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REMOTE METERING OF ELECTRIC POWER DELIVERED TO A CONSUMER

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TABLE OF CONTENTS

LIST OF FIGURES

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REMOTE METERING OF ELECTRIC POWER DELIVERED TO A CONSUMER

PART I

DISCUSSION OF THE OVERALL PROBLEM

1.1. Introduction

The purpose of this report is to assemble pertinent information on the subject of remote metering of electric energy delivered to a consumer, and to consider the feasibility of a research program pointed toward the development of a suitable system for this purpose.

Recent trends in industrial processing and control place increasing emphasis on the transmission of information concerning certain variables such as temperature, pressure, voltage, and rates of flow of various quantities from the point of direct measurement to some remote location. This type of transmission of information has been given the general name of telemetering.

The increasing complexity of modern science and industry and the need for complete and accurate information has made telemetering an important part, not only of the present-day factory or electrical generation and distribution system, but also of many other complex integrated systems. The rapidly growing technology of guided missiles, for example, makes extensive use of telemetering, employing air-to-ground radio links. The interest generated as a result of the more recent applications has contributed to rapid progress in both techniques and equipment.

Because of this progress, it is perhaps wise at this time to reexamine the problem of reading the electric watt-hour meter of each individual consumer from a remote centralized location. This is a telemetering problem that has intrigued inventors and engineers since the early days of the electrical generation and distribution of energy. Potentially, the information obtained by telemetering could be used by an automatic computing machine for determining customer billing.

1.2. Survey of Previous Work on Remote Metering

As early as 1903 a system had been designed for the remote reading of a watt-hour meter.[1] The device incorporated a series of counting dials actuated by a meter shaft, each winding up a small spring as it was displaced from zero. An electrical impulse sent from a central station released the wheels in succession, and as it returned to zero each wheel actuated contacts to transmit pulses representing its displacement from zero. These pulses, received at a central point, could be interpreted to represent the meter reading.

A system patented in 1927 made use of coded impulses transmitted by a scanning device located at the meter register.[2] These coded impulses were received audibly over a telephone circuit, and manually decoded.

A scheme developed about 1931 made use of resonant reeds located at the meter register.[3] Associated with each decade dial of the meter was a set of ten reeds, each resonant at a different frequency. An electromagnet energized by a variable-frequency generator at a remote location tended to set the reeds in motion. Located on the meter spindle was a set of helically arranged segments. As the different reeds vibrated, contact was eventually made with a particular segment determined by the dial setting, short-circuiting the electromagnet. This caused a change in the signal to which an observer was listening, thus indicating the dial position.

About 1934, a British affiliate of the Sangamo Electric Company devised a system which involved equipping each meter dial with a spiral-shaped cam.[4] Motor-driven wipers traveling at a uniform speed could be made to traverse the cams, producing a contact with a duration time dependent on the dial position. Other fixed cams produced a code identifying the meter. This code, received at a central location, was automatically decoded and recorded. The communication link was a wire line installed specially for this purpose.

Probably the most elaborate system yet devised is described in a set of patents issued to Ward Leathers from about 1941 to 1943.[5] The patents disclose a considerable number of modifications, but make use generally of a rheostatic element located at the meter in which resistance units corresponding to the dial positions form parts of the rheostat, so that each significant dial position is represented by a definite resistance value. This resistance is measured automatically from a remote location and the corresponding dial readings are recorded automatically. Apparently the International Business

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[1] U.S. Patent No. 784,713 granted to C. H. Thordarson.

[2] U.S. Patent No. 1,621,939 granted to H. C. Lowe.

[3] U.S. Patents Nos. 1,849,870 and 1,889,597 granted to A. S. Fitzgerald, assigned to the General Electric Co.

[4] British specification No. 15569/34.

[5] See, e.g., U.S. Patents Nos. 2,319,412, 2,304,698, and 2,283,070.

Machines Corporation, by whom Leathers was employed, spent considerable time and effort investigating remote metering during this period.

As indicated above, there has been much interest in the problem of remote metering of electricity delivered to the ultimate consumer. However, none of the above methods has been able to compete successfully on an economic basis with the "manual" method of reading meters on a large scale.

1.3. Gross Consideration of System Requirements

In order to obtain a successful solution to the remote metering problem, technical and economic considerations must be satisfied. These two considerations are necessarily interdependent; therefore a very careful analysis is indicated, noting that recent technical progress may allow and facilitate an economic solution to the problem.

It is apparent from review of the earlier work noted above that little serious attention was given to the manner in which the desired meter information should be communicated to the central point. This factor alone could prove to be the most crucial element in a general solution to the problem.

In the present approach to the problem it is assumed that the meters now used to measure electricity will, with minor modifications, still be used as measuring devices. The remote metering system then transfers the operation of meter reading from the meter to a receiver at a remote location and there makes use of the reading for automatic billing. Although it is possible that some other methods of measurement might be used in a remote metering scheme, the present investigation has not indicated one.

It seems reasonable to assume that the transfer of information over the distances normally involved in a remote metering scheme can be done most readily by electrical methods of communication. Such an assumption is made in the following analysis.

For a functional analysis, a remote metering system may be thought of as having three general components. These will be referred to as the end organ, the information-carrying link, and the substation unit. The substation unit accepts the information from the information-carrying link in coded form and converts it to a form suitable for whatever use is desired, such as automatic billing of consumers.

The costs of a remote metering system may logically be divided into initial costs and maintenance costs. Any system analysis must, however, consider these two together, since they are not in general independent. Both the initial and operating costs of the meter end organ must be minimized.

Of necessity, then, the end organ must be as simple as is practical. The substation units, on the other hand, can well be more elaborate since there will be fewer of them. The communication link must have a small cost per customer and thus must almost of necessity be some existing installation.

Because the information-carrying link represents the most challenging aspect of the overall problem, it will be considered first.

1.31. Information-Carrying Link. Several types of transmission channels are technically possible, such as the power distribution lines, existing telephone circuits, separately installed wire communication circuits, and radio communication channels. In Table 1.1 these various possibilities are listed, together with some merits and shortcomings of each.

Of the possible channels, the combination of economic, administrative, and technical considerations would seem to favor either the existing power distribution lines, or separately installed lines, or a combination of these, as will be discussed in a later section of this report.

1.311. Power distribution lines: For the past twenty years or so, considerable use has been made of electric high-voltage transmission lines as channels for transmitting direct communication, metering, and control information by means of carrier-frequency methods using frequencies usually between 30 and 450 kc. There have also been several applications of the distribution system (voltages between about 2400 and 7200) as a carrier channel, particularly by radio amateurs operating during World War II,[6] and by civilian defense communication networks. Various branches of the Bell Telephone System have also used electric distribution circuits in setting up carrier systems designed mostly to serve rural or remotely located customers.[7] Although these have apparently been successful, much of the published information dealing with the functioning of the information link is of a qualitative nature. All of it indicates that many variables effect the transmission of radio-frequency energy over distribution circuits.

However, enough information is available (see Appendix II) to indicate that the region in the spectrum above 100 kc might be used for transmission of remote metering information.

From available information about the electrical noise spectrum to be expected and the transmission characteristics needed for a possible system, a brief study was made (see Appendix I) which indicated that, with power from the end organ, of a reasonable value, transmission of information over the

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[6] See, for example, Wrightman, P.E., and Lyar, H. H., "Wired Wireless in Civilian Defense", QST August 1943, p. 14.

[7] Barstow, J. M., et al., "A Carrier Telephone System for Rural Service", Paper 47-80, AIEE Trans. 66, p. 501 (1947).

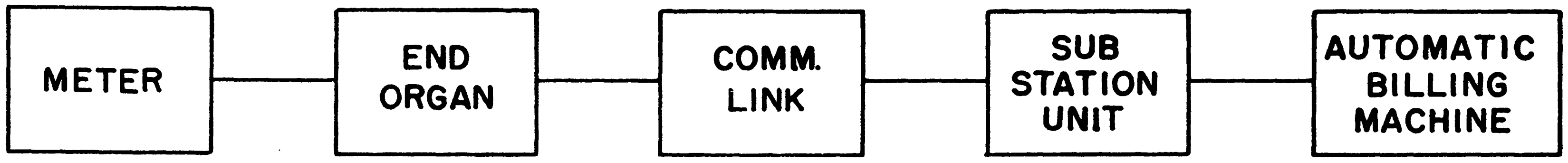

FIG. 1.1

ELEMENTARY BLOCK DIAGRAM
OF A REMOTE METERING SYSTEM

TABLE 1.1.

POSSIBLE COMMUNICATION CHANNELS FOR REMOTE METERING SYSTEM

Communication Channel	Merits	Shortcomings
Power Distribution Lines	Owned and controlled by utility (except in case gas alone is supplied customer by utility). No additional installation of lines necessary. Can be adapted for use at all times without affecting power distribution.	Line termination impedance varies considerably with the 60-cycle loading of the transformers; thus some provision for producing desired terminal impedances for the signal frequency would be needed. The multiplicity of paths must be considered in making this provision. High noise voltage may be present, which means that large signal voltage may be necessary to override the noise. Probably the substation represents the largest unit of centralization.
Existing Telephone Circuits	Fairly constant line and termination impedances. Low background-noise level on channel. Centralization possibilities large. Probably a whole city could be handled from one location.	Telephone company would charge for use of lines. Care would be necessary to prevent interference between ordinary uses of telephone lines and metering. Electrical building codes might have to be revised to permit connection of telephone circuit to metering circuit.

