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Low cost data communications equipment for use on the electric power distribution system

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Low cost data communications equipment for use on the electric power distribution system

by

Gerald Norman Johnson

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GLOSSARY

Baud: Bit per second.

Commutation: When applied to thyristors, refers to the stopping of conduction.

Cycloconverter: A static power frequency changer that uses controlled rectifiers to generate the new frequency at the output.

Distribution system: That portion of the electric power system used to connect individual customers to the transmission part of the system. Primary distribution generally uses voltages in the range of 2400 to 25,000 volts. Secondary distribution generally uses voltages from 110 to 600 volts.

Downstream: In the direction of power flow from power source to loads.

EXCLUSIVE-OR: A two input logic gate whose output is false when both inputs are in the same logic state and true when the inputs differ from each other.

Mark: A term used in telegraphy which originated from the pen and ink telegraph recorder of the 19th century. The pen made a mark on the paper strip when the circuit was closed, and stands for a logical true.

Natural Commutation: Thyristors are naturally commutated in ac circuits when the polarity of the ac supply reverses and causes the thyristor to stop conducting.

Primary network: Primary distribution system with multiple energy sources and interconnected power lines leading to a circuit often pictured as a mesh. Provides redundancy in power sources and circuit paths for improved reliability of service to customers.

Radial network: A power distribution system with no redundancy in either power source or power line. Often pictured as spokes of a rimless wheel.

Ripple control: A method of downstream remote control on the power system using audio frequency signals. The German term is Rundsteueranlagen which freely translated is round switch control.

7.5 unit character: In asynchronous serial communications, a part of the transmitted character is used to synchronize sending and receiving apparatus. A common system uses a bit of relative length one for a start bit, five data bits each of length one to represent the character, and a stop bit about 1.5 units long for a total length of 7.5.

Space: The opposite of mark. Logical false in a telegraph circuit.

Transmission system: That portion of the electric power system used to move relatively large amounts of electric energy from the power source to the substations supplying the distribution systems. Distinguished by voltages from 30,000 to 750,000 volts and up.

A CONCISE HISTORY OF ELECTRIC POWER LINE COMMUNICATIONS

The use of the electric power line as a communications path as well as the conveyor of power has been a gleam in the eyes of communications people ever since the capabilities of resonant circuits were discovered. A great deal of supervisory control and metering is performed by the use of power line carrier systems on the power transmission system. Carrier frequencies in the range of 15 KHz to 500 KHz are used. The signals are capacitively coupled to the transmission line with a carrier frequency isolation filter between the coupling capacitor and the substation transformer to prevent the signal being dissipated in the transformer. Very early power line carrier work in the 1920's used tuned antennas to couple the carrier transmitters and receivers to the line, albeit very inefficiently (22). Due to the complexity of the connections and filters required to prevent the loss of excessive carrier energy in transformers and shunt capacitor stations, the use of power line carriers has generally been restricted to high voltage transmission lines. Carrier systems using frequency division multiplex techniques very similar to those used for long distance telephony have proved to be very useful for communication between installations in the high voltage transmission systems.

The components of the distribution system[1] with its multiple voltages and distributed loads severely restrict the use of carrier for communication on the distribution system. Strictly speaking, the term carrier means any regular waveform at any frequency which serves to convey information by means of some modification or modifications of its characteristics such as amplitude, waveform, frequency, or phase. In the power system context, carrier means the use of a sinusoidal transmission and reception waveform (in the frequency range of about 15 KHz to 500 KHz) with suitable modulations impressed.

Until recently communication on the distribution system has been limited to control functions. Devices at load locations can be controlled by commands from central locations. By the early 1930's several systems of remote control using the distribution system were in use. One of these early experiments signaled by means of momentary interruptions of the supply (7). These interruptions could not have been very popular with the customers! An American system was developed that used audio frequency signals to control street lights and other interruptible loads. In many circles this technique is referred to as "ripple control". The main use

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[1]See Glossary.

was initially for the control of multiple (parallel connected) street lights which are more convenient than series connected street lights in that they require no special circuit of their own but can be supplied with the regular power distribution system. However with such a connection, each fixture must be individually switched. Graham (9) described such a system as follows:

> The control currents are transmitted over the lines just like power currents. The frequency of the control currents used is sufficiently higher than the power frequency to make it easy to separate the control currents from the power currents.
>
> Special relays employing tuned circuits are provided at points where control is desired. These relays are connected across the 110 volt mains which feed the individual street light or group of lights. The relays respond only to currents having the particular frequency for which they are tuned.
>
> Sufficient energy is fed through the power system to the control relays to operate them by the direct electro-magnetic pull of the control currents themselves without the use of vacuum tubes, amplifiers, or rectifiers of any kind. This avoids complication and delicacy in the control units and also avoids using parts requiring periodic replacement.
>
> Two control frequencies are used, one to turn the lights on and one to turn them off....
>
> The control currents are fed into the power system at the substation....The control currents flow along the conductors just as though the power currents were not present.
>
> The frequency of the control currents is selected so as to avoid serious loss in transmission and to permit being efficiently stepped

> up or down through the existing power transformers. Frequencies of about 500 cycles [Hz] are used....
>
> The existing wires and cables of a power system therefore provide an efficient channel for the transmission of independent control currents for all sorts of purposes. There is no difficulty in transmitting control currents, having sufficient energy to directly operate suitable relays, to all parts of the system.

