DELP = .15000000+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T

-------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED     45.00+++++
 $OUTPF1
I =           3,PPRED = .51999999+002,EPRED = .43333333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .28333333+001
$END
 $NAM2
SUMP = .00000000
$END
 $OUTPUT
ITIME =          23,PDATA = .50000000+002,IRESET =           0,DELP = .45000000+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
-------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED     63.00+++++
 $OUTPF1
I =           4,PPRED = .57399999+002,EPRED = .47833333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .30833333+001
$END
 $NAM2
SUMP = .00000000
$END
 $OUTPUT
ITIME =          24,PDATA = .67000000+002,IRESET =           0,DELP = .63000000+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
-------------------------------------------------------------------------------------

 $OUTPF1
I =           0,PPRED = .57399999+002,EPRED = .47833333+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .50333333+001
$END
 $OUTPUT
ITIME =          25,PDATA = .80000000+002,IRESET =           1,DELP = .00000000     ,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
-------------------------------------------------------------------------------------

    +++++ POWER TO BE RESTORED     12.50+++++
 $OUTPF1
I =           1,PPRED = .68000000+002,EPRED = .50000000+001,EMAX = .62500000+001,EMIN = .58333333+001,ENCAL = .10000000+001
$END
 $NAM2
SUMP = .00000000
$END
 $OUTPUT
ITIME =          26,PDATA = .40000000+002,IRESET =           0,DELP = .12500000+002,FIXINT = T
$END
  1   2   3   4   5   6   7   8   9  10  11  12
  T   T   T   T   T   T   T   T   T   T   T   T
```

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10. SUPPLEMENTARY NOTES

[ ] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Demand limiting control is one of popular control strategies for electrical energy management in Energy Management and Control Systems (EMCS) in commercial/office buildings. The purpose of demand limiting is to maintain the peak demand level below a predetermined limit by shedding nonessential loads in a building during the peak demand period. In this present report, description of fixed interval metering and sliding window metering for electrical demands are included. Demand limiting calculation procedures discussed are the ideal rate, the predictive, and the instantaneous rate methods. Demand limiting algorithms, which were developed based on available information, are presented. Computer program listings of demand limiting control algorithms in Fortran 77 and an open-loop computer simulation result are included in the appendices.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

electrical demand; electrical energy management; electric power; energy management and control systems; fixed interval metering; ideal rate method; instantaneous rate method; load control; predictive method; sliding window metering.

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