A MICROPROCESSOR BASED RESIDENTIAL ENERGY CONSUMPTION MONITOR

A THESIS SUBMITTED TO THE
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by
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A MICROPROCESSOR BASED
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ABSTRACT

The design of a novel appliance load monitoring system is described. The system comprises a data collection unit, located at the residential distribution transformer, and distributed load monitoring transponders, located in the customer's home. Communication between the data collection unit and the transponders is over the residential and utility wiring using a frequency shift powerline carrier modem.

The remote transponders are capable of metering real and reactive power on a demand and peak basis. A isolated pulse accumulator input is provided for interface to pulse initiation meters. Load control under the command of the central data collection unit is provided. The thesis describes central unit design generally and the transponder hardware and software in detail.

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1 INTRODUCTION

1.1 UTILITY PROBLEM

Canadian utilities have recognized the need to take a closer look at residential distribution systems in the face of rising costs, and rapidly accelerating technology. Concepts such as residential load control, automatic meter reading, and transformer load management are more feasible as technology develops and costs decrease. Currently, the data used in investigation of these techniques is obtained from billing data. Unfortunately, billing data is not sufficiently detailed for utilities using new load diversity modelling packages or investigating residential load control, both of which require consumption data on individual appliance loads. This document describes the system design of a data acquisition system capable of gathering appliance load data and of testing the effectiveness of various forms of load control.

To be applicable to load control, automated meter reading, and transformer load management, the data must be collected at the lowest possible level, that is, at the individual household or appliance level. Demand data for individual appliances, and households may be combined statistically[1] to model residences, local and sub-station transmission feeders. Appliance demand data is vital in determining the impact of load management, and useful in generating accurate load model for distribution system design. The data required is the peak and average consumption, both real and reactive, over a demand interval for groups of appliances and houses. The demand interval and peak averaging interval must be user selectable. Provision for a pulse initiation input for determination of house consumption or for automatic meter reading is desirable. Typically ten points per house would be monitored in a load survey covering up to twenty dwellings, a total of 200 monitoring points.

This docuement describes a system capable of meeting the above requirements in an urban, residential environment. The overall system design presented consists of three major components, the remote transponders equipped with transducer boards, the communications link, and the central controller. The design of the transponder and the communications link is considered in detail here. The design of the transducer boards and the central unit is covered in a general way.

1.2 THESIS STRUCTURE

The thesis contains five chapters. The preceding section has introduced the problem and the remaining sections of Chapter 1 will explore the problem further and propose a solution. Chapter 2 will discuss the communications system design. Chapters 3 and 4 present the transponder hardware and software implementation, respectively. Conclusions and recommendations are listed in Chapter 5. Technical details have been included in the appendices where necessary.

1.3 METERING AND LOAD SURVEY EQUIPMENT

The state of the art in load survey acquisition systems is primitive considering the power of modern electronic technology. Present systems mostly rely on manual collection of data from modified watthour meters, or from demand recorders. Although both make limited use of integrated circuit technology, they do not provide adequate communications facilities for a flexible acquisition system network. Two systems which may be used in load survey applications or for demand recording are discussed in this section.

Sangamo Electric markets the ETR demand recorder for billing and load survey work. The unit records pulses generated by a pulse initiation meter, each of which represent a known quantity of energy. A three track cassette tape recorder stores two data channels and one time track. The time and an identification code are written to the time track every five minutes. Data for approximately 35 days may be stored before the cassette must be replaced. Since the data pulses are not recorded in a standard format, a special translation device is used to read the tapes and provide an output for an analysis computer. Each recorder costs $1,000, and a translator $30,000.

The recorder has a number of advantages. It provides a logging capability over a reasonably long period. It can operate in fairly harsh environments and has built in diagnostics. Unfortunately, it does not have any communications capability which severely limits its flexibility for remote data acquisition or load control. Extra equipment, in the form of pulse initiation meters, is also required for installation at a collection point. These two factors add to an already high initial cost of $1,000 per recorder and $30,000 for a translation system. A system to monitor 200 points would cost $150,000. A more sophisticated approach is taken by another manufacturer.

The EMAX Incorporated Remote Solid State Demand Recorder (RSSDR) is a more flexible system. Four pulse inputs are accumulated over a user selectable demand interval, and then recorded in solid-state EEPROM cartridges. The absence of moving parts increases the recorder's reliability and its ability to erase the media electrically reduces the number of cartridges needed. Up to 34 days of data may be recorded on a single non-volatile cartridge depending on the demand interval set. An optional telephone modem allows remote access for data collection, load control, and status checking. This link can therefore eliminate, or at least substantially reduce, the number of visits to a site.

Once again the major drawback of the RSSDR is its cost. To monitor four channels, including pulse initiation meters, the RSSDR with integral modem costs about $2,600. Additional transducers for temperature and reactive power are also necessary. Add to this the cost of a cartridge reader interface, $8,000, and phone line installation and the initial cost for a 200 sensor installation becomes approximately $150,000. The phone line rental alone adds a monthly operating expense of about $500 to the initial cost.