TABLE I.I. (Cont'd)

POSSIBLE COMMUNICATION CHANNELS FOR REMOTE METERING SYSTEM

Communication Channel	Merits	Shortcomings
Existing Telephone Circuits (cont'd)	No high voltage coupling and associated safety problems.	Some modification of existing telephone switching equipment might have to be made (e.g., a method for inhibiting ringing when contact is made with called telephone line). Switching system which will connect end organ to and disconnect it from telephone lines in response to remote order is necessary. Metering service dependent on continuity of telephone service. Not all of utility's customers have telephones. Memory device at meter is necessary, since telephone lines cannot be used continuously. In some cases meter may be rather remote from telephone circuit.
Separately Installed Wire Communication Channels	Constant termination impedance. Low background-noise level. Owned and controlled by utility. Independent of customer's utility service or telephone.	High cost of original installation. Additional cost of maintaining communication line. Electric building code might cause difficulty.
Radio Communication Channels	Owned and controlled by utility. No line wire maintenance or coupling problems. Independent of customer's electric or telephone service.	High power necessary for each transmitting unit because of spreading of radiation. Privacy inadequate (easily interfered with and might easily interfere with other services). Frequency allocation controlled by Federal Communications Commission. Cost may be excessive.

distribution circuits is probably possible if the number of end organs in any one sectional unit is not too large.

1.312. Separately installed lines: A line installed for the specific purpose of providing a metering communication link is, of course, feasible and attractive from the technical point of view. However, the expense of such an installation would undoubtedly become a major factor in consideration of the remote metering system and could well be prohibitive. Perhaps it should be considered as a possibility only if a thorough investigation of existing lines reveals that their use would be impractical.

1.313. Existing telephone lines: Consideration has been given to the use of existing telephone lines; however, the requirement of coordination with telephone companies would in itself seem to be a problem of sufficient magnitude to preclude their use, aside from any technical complications. Therefore they will not be discussed here.

1.32. End Organ. End organs may be classified, generally, as having or not having memory. Those not having memory transmit information indicating the measurement of, for example, one kilowatt-hour of energy instantaneously as it is recorded by the meter. Those having memory store information indicating the number of kilowatt-hours measured over a period of, for example, one month, for transmission at some arbitrary time. One important difference in the two systems is that for randomly occurring information the end organ with no memory requires the continuous use of a communication channel, while the end organ with memory needs the channel only during the selected interval during which its information is being determined. Since the register of the presently used watt-hour meter is a memory device, it is possible to use it as part of the memory system of the end organ.

The signal received at the centralized location from the nonmemory-type end organ must contain information as to the identity of the originating meter and, as implied by the identity signal, information regarding the consumption of energy. The memory type needs to transmit only an indication of the register dial positions which, of course, constitute the meter reading.

1.33. Substation Units. The substation unit must provide for the following general functions:

Nonmemory type

a) recording the time of reception of signal,

b) decoding of received signal to determine identity of originating meter, and

c) rejection of overlapping or otherwise objectionable signals.

Memory type

a) means for transmitting interrogating signal,

b) means for decoding received signal into meter readings, and

c) storage of information.

1.4. Evaluation of the Problem

A brief study of previous work that has been done on remote metering and a consideration of the efforts of others to utilize power lines as a communications channel, as well as engineering and technical consideration of the problem by the authors and others at the University of Michigan, have led the authors to the firm conclusion that the chief obstacle to the realization of a workable remote metering system, from the economic if not the technical standpoint, lies in the problem of making use of existing power lines as a communication link.

The substation unit does not pose apparent difficulties, and is believed to be readily feasible, both technically and economically, including automatic billing procedures.

The end-organ installation presents a somewhat more difficult problem. However, on the assumption that a communication link can be realized, there are many possible and practical solutions to the end-organ problem, particularly and perhaps essentially due to the advent of the transistor, a versatile and efficient tool. Part II of this report includes descriptions of two possible solutions to the problem, employing rather different end organs. The systems presented there are not to be considered as proposed specific solutions, but rather as illustrations to emphasize that it is not difficult to imagine possible end-organ equipment even in a rather brief consideration of the problem.

Of the two systems described, the first is an example of a memoryless system, and the second an example of a memory-type system.

General comments relative to the two types of end organ may be summarized as follows:

Memoryless

a) The end organ must recognize when a unit quantity of energy has been indicated by the meter.

b) It must transmit a coded signal indicating identity upon accomplsihment of (a).

c) Continuous use of the communication link is required (at least when power is being used).

d) The signal indicating the meter reading is not in general repeatable.

Memory

a) The end organ must recognize a coded signal transmitted from the substation unit.

b) Upon accomplishment of (a), it must transmit a signal containing information relative to the meter dial readings.

c) Use of the communication link is required only at times that may be selected at will.

d) Reading of the meter may be repeated as often as desired and at any desired interval.

Inasmuch as the memory-type system must perform the additional function of recognizing an interrogating signal, it may be presumed that more equipment would be required than in the case of the memoryless system. However, such additional equipment might be worthwhile since (1) continuous use of the communication link is not required, and (2) the meter reading may be repeated, if desired, for verification. Moreover, an interrogation system precludes the possibility of overlapping signals.

Considering the economic aspect, the memory-type equipment might be expected to be more expensive if for no other reason than the provision for additional function of interrogation. However, in view of the large numbers of equipments that presumably would be required, one is assured of realizing the very substantial economies of a mass-production program, to the point, in our opinion, of making either type of end organ economically feasible.

In connection with the communication link, however, there is a very challenging problem. Certain fundamental characteristics of the power lines pose limitations that may not be avoidable. Any realistic approach to a solution of the overall problem must stem from an acceptance and accomodation of these fundamental characteristics.

The power lines, as they exist today, are not completely suitable for the efficient transmission of remote-metering-signal power levels at convenient signalling frequencies, without adaptation, except at frequencies near the power frequency. But at frequencies near the power frequency, i.e., less than a few kilocycles, appreciable amounts of power are absorbed by various fixtures on the line and by consumer loading, while at higher frequencies the lines become electrically long, resulting in serious impedance irregularities. A prime example of the latter difficulty is the common instance of a line (or stub) of the order of 1/4 wavelength long: if open-circuited to the signal frequency at its far end, it appears as a short circuit at its input end.

Thus, in order to utilize the lines as a communication link these irregularities must be corrected for the chosen frequency. This means, in the case of the 1/4-wavelength line which appears as a short circuit, suitable modification of the far-end impedance, by the use of a capacitance or of a watched termination, or some other terminating device, so that the line presents a desired impedance at the input end, at the signal frequency. Line sections or "stubs" of other lengths present similar impedance irregularities and accordingly will require consideration.

In general, then, it must be considered that the power lines will require some modification in order to present a reasonably uniform impedance at any point, the necessary degree of uniformity being indeterminate without further investigation.

Technically, line adaptation is not at all unrealistic. Practically, it may turn out that the significant adaptations may be made at accessible locations, and may be relatively simple in nature, thereby permitting an economically feasible solution to this phase of the problem.

It should be borne in mind that the fundamental limitation that one must accept, considering all factors including type of system, signal level, degree of adaptation of lines, and choice of signaling frequency, is the ultimate signal-to-noise ratio. The most critical point in the system in this regard is at the substation unit receiver. If the signal-to-noise ratio is unfavorable at this point, no amount of amplification will improve the situation. The signal-to-noise ratio at the receiver of the end organ in the case of the memory-type system is a much less important consideration, for it is always possible, presumably, to increase the transmitted signal level at the substation unit since at this point there is only one transmitter. It may not be possible, however, to increase the end organ transmitter power, if line attenuation results in the signal-to-noise ratio at the substation unit being inadequate, because this means additional cost for each end organ.

1.5. Some Factors in Signal Frequency and Power Line Use

Consideration of the line adaptation problem must inevitably lead to a choice of signal frequency, and a decision as to how extensively the power lines may be used as a communication link. For example, is it possible to utilize the lines, literally, from the substation to the consumers meter or is it more feasible to utilize the lines up to the distribution transformer and from this point provide an independent drop line to each meter? The most practical solution is not presently evident, for in some areas the most economical method might utilize the drop line, whereas in other areas adaptation up to the meter might be indicated. Pertinent factors in a decision in this regard include:

a) number of consumers per distribution transformer;

b) line length between consumer and distribution transformer;

c) type of line to meter, whether twisted conductors or open-wire line;

d) whether or not the remote metering installation involves existing metering or a new consumer installation;

e) fundamental nature of the end organ, i.e., whether sensitive to signal voltage or perhaps signal current;

f) signalling frequency; and

g) possibility of tampering by the consumer.

Adaptation fundamentally involves the proper location of appropriate inductance and capacitance, the use of which implies consideration of signal frequency, 60-cycle voltage, and 60-cycle current level. Increasing the signal frequency is desirable in order to minimize the amount of inductance and capacitance that must be inserted. However, other factors naturally are important in a decision regarding signal frequency, perhaps the most significant being consideration of attenuation per mile of the signal along the power lines.[6]

The 60-cycle line current determines to a substantial degree the physical characteristics of any chokes (inductances) that may be used, for the chokes must not only handle the expected line current without appreciable loss, but must also handle anticipated short-circuit currents.

Condensers, on the other hand, must of course withstand the normal line voltage and, in addition, excessive surges due to transients and atmospheric storms, except as limited by lightning arrestors or the equivalent.

These considerations rather definitely indicate that chokes can reasonably be used only in relatively low-current lines.

The foregoing serves to illustrate certain basic problems and also serves to indicate that a natural direction of desirable investigation and research is consideration of the use of power lines as a communication link. Study of lines in this regard both in the laboratory and in the field would permit decisions and recommendations regarding probable extent and manner of line utilization, optimum signal frequency, and other related problems.

It is encouraging to note from the references that line adaptations have been accomplished in several isolated instances, and that a successful communication system has resulted.[6] In many of these cases a telephone system has been the objective; however it should be noted that the telephone system imposes ever more stringent requirements on the communication link than does a remote metering system.

PART II

ILLUSTRATIVE SYSTEMS

2.1. Introduction

For the purposes of this report two different illustrative remote metering systems have been chosen for description, as an aid in evaluation of the remote metering problem. It is realized that there are many other possible systems, but these two should serve to illustrate the problems involved.