These two systems share a number of disadvantages as they are both primarily aimed at billing applications. They are physically too large to easily monitor a number of appliances spread throughout a customer's premises, and are difficult to install. An external transducer with a pulse output which is required for measurement of any quantity, is not practical for all installations. Neither system is capable of measuring peak power during an interval and the use of non-standard recording media requires the purchase of a customized translation system. Considering the capacity of modern mass storage equipment the use of a separate recorder for only a few points is not efficient. Similarly, one phone line per recorder adds unnecessarily to the cost of the system. A smarter system with improved communication capacity, and a denser, transportable storage media would reduce these costs significantly.

1.4 ALTERNATIVE DATA ACQUISITION METHODS

A number of alternatives are investigated in this section. In choosing a preferred method knowledge of the distribution system topology is essential.

1.4.1 Residential Power Distribution

Figure 1.1 shows the components of the distribution system. The high voltage feeder is one phase of the substation three-phase transformer. The voltage and capacity of the HV feeder varies in different locations according to the estimated load. The local distribution transformer steps down the feeder voltage to 240 volts, center tapped, providing two 120 V sources and one 240 V source for the customer. For safety the center tap is grounded at the pole or transformer kiosk, and at the house. One of these transformers may supply energy, via the secondary feeder, to as many as 30 dwellings.

The feeder connection to the house wiring begins at the service panel which serves as a distribution point for 120 V and 240 V circuits. A sixty or one hundred ampere service is usual for residential customers. The feeder enters through a main switch and connects to the distribution panel where separate circuits are connected to the feeder through fuses or circuit breakers. The breaker disconnects the "hot" lead when an over current condition occurs leaving the neutral and ground connected to the load. The "neutral" lead is the grounded center-tap of the local distribution transformer and the "ground" lead is a locally established earth ground. The neutral is connected to ground inside the service panel. For 240 V circuits two parallel breakers are used to fully disconnect the load from the line since both "hot" leads supply these loads.

Loads are either wired directly into the service panel on their own breaker, or connected by outlets to a parallel circuit on a common breaker. The first type usually includes heavier appliances such as stoves, dryers, water heaters, or electric heaters which require a 240 V circuit; however, some 120 V loads also require their own circuit. Different connector types are used for 240 V, 120 V (15 A), and 120 V (30 A) circuits.