2.2. A System without Memory, Transmitting Meter Information Spontaneously

The following discussion concerns a hypothetical example of a possible memoryless system. It is not intended to be a comprehensive description, but rather a thought-provoking consideration of pertinent factors. This system of remote metering would consist of a centrally located receiver and decoder serving a group of meters, with each end organ transmitting an identifiable signal instantaneously as the meter registers a basic unit (e.g., a kilowatt-hour of electric energy). All these signals would be transmitted over a common information-carrying link to the substation unit. The substation unit would provide storage for all the signals received throughout one billing period. At the end of such a period, the stored signals could be sorted and integrated into individual meter totals. This information might then be used for automatic billing machine procedures.

One of the problems of an instantaneous metering system using a common communication link is that of overlapping signals from two or more meters. Such overlapping can result either in loss of signals because the receiver is unable to sort them, or in the recording of a false signal created by the combining of the mixed signals. This problem limits the amount of information that can be handled within a given tolerance of error. An analysis of this problem has been made (see Appendix I) which prescribes certain requirements for the system. These requirements, their effect on system components, and the effects of possible latitudes in these requirements will be discussed after a description of the system

A block diagram, Fig. 2.1, shows the components of the end organ. The operation of the end organ will in principle be as follows: the registering of a basic unit by the meter closes the circuit to the relay. The relay, through its double-pole switch, connects the oscillator output to the lines and applies power to the pulsing switch and oscillator. The pulsing switch goes through one cycle of operation and modulates the oscillator

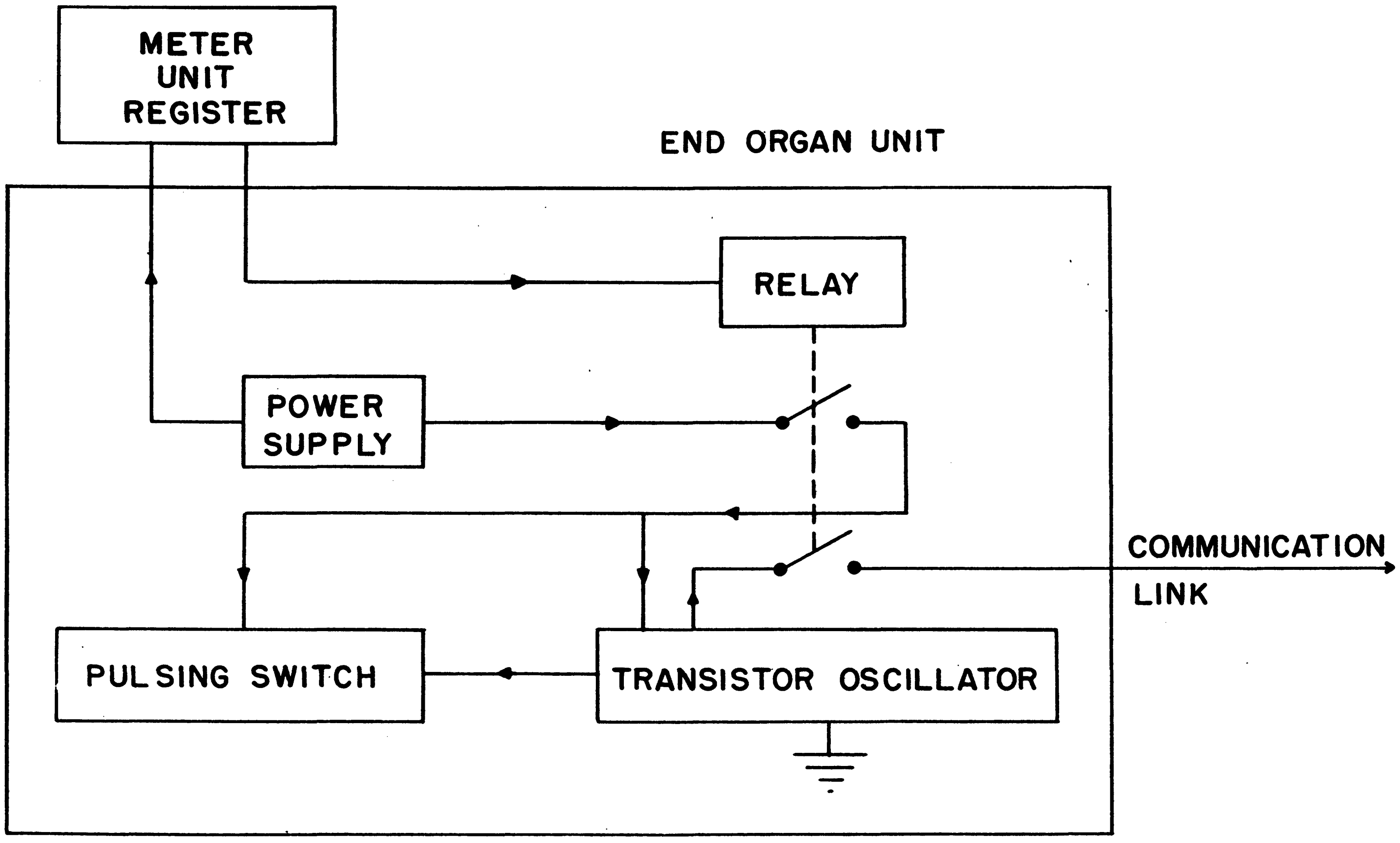

FIG. 2.1

ELEMENTARY BLOCK DIAGRAM
OF END ORGAN UNIT

output into a prescribed series of pulses. The pulsing switch is latched at the end of its cycle. The relay, operating on a time-control basis, opens, disconnecting the double-pole switch. Removing power from the pulsing switch unlatches it, so that it is ready for the next registering of a unit by the meter.

The substation unit would consist first of a conventional r-f amplifier and demodulator. Following the demodulator would be a pulse shaper to shape the pulses to a uniform amplitude for recording. Because of the short signal duration that is necessary to prevent signal losses through overlapping, it might be necessary to record the signals first on a magnetic tape. Later these signals recorded at high speeds could be transferred to low-speed punched tape[8] for operation in a billing machine, which would sort and totalize the signals.

The above description of the system and its operation must in the final design be related to the requirements as set forth in Appendix I. The following set of specifications is taken from Appendix I.

a) The maximum in a group served by one receiver will be considered as 256 meters.

b) Signal identification would be done by pulses arranged in a binary code. Thus, since $2^8 = 256$, 8 digits (for pulse or no pulse) would be needed for the signal itself. Since a marker pulse would be needed to indicate to the receiver that a signal is starting, the signal duration would be effectively 9 digits long.

c) A pulse period of 1 millisecond would be used. This gives a total signal duration of 9 milliseconds.

d) It will be assumed that an average of 200 KWH is registered by each meter in a billing period of one month. As shown in Appendix I, this results in a percentage of coincidences of less than 1 per cent.

e) It will be assumed that there are 9 meters per distribution transformer. This results in 28 transformers in the group.

f) It will be assumed that the longest distance from an end organ to the substations receiver is 5 miles.

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[8] see e.g., Kincaid, M. et al., "Static Magnetic Memory", Electronics, 24, 114 (January, 1951).

g) From approximate information available,[9] the following data on loss calculations will be used:

Distribution transformer bridging loss plus coupling capacitor attenuation, of the order of 0.2 db.
Line attenuation, of the order of 1.0 db/mile.

Using the loss calculation data given above, the losses can be computed for the information-carrying channel as:

28 transformers at 0.2 db/each	5.6 db
Maximum line attenuation: 5 miles at 1 db/mile	5.0 db
Assumed mismatch of impedances between end organ and line	3.0 db
Total	13.6 db

From the calculations of Appendix I for the requirements listed above and available data on electrical noise background, the substation receiver for this particular system would require approximately 1 milliwatt of signal power to operate satisfactorily. Since a reasonable figure for power output of a transistor oscillator is at least 1 watt at the present time, the losses from the end organ to the receiver should be kept below 30 db. It seems likely that future transistor development will increase power output to at least 10 watts, in which case the allowable loss figure could be extended to at least 40 db.

Thus, on the basis of the above calculation of 13.6 db, the losses are low enough so that it should be possible to devise a workable system.

The principal problem in the end organ is that of the pulsing switch, which must operate in millisecond intervals. As a simple illustration to indicate the concept, a mechanical method will be described. Such switching can, however, be done by purely electrical means. In order for the signal not to be chopped off, the relay operating the end organ would stay closed for perhaps 100 milliseconds (or even 1 second), allowing a sufficient blank period before and after the 9-millisecond signal duration. The pulsing switch might be a revolving wheel with switching notches over approximately one-tenth of its perimeter (if the relay "on time" is 100 milliseconds). When the relay is triggered on, the wheel makes one revolution (at a speed of 1/0.1 = 10 rps = 600 rpm). For the first 25 milliseconds the pulsing switch is "off", for the next 9 it is "on" and "off" for the proper code pattern, and for the final 66 milliseconds it is "off" again.

The major problem at the substation unit is the storage of the signals. Because of their short duration and their random occurrence, it would

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[9] Adapted from Barstow, J. M., _et al._, "Rural Carrier Telephony", _Elec. Eng._ _66_, 425 (May, 1947).

be necessary to store them in a memory system with a fast response time, such as a magnetic tape.

2.21. Minor Variations of a Possible Memoryless System. A variation of the receiver storage problem would use immediate sorting of the incoming signals into 256 channels, to be combined additively by an individual register for each channel. At the end of the billing period, the information would be taken from these registers (perhaps with punched tapes) and the registers reset. The use of the information is a standard business machine problem.

Variations can be made by changing the original requirements. If the basic unit of measurement could be changed by a factor of 10 (from 1 KWH to 10 KWH), a number of other variables could be changed, either singly or in combination. This would make each coincidence billing error more expensive, but the average error would be the same.

(a) One such compensating change could be made by increasing the number of meters in a grouping from 256 to 2560, and maintaining all the other requirements, except that the signal code would then require 11 pulses plus a marker. This would not change the end organ much, but it would increase the storage and sorting problem at the substation unit.

(b) If the number of meters is kept at 256, the signal duration could be raised from 10 to 100 milliseconds, using individual pulses of 10-millisecond duration. This would simplify the pulsing problem at the end organ. It would also slow down the recording rate at the receiver. In addition, the increased pulse duration would allow a smaller communication-channel bandwidth to be used and thus allow a smaller power output to be used at the end organ. It should be emphasized that changing the unit of measure from 1 KWH to 10 KWH permits definite simplification of the system. This should make the system both more dependable and less expensive initially.

Using a phase-to-phase connection to the distribution line rather than a phase-to-ground connection reduces attenuation and noise problems (according to power-system carrier-current practice). It also minimizes metering outages due to grounds on the power system.

The need for having more than 256 meters on one line could be met alternatively by frequency division multiplexing, that is, the use of a different signalling carrier frequency by each of several end organs. The receivers could all be installed at one central location. This is illustrated by Fig. 2.2.

In the substation unit described (see 2.2), no provision was made for the rejection of overlapping or coincident signals. From the calculations made in Appendix I, it would seem that the percentage of coincident signals

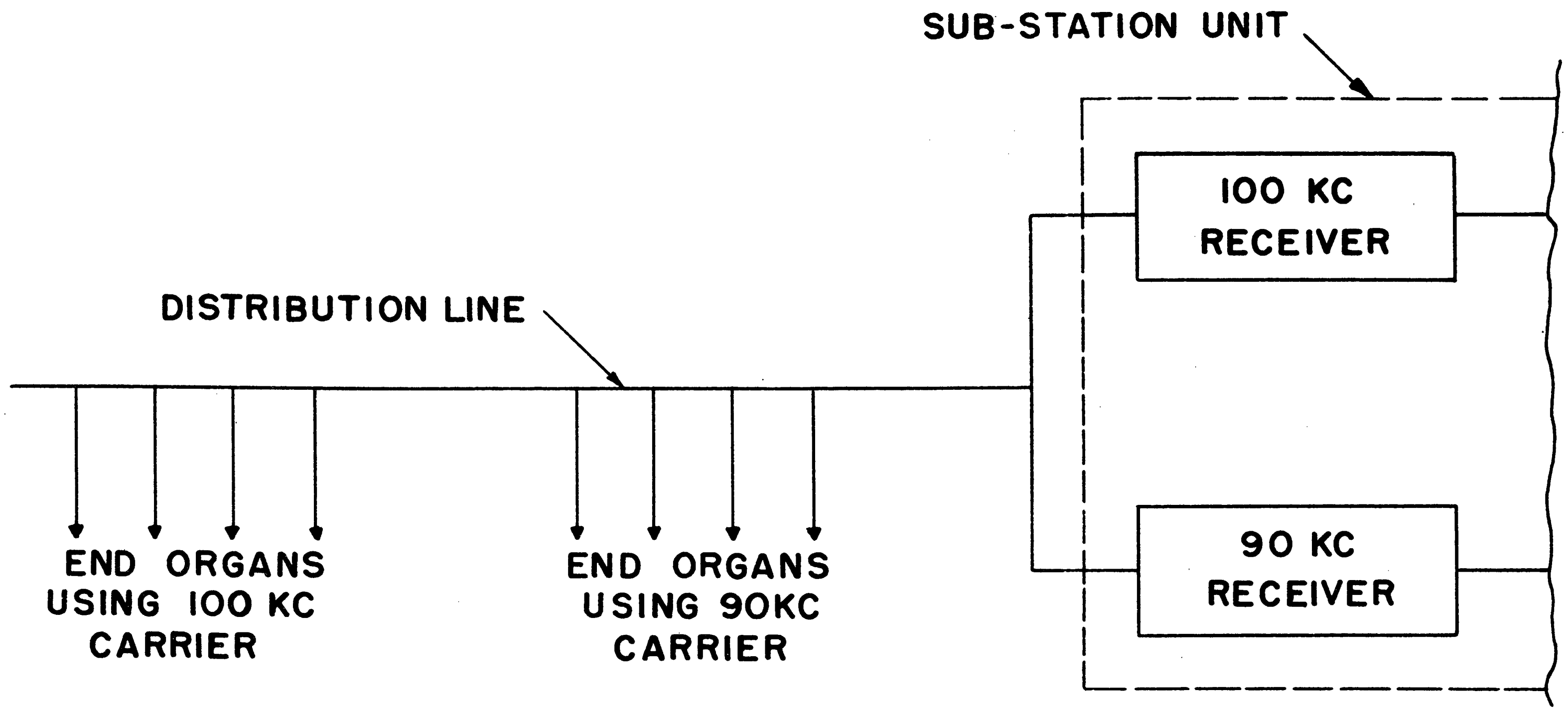

FIG. 2.2

FREQENCY DIVISION MULTIPLEXING

might be so small as to be negligible. However, it must be recognized that such coincidence of signals would result in undercharging some meters through the loss of identification of their signals and overcharging other methers through the creation of false signals. Therefore, it might be advisable to provide some means of preventing such errors caused by coincident signals. If overlapping signals were rejected, no meter would be overcharged, although some would be undercharged.

One solution to this problem would require that each end organ send out two identifying signals for each unit measured, one immediately following the other. The receiver would compare the two signals received and would record a unit only if the two were identical.

There is still a possibility that two different signals could overlap and produce a combined signal which would have two identical halves. Calculations using the single-signal duration of 9 milliseconds considered in the system above, with a spacing of 1 millisecond between signals, show that the percentage of coincidences would then be about 20 per cent of that calculated on the basis of the use of single signals with no rejection method, as follows:

From Appendix I, the percentage of coincidences is equal to 200 RD, where R is the rate of signal production and D is the signal duration in seconds. For the present calculation, R is constant. For a system using only single signals of 9-millisecond duration, per cent coincidences = $200\ R\ (9 \times 10^{-3})$.

If double signals are used, with a spacing of 1 millisecond, uncorrected per cent coincidences = $200 \times R \times (19 \times 10^{-3})$. However, with a rejection system only those overlapping signals starting within ± 1 millisecond of the start of the original signals would not be rejected. Therefore, the chance that the interfering signals can occur without rejection is 2/21, and the corrected per cent coincidences = $200 \times R \times (19 \times 10^{-3}) \times 2/21$.

Then the ratio of per cent coincidences for the double-signal system using rejection to per cent coincidences for the original single-signal system is:

$$\frac{200 \times R \times (19 \times 10^{-3})\ 2/21}{200 \times R \times (9 \times 10^{-3})} = \frac{2 \times 19}{21 \times 9} = 0.201 .$$

For a single-signal duration D, a signal pulse period S, and a spacing S between repeated signals, the condition that D is much greater than S gives a ratio of per cent coincidences of the corrected system to the original system of approximately 2S/D.

A second system of coincidence rejection could make use of the marker pulses which are required at the beginning of each signal. If the marker pulse were made distinctive from the signal pulses (e.g., a double-period pulse), the receiver could measure time intervals between two marker pulses. If markers were received in an interval less than a given time interval (the duration of a single signal), the information accompanying these markers would be rejected.

2.3. A System with a Memory

In contrast to the so-called memoryless system, it is desirable to consider also a basically different approach, that is, a system with a memory. There are many fundamental differences, and therefore several merits as well as some drawbacks.

The illustrative system to be described must accomplish two distinct but not necessarily independent functions: the substation unit of the system must be able to transmit some signal that will interrogate a particular remote meter (one of perhaps several hundred or thousand) and the remote meter must be able to recognize that it is being interrogated and in turn reply to the central station in a manner that indicates its KWH reading.

Thus, the signal transmitted from the central station must be coded and the many remote meters receiving the signal must be equipped to decode the signal, in addition to being able to transmit to the central station information relative to the meter reading, after having recognized that the particular meter reading is requested.

In order to describe a system which can accomplish these functions the following items will be discussed:

1) the type of signal transmitted by the central station,

2) the coding system,

3) the receiver at the remote meter,

4) the decoding device,

5) the recognition device in the remote meter, and

6) the meter reader unit in the remote meter,

1. The Type of Signal Transmitted by the Central Station. The signal to be transmitted to a group of remote meters will be a frequency-modulated carrier of somewhat arbitrary frequency. For the present example we will choose 100 kc. The modulation will be such that pulses are obtained from the detected signal and hence a constant value of deviation is indicated

for the duration of a pulse. As long as the transmitter frequency remains at 100 kc, no voltage will appear at the output of the detector in the end organ, whereas, for example, if for the pulse duration the signal frequency has become 102 kc rather than 100 kc, the detector will produce a d-c signal voltage lasting for the duration of the frequency shift.

2. The Coding System. In order that a particular remote meter be able to recognize and respond to a signal that is transmitted to perhaps thousands of these meters, some system of encoding is required. Figure 2.31A illustrates a series of 20 pulses (short-duration frequency shifts in the transmitted signal). The pulses are equally spaced in time and are of equal length. In a particular encoding the transmitted signal would be composed only of a certain 5 of these 20 pulses, as illustrated in Fig. 2.31B. Referring then to Fig. 2.31A, we arbitrarily select pulses 2, 4, 5, 13, and 15 and call these 5 a particular coded signal, noting that only these 5 of the 20 constitute a particular encoding and are transmitted. (Note that any 5 could be chosen as an example.) This code then would be assigned to one of the many meters.

Many other code groups of 5 are possible; functionally

$$C_r^n = \frac{n!}{r!\,(n-r)!} \ ,$$

where

n = total possible pulses, and

r = number of pulses in code group.

Thus with 20 pulses to choose from, and 5 in a code group:

$$C_r^n = C_5^{20} = 15{,}504 \ .$$

This is the total number of different code groups possible and hence the greatest number of meters that may be accommodated by this illustrative system.