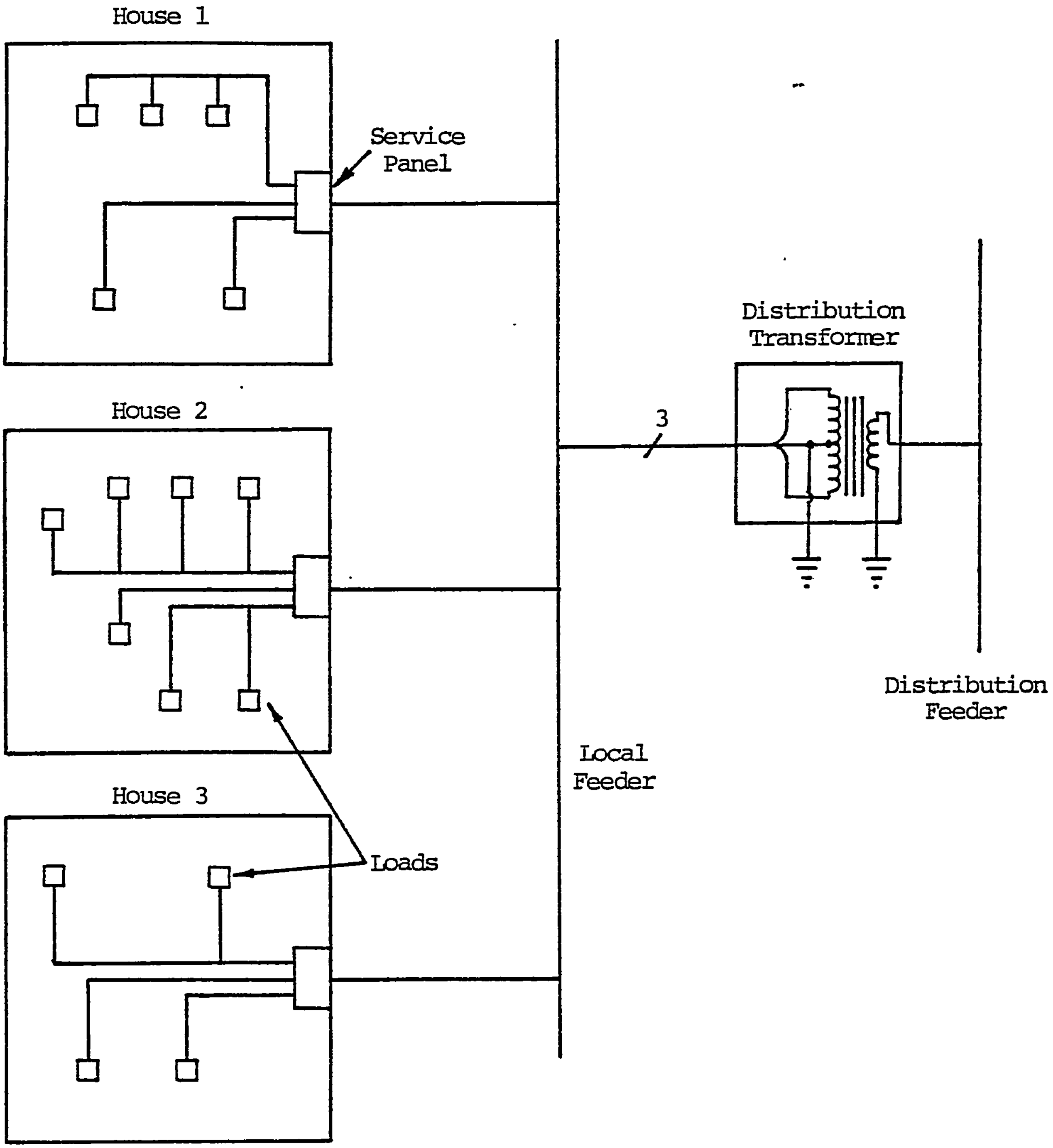


Figure 1.1 Residential Power Distribution

1.4.2 Measurement System Philosophy

There are two points in Figure 1.1 where appliance monitoring may occur. One approach, similar to the EMAX system, would have an acquisition system for each customer wired into each residence breaker panel to monitor circuits. Another method would monitor appliance consumption at the appliance, and log the data at a central location. Both of these methods were considered.

The first approach requires the measurement of circuit loads as they exit the main service panel. Since the points to be monitored are adjacent a number of sensors can share the same converter, communications, and control sections. Load management possibilities remain since each sensor retains its individuality. Installation of this system requires knowledge of the household circuits, since the sensor is not at the appliance but at the breaker box. Loads without a dedicated circuit would be difficult to monitor individually. The switched telephone network, would be the most likely choice for a communications channel. A mass storage medium could be provided in the house to collect data for about a month.

The second method, in which the consumption is measured at each appliance, is the most attractive way to approach the monitoring problem as it yields precise, unconfused information about each appliance. Since each sensor can be separately addressed, a number of commands can be sent to the sensor causing it to perform remote control functions as well as its primary data acquisition function. These sensors can be portable and require minimal installation (plug in), a marked advantage over either of the commercial systems discussed. For hard-wired appliances a sensor can be inserted in the line at the appliance with little or no disturbance of the house wiring. Such a system would minimize installation time and thus intrusion into the home owner's privacy; however, it may be more expensive due to duplication of functions at each monitoring point.

Modern microprocessor technology has decreased the cost of the transducer and control components, and allows design of smart sensors for a low cost. If coupled to a flexible, pervasive communications system some intelligence previously required at the sensor level may be centralized in a main unit which can incorporate the mass data storage and system control interface for the entire system resulting in considerable cost reductions. This approach also has the benefit of maintaining the individuality of each monitoring point in a residence allowing monitoring of any individual load. For these reasons the individual monitoring approach has been selected. An overview of the system designed to implement this approach follows.

1.5 GENERAL SYSTEM OVERVIEW

Figure 1.2 shows a block diagram of the proposed system. A multi-drop network structure with a number of transponders, controlled by one central unit, via a single communications channel is shown. The central unit provides the necessary control for the communications channel and the transponders, while data acquisition takes place at the remote transponders. The functions, and organization of each block are described in the following sections.