The use of additional signalling frequencies e.g., 150 kc, 200 kc, etc., would make codes available for corresponding additional groups of 15,504 meters each.

In addition to the 5 pulses which comprise the coding, an additional initiating pulse is required, as will be explained later. The initiating pulse, however, will precede the code group at a fixed constant time interval.

The complete transmitted signal encoded for a particular remote meter will then appear as in Fig. 2.31C upon detection at the remote meter.

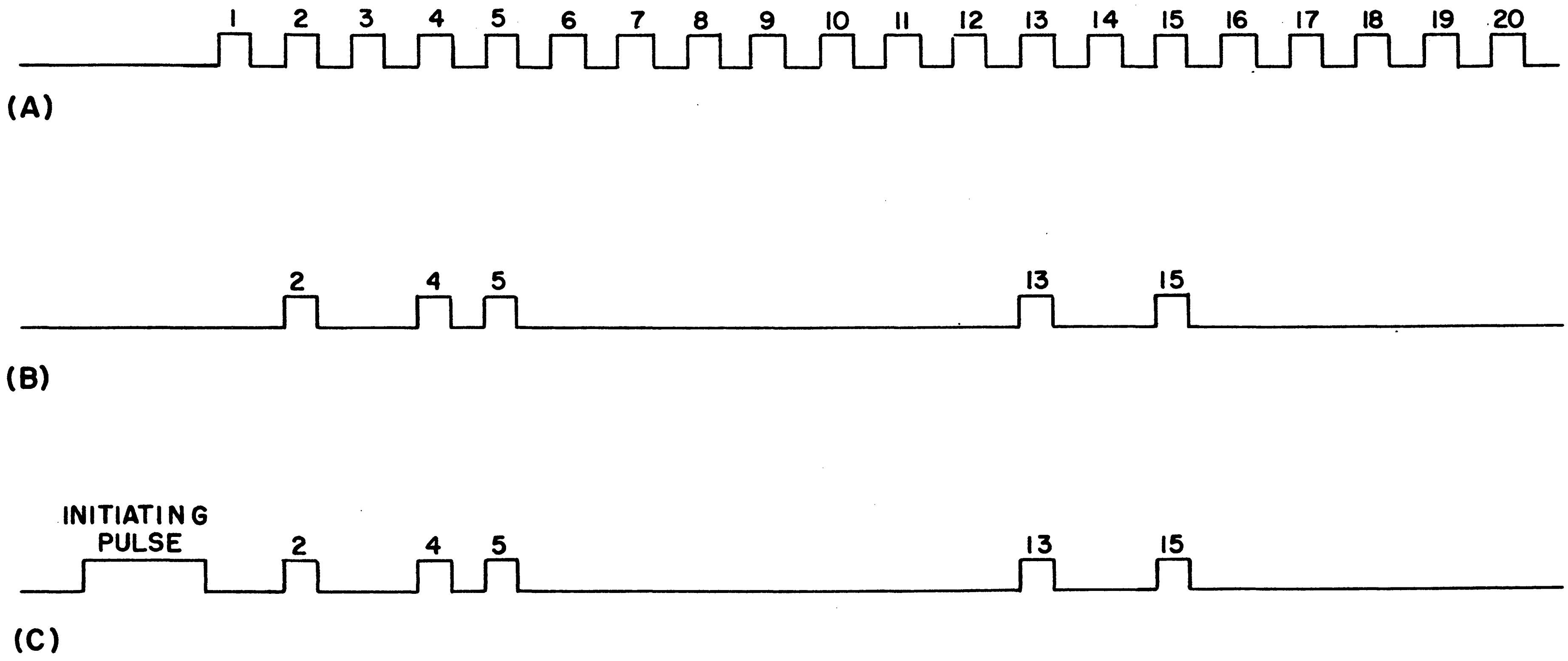

FIG. 2.31
PULSE ARRANGEMENT DIAGRAMS

3. The Receiver at the Remote Meter. Each remote meter must be provided with a receiver to demodulate the FM signal, and hence obtain the pulses in voltage form for recognition purposes.

The receiver (which would use semiconductor devices rather than vacuum tubes) must have a detector, either ratio-detector or discriminator type and perhaps one stage of amplification. Since substantial quantities of signal (100 kc) power may easily be generated at the central station and consequently large signals may be made available at the receivers, little amplification in the end organs should be necessary.

A tuned circuit will also be required to discriminate in favor of the frequency band in the neighborhood of 100 kc.

The voltage pulses obtained from the end organ receiver will be used by the decoding device described below.

The decoding device might in principle be either mechanical or completely electrical in nature. It is, however, easier to convey the decoding concept in terms of a basically mechanical device. Therefore, this illustrative system will assume a mechanical decoder, although it is reasonably likely that an ultimate design would be basically electrical.

4. The Decoding Device. It is necessary to provide, in each remote meter, some device which looks at the received code group (in this example 2, 4, 5, 13, and 15) and determines whether that is the particular group to which the meter should respond. Recalling that there is a definite, fixed time relationship between all the pulses of the transmitted code group, and that this is the only unique property of a particular code group, it is then indicated that the decoding device must in some manner operate in synchronism with the central station.

To envision one way in which this might be accomplished, consider the following:

Assume that when the carrier is initiated and transmitted from the central station, a small 60-cycle synchronous motor is started in each remote meter. Assume further that the synchronous motor is arranged to drive, through a clutch, a small "drum".

This special drum is constituted as follows: It is provided with 20 sets of contacts, there being 2 contacts per set; the sets are equally spaced along a portion of the drum periphery as shown in Fig. 2.32A. Figure 2.32B illustrates the drum as it would appear if it were possible to "unroll" the surface. Two wiping contacts are provided outside the drum. These complete the circuits to each set of drum contacts consecutively as the drum is rotated; the concept is similar to that of the brushes and commutator of a d-c motor.

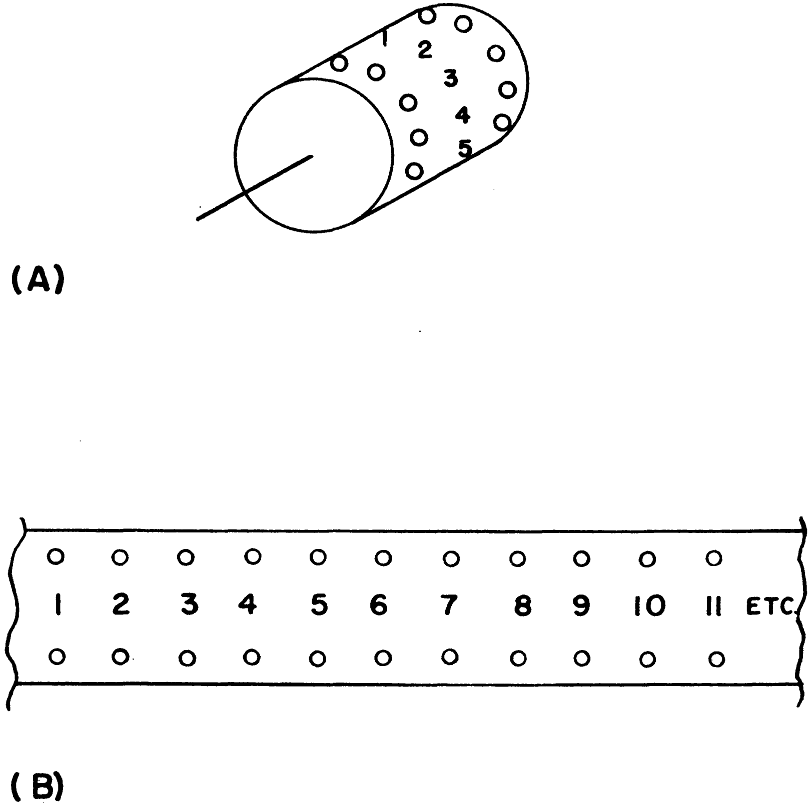

FIG. 2.32

DECODING DRUM ILLUSTRATION

The functional and physical arrangement of the motor, clutch, and drum is such that before the arrival of the initiating pulse (Fig. 2.31C) but after the arrival of the carrier, the motor is running, the clutch is disengaged, and the drum is at rest in a reference angular position. Upon arrival of the initiating pulse, the clutch is engaged and consequently the drum rotates. The code group follows at a known and fixed time interval after the initiating pulse, and the drum rotates in synchronism with the sequencing of the incoming code group. Thus the brushes external to the drum are in position to make contact with drum contact set 1 at the pulse 1 moment, set 2 at the pulse 2 moment, and so on through all contact sets.

Continuing, assume that small condensers are connected only across those particular drum contact sets corresponding to the positions 2, 4, 5, 13, and 15 (the code group chosen for the Fig. 2.31 example) and that the 5 condensers so utilized are all connected in series inside the drum.

Thus as the drum rotates in synchronism with the code group received from the central station, the condenser in position 1 will become charged to the voltage of pulse 1, the condenser in position 4 to the voltage of pulse 4, and so on for the 3 remaining condensers. The voltage due to all pulses is the same; thus the total voltage across the series-connected condensers will be 5e volts, where e is the voltage of each pulse.

It should be noted here particularly that only in the case of complete synchronism between the 5 condensers in these particular locations (2, 4, 5, 13, and 15) and the incoming pulses will 5e volts be obtained. Since only one meter has condensers in these locations, only this meter will store charge to produce 5e volts. If all possible combinations of the 5 pulses are considered, many meters will have 4e volts, many 3e, and so forth, but only one will have 5e. Thus decoding is accomplished and recognition becomes possible.

5. The Recognition Device. The recognition device must be of such a nature that it may observe the voltage appearing across the 5 series-connected condensers, and, if the voltage exceeds some value, for example 4.5e volts, supply evidence thereof. The evidence presumably would be a voltage which would in turn initiate the means by which the meter transmits its reading to the central station.

A device which will respond to a voltage in excess of 4.5e volts may be simply a transistor switching circuit. Simplicity and extremely low power consumption are easily attained, and such operation of a transistor is well within its limitations, even in the present early stages of transistor development.

6. The Meter Reading System. Up to this point in the discussion, the first of the two necessary functions, that is, identification or interrogation of a desired meter, has been provided. It remains, then, to cause

the activated end organ to transmit the meter reading to the power lines for transmission to and reception at the substation unit.

As in the case of the decoder, this operation also may in principle be either basically mechanical or electrical. In order to facilitate understanding of the desired operation, however, a mechanical system is chosen for this example.

A true memory device already exists in meters in the form of the dial indicator. It is not proposed to replace this device, but rather to add another which will translate the individual dial positions into time sequence information for transmission to the substation unit.

The signal obtained from the recognition device is used to initiate the meter reader system, which produces in essence a reference pulse and several subsequent short-duration pulses from a transistor oscillator. The times at which the sequential pulses occur are proportional to the regular meter dial positions and hence indicate the meter reading. Figure 2.33 illustrates a possible pulse sequence such as would be received at the central station. The time between the leading edge of the reference pulse and the leading edge of the second pulse indicates the reading of the units dial; the time from reference to third pulse, the reading of the tens dial; and so forth for as many dials as desired.

In order to accomplish this sequencing, special rotary switches could be mounted so as to be driven by the same shaft which drives the decoding drum.

The switches are identical and are arranged to operate as follows: when recognition occurs the reference pulse is transmitted and switch 1 is operated through its cycle. When it reaches the end of its cycle switch 2 operates similarly and so on for all switches employed. At some point in the cycle of each switch a circuit to the transistor oscillator is closed momentarily, transmitting a pulse to the lines. The time of closure is indicative of the meter dial reading.

Figure 2.34 illustrates functionally one switch. Note that "A" is mounted on and rotated by the common shaft, and "B" rotates with the dial pointer, the tab indicating dial position.

The section marked "A" (driven by the same motor as the decoder drum) rotates through only one revolution. Part "B" is rotated by a particular meter dial, its tab position corresponding to the dial position.

7. <u>Summary</u>. Figure 2.35 is an overall block diagram, showing the complete remote installation, both electrical and mechanical links being shown.

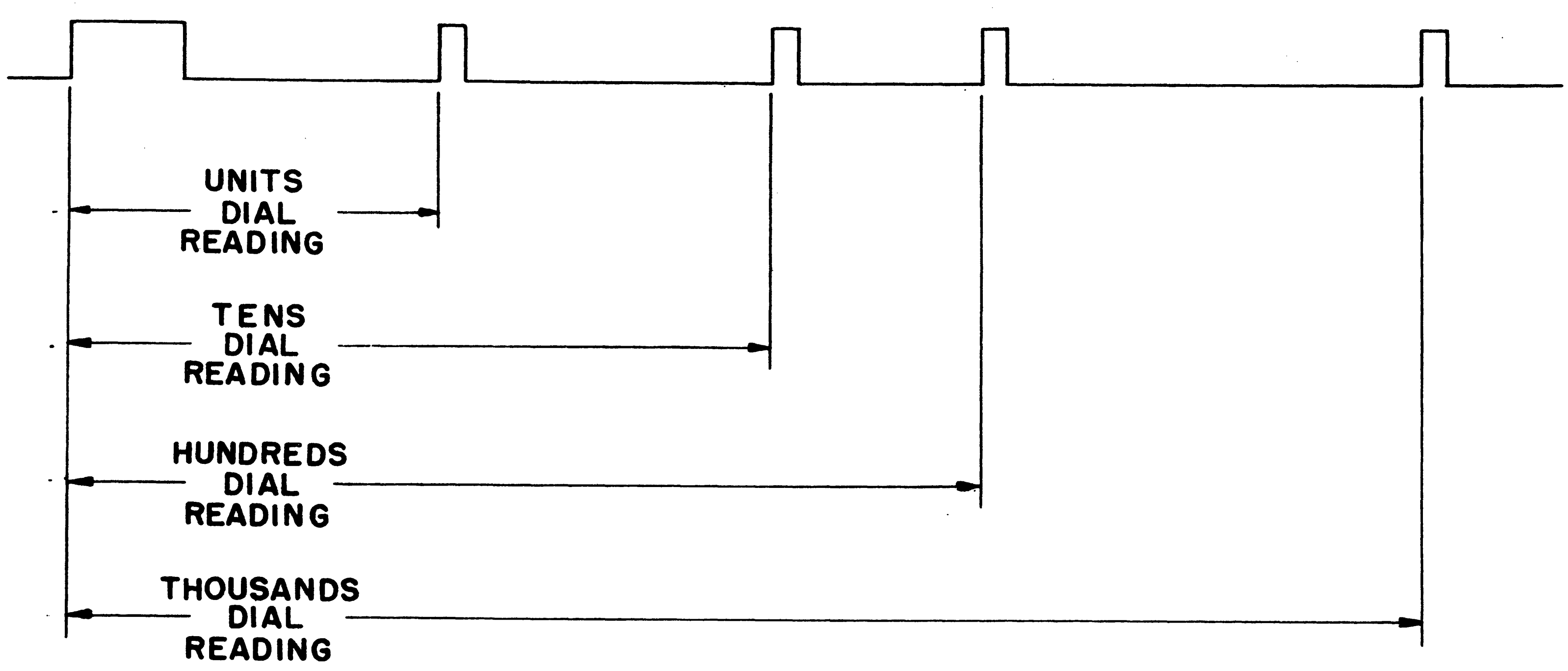

FIG. 2.33

TYPICAL PULSE SEQUENCE INDICATING METER READING

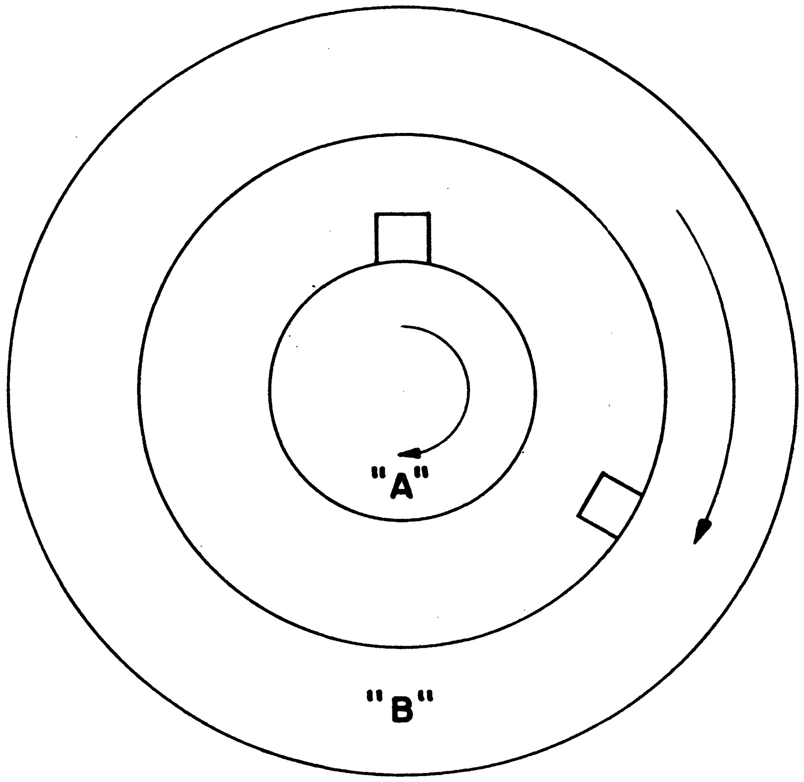

FIG. 2.34

DIAGRAM OF METER READING SWITCH

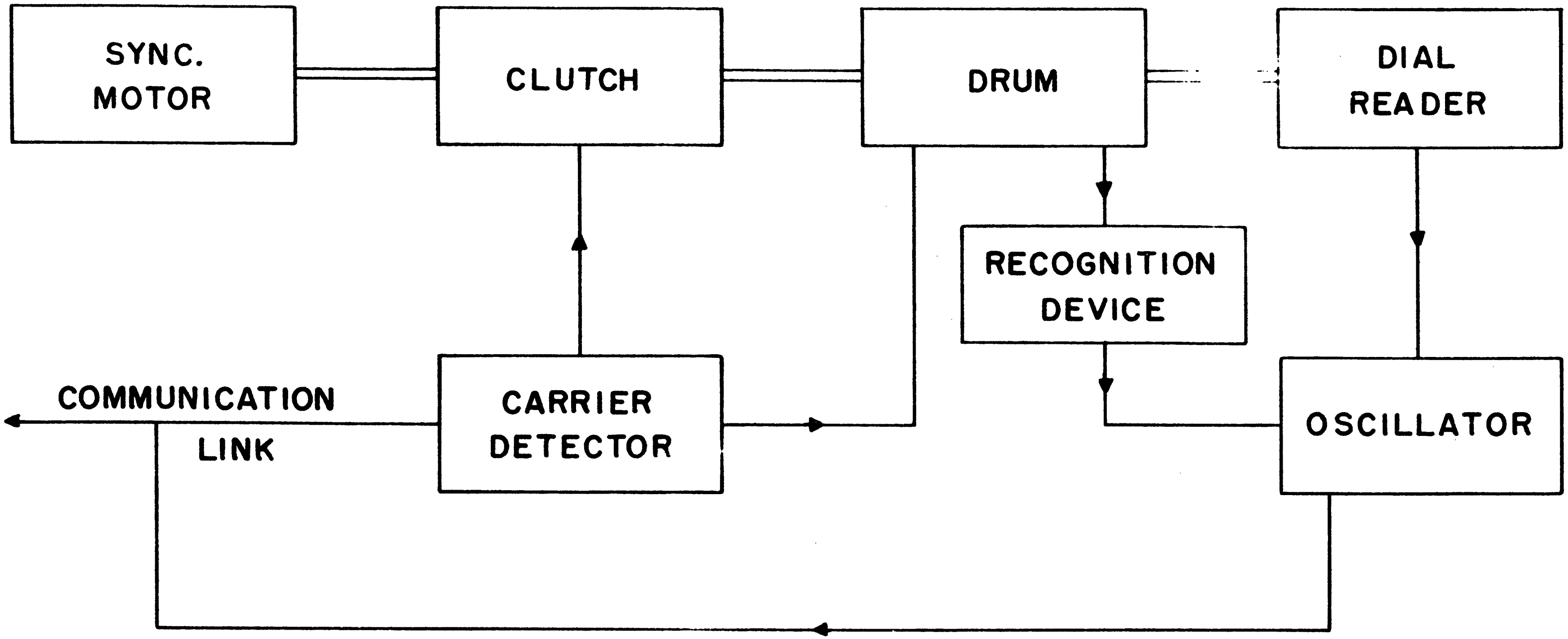

FIG. 2.35

FUNCTIONAL BLOCK DIAGRAM OF MEMORY TYPE END ORGAN

The significant features of this illustrative memory-type system may be summarized as follows:

1) A substation unit transmits a coded signal to all remote meters in a predetermined group.