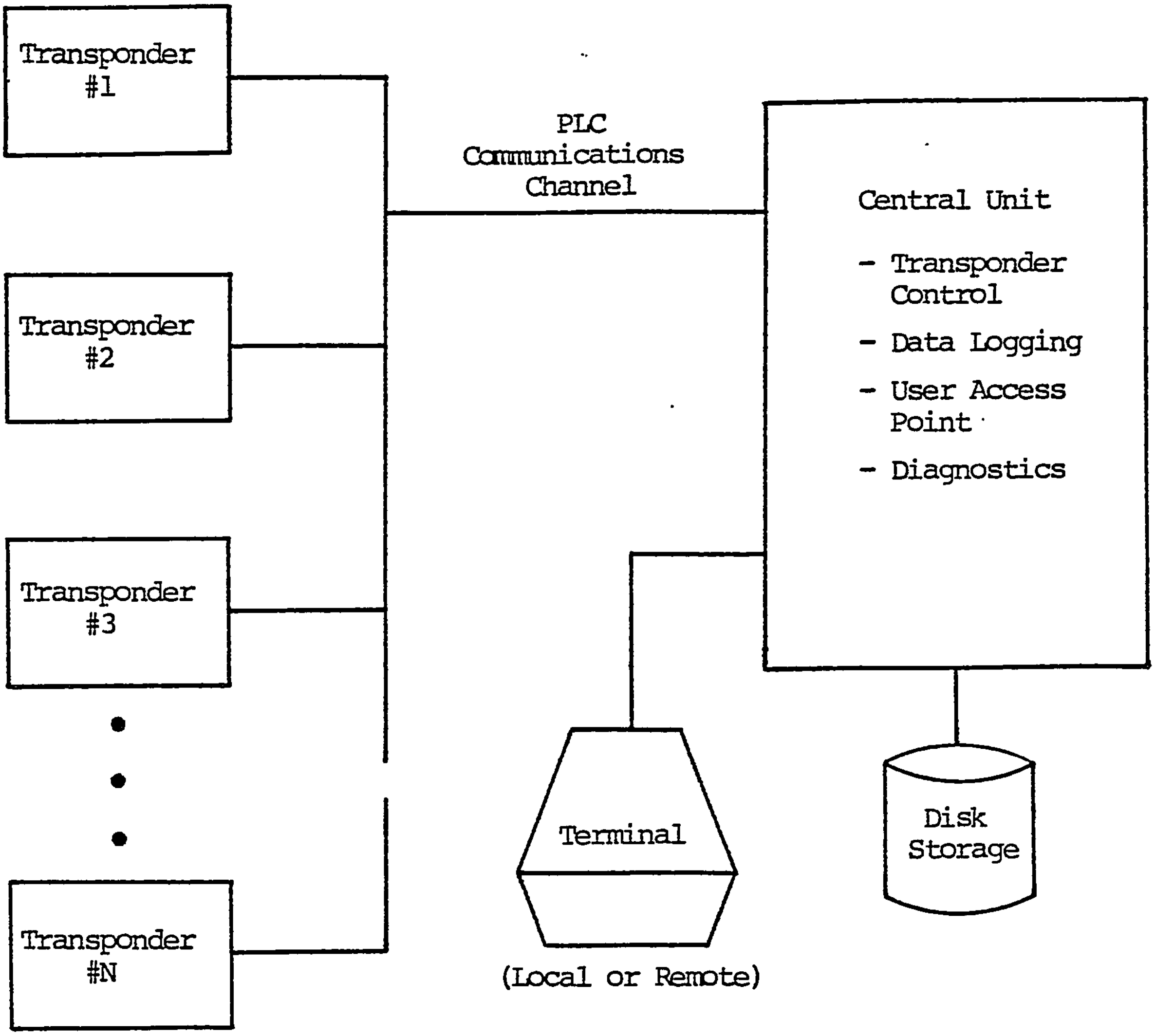


Figure 1.2 Proposed System Configuration

1.5.1 Central Unit

The Central Unit oversees all activities of the acquisition system. Its main tasks are master control of the communications channel, synchronization of data acquisition, and interface with the user. Figure 1.3 shows a block diagram of the central unit system.