2) A particular remote meter recognizes a particular encoding.

3) Upon accomplishment of (2), the particular meter (selected by the substation unit) transmits its reading for reception at the substation unit.

4) Steps (1)-(3) may be repeated for verification.

2.4. Comparison of the Two Illustrative Systems

It is the purpose of this section of the report to point out the fundamental relative merits of each of the two illustrative systems described. Before proceeding it seems well to emphasize a point made earlier.

Both systems require use of the power lines and therefore fundamentally it must be recognized that the transmission and noise characteristics of the lines at the signalling frequencies must be accommodated in any system. The degree of line adaptation is somewhat dependent on the choice of system; however, the extent and kind of adaptation necessary must be an important consideration in any research program, regardless of the system which may at this time appear most feasible.

Considering, for the moment, the memoryless system which transmits meter-reading information spontaneously on consumption of a unit quantity of energy, perhaps the most significant advantage is its presumed relative simplicity, insofar as the end organ instrumentation is concerned. Fewer components are required, which implies less initial cost and less maintenance, both being important considerations.

However, if at the end organ the mechanical motor-driven switch were to be adopted and proved to be a major component, there then would exist some question as to whether the addition of a memory would increase cost and maintenance substantially, since the motor-driven switch of the memoryless system could be adapted to provide the decoding drum function in the case of the memory system. If, on the other hand, the motor-driven switch is not a major part of the end organ instrumentation, then the addition of a memory might increase cost and maintenance significantly, and a memoryless system would then be more attractive.

The memoryless system has the following immediately apparent weaknesses:

a) Since it transmits information randomly, continuous availability of the communication link is indicated. Thus, periods when power line use may be most desirable, for example low-noise periods, may not be utilized to advantage.

b) As pointed out, a small probability of signal overlap must exist. This implies some loss of meter information in the substation unit, therefore producing some loss, however small, of revenue to the company.

c) The nature of the system does not allow repetition of a meter reading for purposes of verification.

The memory-type system, on the other hand, appears to have strength in regard to the following points:

a) The time at which the meter reading data are obtained is arbitrary, permitting utilization of the power lines during periods which may be most desirable, as for example when the noise level is low.

b) The possibility of overlapping signals does not exist.

c) Data may be obtained from a particular meter as many times as desired, thus permitting verification of a questionable reading.

Offsetting these significant points somewhat is the possibility of increased complexity of the memory-type system, implying perhaps greater initial cost in the end organ.

A final decision regarding the most desirable system should not be made without further investigation and study of the overall problem. For suitable design of either system, a knowledge of noise-level problems is necessary.

PART III

CONCLUSIONS AND RECOMMENDATIONS

3.1. General Comments

The statements to be made in this section represent the opinions and conclusions of the authors at the time of writing, following a rather preliminary survey of the problem, and a review of the material presented in Parts I and II of this report.

This report has been concerned primarily with application to areas of relatively low meter density such as rural or suburban residential regions. Accordingly, it seems reasonably certain that a system is feasible for at least portions of power company facilities, in particular rural areas and installations where consumer density is not too great and where distribution is limited to open wire lines. The extent of such an application could well be appreciable; utilization where power-line (communication-link) lengths are of the order of 20-50 miles appears definitely possible of realization.

It seems likely, also, that application to small towns or residential portions of cities with populations of only a few thousand would have a reasonable likelihood of success.

The application of a remote metering system to areas of high meter density, or areas where power transmission is, for example, restricted to underground lines (Manhattan Island is a striking instance) may require techniques quite different from those discussed in this report. This problem is also very challenging, and the potentialities tremendous.

The high-meter-density problem might prove to be susceptible to a much simpler solution than may first appear probable. On the other hand, it may be very difficult and not feasible at present either technically or economically.

In any event, a research program oriented to provide a reasonable likelihood of success in the direction indicated by this report would presumably permit, upon its completion, more realistic consideration of the application of remote metering to areas of very high meter density.

3.2. Summary

In summary, it seems at the present state of our knowledge that the likelihood of obtaining significant economy and operational benefit from suitably chosen applications of remote metering systems is great enough to warrant appropriate investment in research toward determining the engineering characteristics of workable systems.

We are inclined toward a rather general initial approach to the problem, with emphasis on the communication-link phase, at the same time considering associated system details. It would appear that the conception and fairly early field installation of an experimental system limited perhaps to a single substation unit and a few end organs in some suburban area would be very desirable.

APPENDICES

APPENDIX I

FURTHER NOTES ON A MEMORYLESS END ORGAN SYSTEM

A. Analysis of System Using Memoryless End Organ

Consider a remote metering system having a memoryless end organ and using a communication link which is common to a group of end organs and a substation unit. Some method of identifying the signal sent by a particular end organ is needed. One possibility is the use of a group of pulses so arranged as to represent a number in the binary number system. Each end organ would then be represented by a different number or pulse arrangement. This characteristic code group would be transmitted once by the end organ for each unit of the quantity being measured. The complexity of this signal would depend on the number of individual meters in a group that must be separately identified. For example, a grouping of 256 meters requires for identification of a particular meter a binary number of 8 digits (or individual pulses) in the characteristic signal ($2^8 = 256$).

In order that a substation unit make positive identification of a signal it must, of course, have a recognizable form when it arrives at the receiver. Those influences contributing to distortion of the transmitted signal may be divided into two categories, (1) signals from other meters or end organs and (2) extraneous or noise voltages in the information-carrying link. The first source of interference can be treated as a problem in probability; i.e., knowing the number of meters and the average signalling rate, the probability that two signals will occur within a specified interval can be calculated. The second source can be treated if sufficient information is available concerning the noise-voltage characteristic of the transmission channel and the method of transmission used.

"Signal-Signal" or Coincidence Interference. Assume:

1) a 250-meter group of electric meters,

2) average consumption of 200 KWH per month per meter,

3) one identifying signal transmitted per KWH,

4) a 9-digit code group used for identification of a meter, the first digit being used as a marker for the beginning of a group, and

5) a 0.001-second period of each individual pulse.

If calculations are made on a per-second basis for the group, the average consumption rate is

$$\frac{\text{KWH}}{\text{sec}} = \frac{200 \times 250}{30 \times 24 \times 3600} = 1.93 \times 10^{-2} \qquad \text{(A-1)}$$

Assume that at peak periods the consumption is ten times average; thus

$$\left(\frac{\text{KWH}}{\text{sec}}\right)_{\text{peak}} = 0.193 \, . \qquad \text{(A-2)}$$

If the identifying signal consists of 9 digits, each of 0.001-second duration, the signal duration is 0.009 second. The coincidence rate at peak periods may be computed as the product of the probability that a signal will occur in some designated 0.009-second interval during this period and the probability that another signal will occur within 0.009 second of the starting time of the first (either before or after), multiplied by the number of 0.009-second intervals in 1 second. The first factor is simply the average rate of signal occurrence at the peak period times the length of the 0.009-second interval. The second is the average signal rate times an interval of 2 x 0.009 second. The third is 1/0.009, or 111. Thus:

$$\begin{aligned} \text{coincidence/sec} &= (0.193 \times .009)(0.193 \times 2 \times .009) \times 111 \\ &= (0.193 \times .009)^2 \times 2 \times 111 = 6.69 \times 10^{-4} \end{aligned} \qquad \text{(A-3)}$$

Then percentage of signals that will occur coincidentally is

$$\%C = \frac{6.69 \times 10^{-4}}{0.193} \times 10^2 = 0.347 \text{ per cent} \, . \qquad \text{(A-4)}$$

If it is assumed that a coincidence results in billing the wrong customer, and further, if one assumes that the probability of incorrect billing because of a coincidence is the same for each customer, then the percentage error in customer billing will, on the average, also have a maximum value of the order of 0.347 per cent. (It is, however, probably not correct to assume equal probability of incorrect billing due to coincidence, since presumably the customers with the largest numbers of pulses normally present in their identifying signals will be billed incorrectly more often that the others.) Note that the above calculation gives the coincidence rate for the peak-load period. A more complete calculation would consider the coincidence as a function of the varying daily load.

Noise Interference. It is characteristic of the response of narrow-band circuits to impulse noise that the peak values of the output voltage are directly proportional to the bandwidth, despite the fact that the mean square voltage also is proportional to the bandwidth. Clearly, the signal level and the code used must be so chosen that the number of spurious signals registered by the receiver due to noise always remains below a tolerable limit. If a redundant code is employed, a certain number of spurious pulses can be tolerated before a false signal is registered. Let K be the peak voltage response occurring with the frequency N in a receiver of unit bandwidth. The threshold signal voltage S in a receiver of bandwidth B then is:

$$S = \sqrt{2}\, KB \, , \tag{A-5}$$

where S is the rms voltage during each signal pulse.