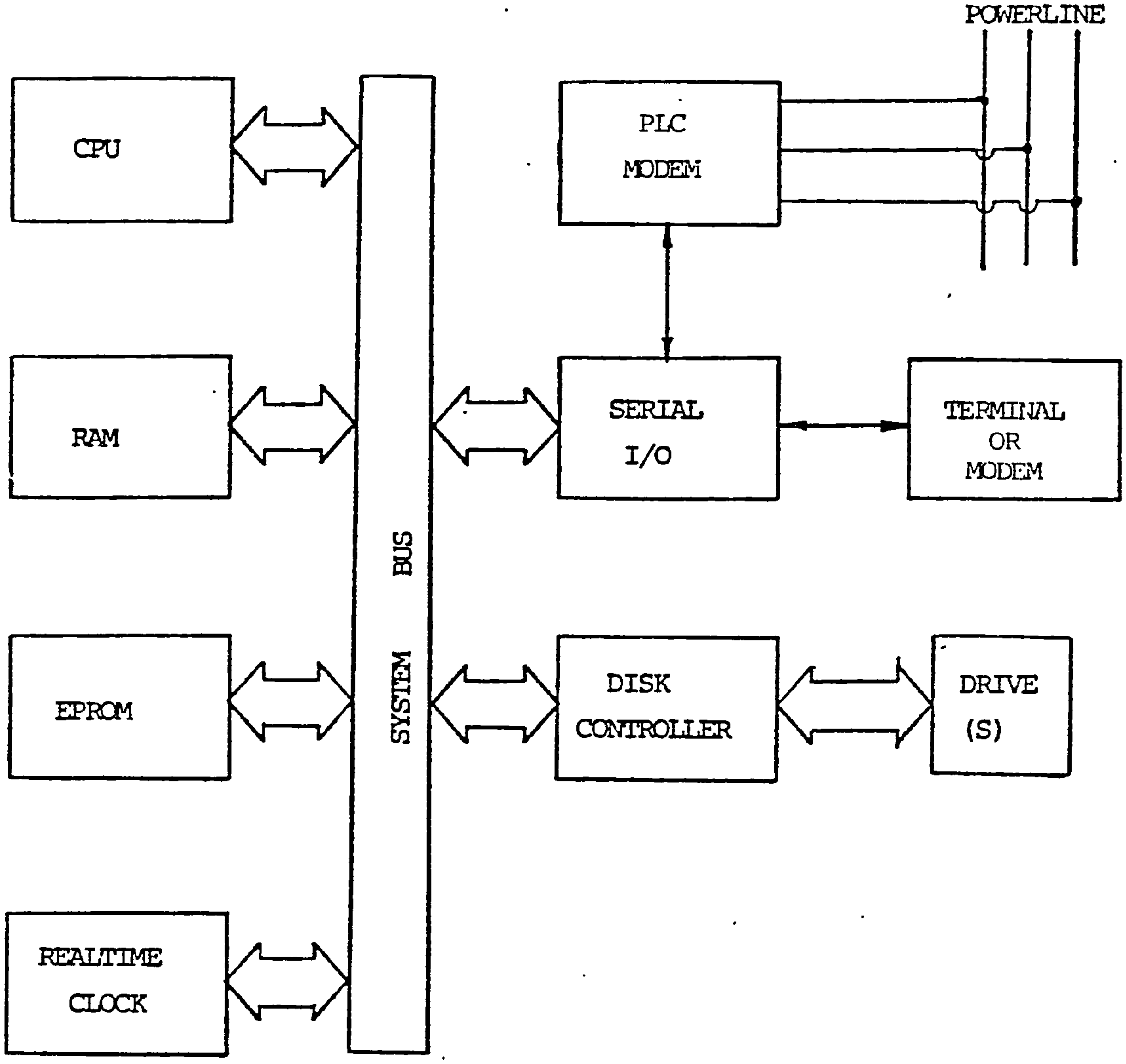


Figure 1.3 Central Unit Design

A small, inexpensive, microprocessor based computer is used to implement the Central Unit. The CPU configuration includes extensive communications and mass storage facilities, and the use of removable mass storage media eases the problem of transferring data to an analysis facility. Power is supplied to the unit by an A.C. to D.C. switching power supply, and battery back-up can be provided for continuous operation if required. The two serial communications ports provide the means to gather data, and enable local or remote control of the Central Unit.

The modems attached to the serial ports perform different functions. The powerline carrier modem links the central unit to the transponders over the residential powerline, while the other serial port is used for control either on site, by use of a portable terminal, or remotely, via a telephone modem. Normally the Central Unit operates in a stand-alone mode.

The detailed design for the central unit hardware and software has not been considered in this thesis, rather the work stresses the design of the remote transponders and the communications system.

1.5.2 Remote Transponders

The data acquisition task is performed at the appliance to be monitored by the remote transponders, which monitor various quantities, and process and temporarily store data on command from the Central Unit. Load control is also available at the remote transponders (Figure 1.4).

The control centre of the transponder resides in a single chip microprocessor. Volatile, and non-volatile memory allows this circuit to manipulate data, and store programs, and input and output capabilities are also provided. A number of peripheral devices are accessed by the computer including: address switches, a PLC modem, the load control relay, and an analog to digital converter.

Communication with the central unit is established via the powerline carrier modem which uses the 120/240 residential powerlines as a communications medium. On reception of the appropriate command sequence the transponder compares a received address with the address set on the address switches. If they match, the command will be executed.

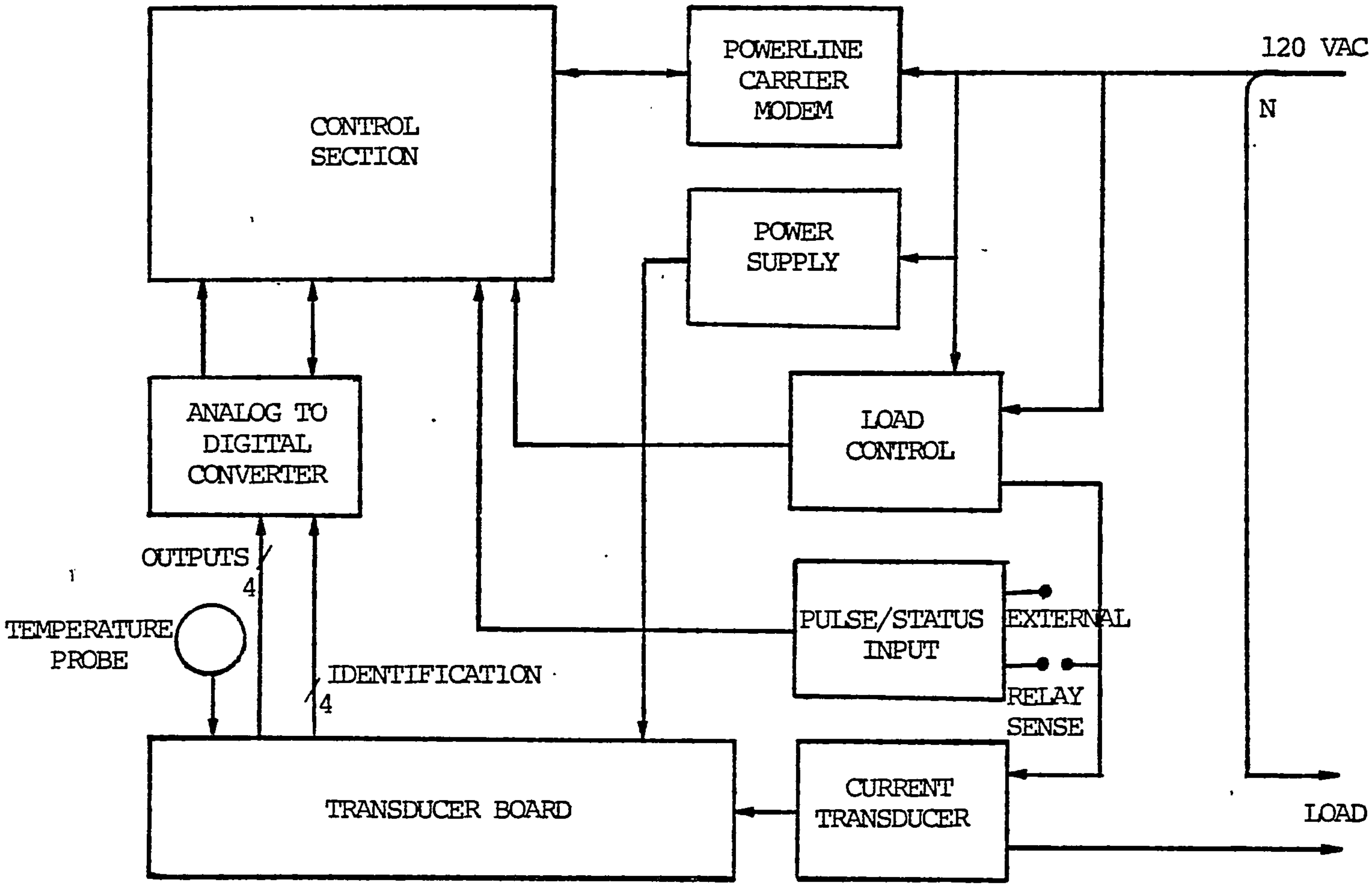


Figure 1.4 Remote Transponder Configuration

The physical quantities to be measured are converted to voltages acceptable to the A/D converter by the transducers. Each transducer identifies itself to the microcomputer for transponder configuration verification. The transducers are independent of the main transponder circuitry which allows stand-alone operation of the transducers or incorporation of custom transducers for other applications. Only the interface to the transducers has been considered here.

This completes the general overview of the system's design. A detailed consideration of the communications system follows in Chapter 2.

2 COMMUNICATIONS SYSTEM DESIGN

Communications is perhaps the most important section of any distributed data acquisition scheme, as it carries all data to be recovered and the control messages necessary to affect this recovery. The system must be capable of accessing all transponders from a central location, and installation of the system should be simple and inexpensive. For these reasons a decision was made to design and test a low speed, residential, digital powerline carrier system.

As distribution systems are not designed for use as a communications medium, little work has been done to characterize the noise, attenuation, and input impedance characteristics. Most of the work that has been done is concerned with applications requiring communication with one or two points per house over long distances[2,3]. The channel in these cases links a distribution substation to load points through the local distribution transformers, and other distribution apparatus to provide a central control/collection point for load management or automatic metering schemes. These differ from this project which requires the monitoring, and control of many points in a few residences from a local point; however, this work has served as a guide for this design.

2.1 THE DISTRIBUTION SYSTEM AS A COMMUNICATIONS MEDIUM

Papers have been published on the use of PLC communications for load management or automatic meter reading but few report quantitatively any characteristics of the medium. However, I. A. Whyte of Westinghouse[2] and G. Bowling of Rockwell[3] discuss noise, and attenuation characteristics at high frequency on the residential distribution system.

2.1.1 Noise on the Powerline

Whyte's paper suggests that noise varies as 1/f or 1/f**2 identifying transformer losses as the primary source. The nature of the interference encountered is burst or impulse, and seemed to be due primarily to the load on the secondary of the local distribution transformer. This observation may be explained by the attenuation characteristics of power transformers at high frequencies, which is discussed in the next section. Periods of high noise level were found to correspond to high load levels. Whyte quotes levels for noise at various frequencies with typical values between 200 and 400 uV per kilohertz at frequencies about 100 kHz increasing at lower frequencies to 20 mV per kilohertz at 20 kHz. Variation in these results is greater at lower frequencies, and is proportional to secondary load. The method used to obtain these numbers is not discussed but it is probable that they are averages. Actual impulse or burst noise levels would likely be higher.

The choice of a higher frequency carrier is preferrable due to the lower noise and lower power requirements at higher frequencies. Since signal attenuation increases with frequency, a practical upper limit is placed on the carrier frequency.

2.1.2 Attenuation Characteristics

Attenuation of signals on a powerline is due to both the line and the distribution apparatus. In general attenuation increases with frequency; however, the increase is not uniform, but is broken by regions of high attenuation called dead-bands. These appear as dips in Whyte's transmission curves shown in Figure 2.1. Considerable variation is reported between different distribution configurations, even in one type of installation.

Whyte calculates that attenuation levels in the 10 kHz to 10 MHz band may vary from 0.1 to 10 dB/mi for overhead lines with the variance due to the wide frequency range, differences in line construction, and variable weather conditions. For underground lines the same range of attenuations are quoted for a lower frequency band, from 1 kHz to 50 kHz. Overhead and underground attenuation characteristics would be expected to differ due to the closer proximity of conductors in underground installations.