For the transmission of 0.001-second pulses, the minimum bandwidth is 5×10^2 cycles.[10] Knowing the peak impulse noise response per unit bandwidth at the appropriate frequency, the peak noise for a channel of specified bandwidth may be computed. The frequency spectrum in the region near 100 kc seems to be a promising one for transmission of signals over the power distribution circuits. The memoryless signalling system might be used in this region by pulse modulating a 100-kc r-f carrier. The noise spectrum of interest will thus be near 100 kc.

Measurements reported by Cheek and Moynihan[11] seem to indicate that a value of K equal to 1.25×10^{-3} volt/cycle may be reasonable. Thus for the system using the 500-cycle bandwidth mentioned above,

$$S = (1.25 \times 10^{-3}) \times \sqrt{2} \times (5 \times 10^2) = .883 \text{ volt} \tag{A-6}$$

gives the pulse rms voltage. If the pulses amplitude-modulate an r-f carrier,

$$S_{RF} = \frac{S}{\sqrt{2}} = \frac{.883}{\sqrt{2}} = .625 \text{ volt} \, . \tag{A-7}$$

If a value of 300 ohms is assumed for phase-to-ground impedance,[12]

$$P_{RF} = \frac{(.625)^2}{300} = 1.3 \times 10^{-3} \text{ watt} \, . \tag{A-8}$$

This represents the average power of a signal at the receiving point that will be at the threshold.

Additional calculations are shown in Appendix I-B for other meter groupings and several different signal pulse periods.

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[10] Goldman, S. - Frequency Analysis Modulation and Noise, McGraw-Hill Book Co., Inc., New York, 1948, p. 85.

[11] Cheek, R. C., and Moynihan, J. D., AIEE Trans. 70, Part I, 1127; Part II, 1325 (1951).

[12] See Burridge, G. E., and Jong A. S. G., AIEE Trans. 70, 1338, (1951).

B. Additional Calculations

In Table I-C-1 are results of calculations for additional groupings of meters. Note that three factors determine coincidence rate. They are rate of energy consumption measured by the individual meters, number of meters in a group, and the length of the identifying pulse code group. The threshold for the pulsed radio-frequency signal is determined entirely by the period of the individual pulses used, since this period determines the necessary communication-channel bandwidth.

From the table it is evident that the coincidence rate is decreased by decreasing the period of the individual pulses. The threshold is, however, increased by this decrease in pulse period, requiring more power in the end organ. Thus a compromise must be effected between coincidence rate and the signal power required in the end organ.

The usage rate assumed for the computations in the table is ten times an assumed average rate of 200 KWH per month per meter except for numbers 5, 6, and 7. For these calculations a peak usage rate of forty times the average is assumed.

TABLE I-C-1

No.	No. of Meters in Group	Usage Rate for Group, KWH/sec (Max.)	No. of Pulses in Identifying Code Group	Period of Individual Pulses, sec	Length of Code Group, sec	Coincidences per sec	Percentage Coincidences at Peak Usage Period	Bandwidth, Cycles (Minimum Required)	Thres. Power at Substa. Recr., Watts (300-ohm line to Ground)
1	100	0.077	8	10^{-3}	8×10^{-3}	9.48×10^{-5}	0.123	5×10^{2}	1.3×10^{-3}
2	250	0.193	9	10^{-3}	9×10^{-3}	6.69×10^{-4}	0.347	5×10^{2}	1.3×10^{-3}
3	500	0.385	10	10^{-3}	1×10^{-2}	2.97×10^{-3}	0.770	5×10^{2}	1.3×10^{-3}
4	1000	0.77	11	10^{-4}	1.1×10^{-3}	1.31×10^{-3}	0.170	5×10^{3}	0.130
5	1000	3.08	11	10^{-4}	1.1×10^{-3}	2.09×10^{-2}	0.678	5×10^{3}	0.130
6	1000	3.08	11	10^{-5}	1.1×10^{-4}	2.09×10^{-3}	0.068	5×10^{4}	13.0
7	1000	3.08	11	5×10^{-5}	5.5×10^{-4}	10.45×10^{-3}	0.339	1×10^{4}	0.52
8	1000	0.77	11	5×10^{-5}	5.5×10^{-4}	6.53×10^{-4}	0.085	1×10^{4}	0.52

APPENDIX II

NOTES ON FREQUENCIES USED FOR POWER-LINE CARRIER SYSTEMS

In the last twenty years there has been extensive use of electric power lines as carrier channels for communication, telemetering, or relaying. The more successful results can be divided into two general ranges of frequencies, radio and audio, each of which requires different analysis and technique. As a general classification here, the term "audio" will cover those frequencies above the power-system frequency (50 or 60 cycles) up to perhaps 1000 cycles. "Radio" frequencies will be considered as those of 30 kilocycles and above.

Electric power systems are designed and analyzed in terms of a 60-cycle frequency. With this approach, the design equations and specifications are obtained by starting with fundamental equations and examining them with relation to the magnitudes involved at 60 cycles. As a result, some terms of these equations can be ignored or modified.

When a system which has been designed and built for 60-cycle operation is to be used at other frequencies, the basic equations must be reexamined. And, as might be expected, factors that were unimportant at 60 cycles sometimes become of major importance and vice versa.

The major factors that limit the use of radio frequencies on power lines to an upper limit of about 450 kc are the line attenuation of the signal and the electrical length of the line. At 60 cycles, a wavelength is approximately 3000 miles and even the longest transmission lines are electrically short. However, at 60 kilocycles, the wavelength becomes 5000 meters (about 3 miles) and at 600 kilocycles, which is at the lower end of the broadcast band, the wavelength is only 500 meters, or about 1/3 of a mile. The reference presents some data on line attenuation versus frequency.[13]

At these high frequencies, short tap lines and spurs can easily be a wavelength, or a multiple thereof, long, necessitating additional consideration of undesirable loading or reflections. Also, if frequencies above 200 kilocycles are used, interference problems with broadcast transmission and reception may be encountered.

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[13] Rives, F. M., "Application of Carrier to Power Lines," AIEE Trans., 62, 835 (1943).

While many power-line carrier-current applications have had a high-frequency limit of 200 kilocycles, recent work has been done using rural power distribution lines for telephone communication, and using modulated radio-frequency carriers.[6] In these systems, in order to provide a sufficient number of channels, frequencies up to 450 kilocycles have been used.

In using radio frequencies on a power-line carrier system, techniques which have been developed for regular radio service are used in the transmitting and receiving equipment. As lower and lower frequencies are used, the tuning and coupling circuits tend to become bulky and difficulty is encountered in the design of tuned circuits with proper bandwidth. These problems have put a low-frequency limit on the use of such techniques at 30 kilocycles. However this situation might be modified by the use of more recent materials and circuit techniques.

While the actual application of radio-frequency carriers to power lines is still semi-empirical and semi-analytical, a number of basic ideas have been formulated. These are summarized in various articles in the literature.[13,14] Some of these points are:

a. Coupling to the high-voltage line is done by means of capacitors. Tuning equipment in the form of series and parallel resonant circuits is often used with the capacitor.

b. Transformers designed for power transmission and distribution will not pass radio-frequency signals. They must in general be bypassed by capacitors if such signals are to go from one side of the transformer to the other.

c. The bridging loss of distribution transformers up to a 5-KVA rating is small, being about 0.2 db per transformer for signals in the 100-kilocycle range.

d. Attenuation loss along distribution lines at 100 kilocycles is generally important but not prohibitive; a rough order of magnitude might be 1 db per mile.

e. Line traps are used extensively to keep the signals out of parts of the power system that are not part

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[14] Cheek, R. C., "Power Line Carrier Applications," *Electrical Transmission and Distribution Reference Book*, Westinghouse Elec. Corp., Fourth Edition, 1950, p. 401.

of the communication line. Carrier-system losses in spur lines and taps (of length greater than 1000 feet and less than 20 miles) are of the order of 3 db per tap, which justifies such trapping.

f. Since so little carrier power is passed through transformers to the power load, the carrier losses in this load can be neglected.

The use of audio frequencies has been developed more as a means of mass relay operation than for point-to-point communication. In this country, the General Electric Company has developed a system using 720 cycles as a means of turning on and off from a central location street lights and hot water heaters connected to power systems. This system, or modifications of it, have been used by a number of power companies.

In England and Europe, extensive application of this method has been used for such control.[15] Systems have been developed which use a number of frequencies (320, 370, 420, etc., to perhaps 670 cycles) to turn street lights off and on (sectionalizing control to main and secondary streets at different times), operate store window lights, sound air-raid alarms, etc.

In most of the systems which have thus far been reported, a single large generator at a central location operates a large number of relays at remote locations simultaneously.

Whereas radio-frequency carrier systems utilize vacuum-tube and radio-circuit techniques, the audio systems developed are adaptations of power-system design. One article describing the General Electric 720-cycle system[16] and the article describing the English and European systems give design analyses. The existing 60-cycle system, as it might be altered by the application of voltages of higher frequencies, is used for the analysis. The result is that, while impedance values change, the system is still a large-current system. In the final design, alternators are used as a source of signalling power and large-current relays and controls are employed. The KVA rating of the generators is an appreciable fraction of the rating of the distribution lines on which they are used (since all the 60-cycle power equipment also takes power at the audio frequency). A voltage of 5 to 10 volts at the audio frequency is used on the 120-volt lines for the relay operation.

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[15] Barker, H. P., "Centralized Control of Public Lighting and Off-Peak Loads by Superimposed Ripples," Jour. IEE, 83, 823-836.

[16] Woodworth, J. L., "Application of 720-Cycle Carrier to Power Distribution Circuits," AIEE Trans. 62, 903 (1943).