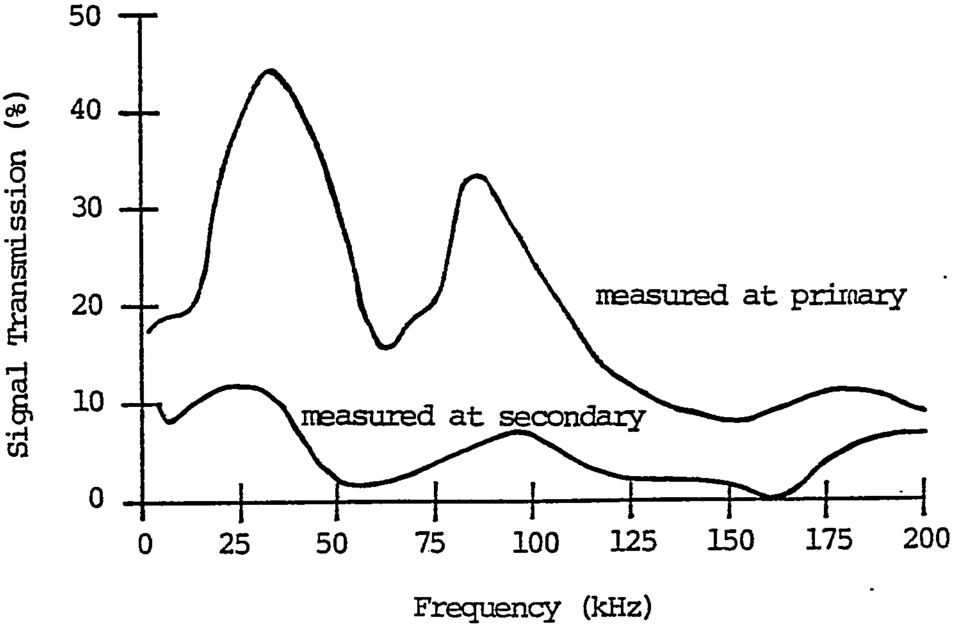


Figure 2.1 Powerline Transmission Charateristics[9]

The other main component contributing to attenuation is the local power distribution transformer. Difficulty is encountered when trying to specify transformer high-frequency characteristics due to the multiplicity of manufacturers and the number of units in service, but some qualitative results have been reported[2]. The secondary input impedance, is generally capacitive, with an amplitude of 5 to several hundred ohms, and is dependent on frequency and load below 50 kHz but is approximately independent of load over 50 kHz. Feedthrough attenuation of a distribution transformer is typically 40 dB primary to secondary and 30 dB secondary to primary, probably the principal reason noise is observed to be dependent mostly on secondary load. Noise generated by a load on another distribution secondary will therefore be attenuated by 70 dB propagating through the two transformers. The attenuation characteristics of the transformer also effects the carrier signal of the communications channel, and effectively isolates two acquisition systems in close physical proximity.

Due to the noise and attenuation properties of the lines and distribution apparatus Whyte specifies three primary bands useful in PLC communications: 20-30 kHz, 50-100 kHz, and 200-300 kHz. Referring to Figure 2.1, it can be seen that these bands correspond to intervals of low attenuation, and are located in the higher frequency range where noise is less severe. The Rockwell system[3] uses a lower frequency carrier, 12 kHz. The Westinghouse design utilizes the 50-100 kHz region. The choice of the two lower bands was no doubt dictated by the need for long distance communication through distribution equipment. Rockwell was able to use a lower band due to their development of a special transmitter and receiver which placed components of the signal between harmonics of 60 Hz (noise components). The middle band, chosen by Westinghouse, has a lower noise level while maintaining relatively low attenuation suitable for their 2kHz deviation, FSK modulation scheme. From these two choices it is apparent that the choice of band depends, in part, on the type of modulation employed and its susceptibility to noise and attenuation. If the modulation scheme is more resistant to noise, lower bands may be used to take advantage of lower attenuation, otherwise a higher band must be chosen. The choice of modulation based on these and other factors is discussed in the next section.

2.2 SELECTION OF MODULATION METHOD

Points raised in the preceding sections effect the choice of modulation method. The modulation scheme must be simple to implement to keep the cost and size of the transponder unit to a minimum. The chosen method should exhibit tolerance to changes in amplitude due to load switching, and changes in attenuation. Finally, all significant frequency components produced by the modulation should be well above the 60 Hz power frequency.

There are many types of modulation used for digital data transmission which are classified as one of three types: amplitude modulation, frequency modulation, and phase modulation in which the carrier signal is varied according to a digital input of one or more bits of data. If more than one bit of data is represented by a particular signal the method is known as multi-level. Only two level or binary transmission was considered as it is the most common and easiest to implement. When a binary system is used the above modulation alternatives are called Amplitude shift keying (ASK), Frequency shift keying (FSK), and Phase shift keying (PSK). These methods are compared in Table 2.1[4] on the basis of complexity, bandwidth efficiency, signal to noise performance, and tolerance to various forms of transmission distortion.

Although they have superior signal to noise performance, methods four to seven in the table were eliminated due to their complexity, and/or their requirement for synchronous communications. Binary Polar Baseband, method one, is not suitable for PLC since it may have DC frequency components, and requires a wide bandwidth. Methods two and three, on the other hand meet the criteria presented at the start of this section. Method three, Binary FM or FSK, was chosen above method two due to its superior noise performance, and its tolerance to amplitude changes. FSK is widely used in the telephone industry for low speed data communications, and power utility powerline carrier installations.

				SNR Performance		Tolerance To				
System	Complexity	Bits/Cycle of Baud	Variable Speed Asynchronous Operation	Equal Bit Rate	Equal BW	Parabolic Delay Distortion	Linear Delay Distortion	Amplitude Change	Frequency Offset	Phase Jumps
1. Binary polar baseband	1	2	Yes	1	3	2	—	1	—	—
2. Binary on-off AM	2	1	Yes	5	5	2	1	3	1	1
3. Binary FM	3	1	Yes	4	4	1	2	1	3	2
4. Binary PM differentially coherent	4	1	No	2	2	3	3	2	3	2
5. Binary PM coherent	5	1	Yes	1	1	2	1	1	1	4
6. VSB AM suppressed carrier	6	2	Yes	1	3	2	5	1	2	4
7. Quaternary PM differentially coherent	7	2	No	3	5	4	4	2	4	3

1 = highly tolerant
2 =
3 =
4 =
5 = intolerant

Table 2.1 Characteristics of Modulation Methods

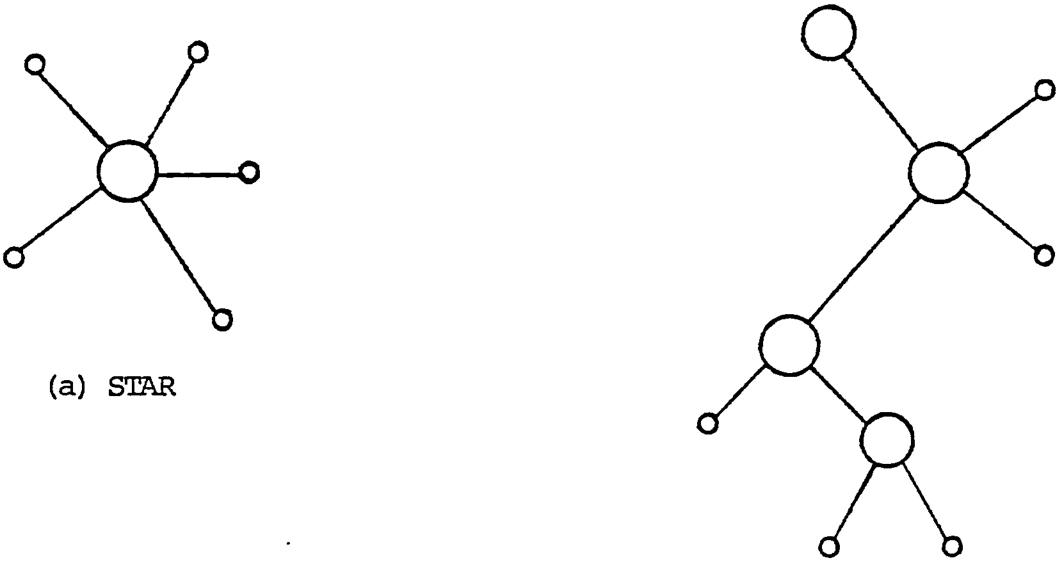
2.3 NETWORK DESIGN

Other considerations in the design of a communication system are the type of network structure and the network control protocol to be used. The choice of a network structure or topology is affected by a number of factors such as the physical medium, the complexity of control possible, and the reliability of the communications channel. The network control protocol is also dependent on these factors.

2.3.1 Network Topology

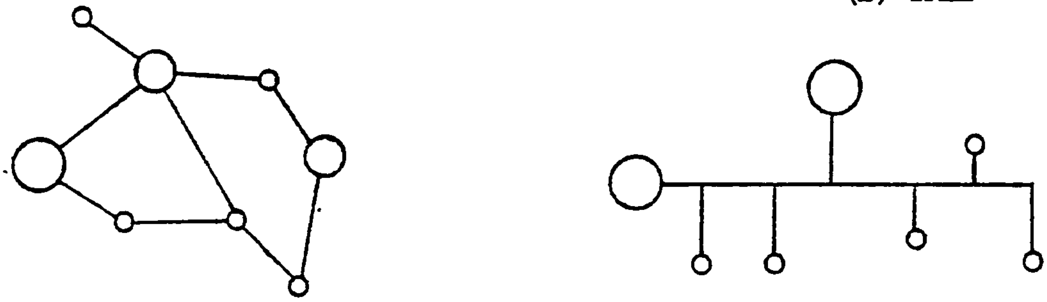
Many types of network topologies are possible, limited only by cost and capacity. Some of the more common types are shown in Figure 2.2, where the lines represent communications links, and the circles at line junctions represent nodes.

As is evident from Figure 2.2c, all networks may consist of trees, and loops. The network proposed for this application has no loops since only a single communications channel is used, and all information is passed back to the central unit. Figure 2.2d shows the configuration of the proposed physical system, known as a multidrop topology, a type of tree network. Since information passes directly to the central unit, and is not usually interpreted by the other units, the system may also be thought of as a "star" network (Figure 2.2a). The nodes at the end of the drops in the multidrop structure of Figure 2.2d represent the transponders, while the main node is the central unit. One central unit controls up to 224 remote transponders. Information, in the form of commands from the central unit, and responses from the transponders, flows directly to the central unit and only one transponder interacts with the central unit at a time in what is known as a polled network. The central unit, on the other hand, may access all the transponders simultaneously taking advantage of the multidrop (parallel) structure of the network. To implement these features a suitable protocol must be developed.



(a) STAR

(b) TREE



(c) TYPICAL

(d)

Figure 2.2 Network Topologies