The basic principles used for remote control have changed little since then.

Most modern systems use solid state audio frequency generators (14) rather than the rotating machinery of the past (5) and slightly more complicated receivers (15). Because of the large number of receivers, however, a trade has been made between receiver complexity and cost and transmitted power. The result is a very simple receiver and relatively great transmitter power. The use of audio frequency control systems in the United States seems to have been abandoned so long ago that very few American power system engineers today remember such systems although these systems are still commonly used in Europe. With energy conservation in mind, American utilities are beginning once again to look at ripple control systems as a way to help reduce peak load demands by permitting the disconnection of nonessential loads during peak demand hours (17).

The foregoing is primarily downstream communication. Of equally great interest is communication from "the periphery to a central" (14) point (or upstream) rather than always from the center outwards (or downstream). Several schemes have been proposed. Charles Haberly (10) communicated from the Iowa State University Electrical Engineering building to the University Power Plant at a rate of about 1 bit per second (or one Baud) by using a receiver with a narrow bandwidth tuned to a modulation product generated by switching a load on and off the line every two cycles. Spälti (25) of the Landis and Gyr Company of Zug, Switzerland, generates a damped wave oscillation at 575 Hz by switching a 575 Hz tuned circuit on and off the line in synchronism with the 50 Hz line frequency. His receiver also has a bandwidth of about 1 Hz so that his data rate would be no greater than one Baud. Kniel (14) uses an amplifier with a "well-known simple output stage" to impress a current at 125 Hz on a 50 Hz distribution system. The signal frequency is shifted ±0.1 Hz to send data on switch positions and overload indications from a distribution substation (16KV/220V) to a manned control point located at a 50KV/16KV substation. From the photograph of the data transmitter it appears that almost half of the volume of the transmitter box contains a LC filter network to protect the amplifier from the 50 Hz load currents. Such filter networks are luxuries not economically feasible in systems using many data transmitters such as utility metering systems.

A number of publicity releases have been made about other schemes for remote metering using the power lines but little concrete data is available on the techniques used. Automated Technology is apparently using power line carrier techniques at a frequency about 15 Hz. The signal losses in distribution transformers present a significant obstacle to such signals. One method of overcoming these obstacles is to allow the losses to occur but to use a better (more sensitive and selective) receiver at the central point to compensate for the signal loss. Another method is to connect coupling capacitors around all distribution transformers in order to couple the signal past the transformers. This could be a source of consumer distress when the coupling capacitor's insulation fails, thereby applying the primary distribution voltage to the secondary system with much ensuing damage to customer equipment (11). A third method proposed is a repeater at each transformer. The repeater consists of a receiver, a coupling device and a transmitter. The circuit can be relatively simple, the receiver and transmitter - amplifiers tuned to the carrier frequency and the coupling device using electro-optical techniques involving light emitting diodes, light pipes or fibers, and phototransistors. The safety of such devices can be much better than a capacitor. Such systems are not in keeping with this dissertation's topic of low cost systems.

General Public Utilities Co. (20) has demonstrated communications for meter reading using frequencies of 900 to 1100 Hz with a variable data rate of up to 60 Baud. General Electric (20) has experimented with communications using a carrier frequency of 8 KHz. Allowing for line frequency variations the available bandwidth between harmonics for low power communications is only 21 Hz.

Shintron Corporation (20) of Cambridge, Massachusetts, has explored the possibility of using a signal of very narrow bandwidth (approximately 0.001 Hz) in the vicinity of 60 Hz as a means of communicating meter reading data over the power distribution grid. This work is said to be in a "patent-applied-for status" with no further activity contemplated. As of August, 1975, the writer could find no patents of this nature issued to the Shintron Corporation (29).

The best documented remote utility meter reading systems involve the use of telephone company lines to gain access to the customer meters. At the present time the cost involved in these systems and the friction inherent between the electric and the telecommunication utilities limits such metering operations. Rochester Telephone Company (Rochester, N.Y.), an independent telephone company, has been testing a system that reads individual customer meters while it tests the telephone lines. Such a dual system may prove economical in certain situations (23).

AN ANALYSIS OF THE UPSTREAM COMMUNICATIONS PATH ON A POWER DISTRIBUTION SYSTEM

In order to design a communications system one must know the characteristics of the communications path to be used. For the techniques to be proposed later in this dissertation, a practical transmission path is a single phase distribution system supplied from a three phase source. A substation usually supplies multiple single phase primary distribution circuits from a three phase transmission line and consists of a transformer with circuit breakers for transformer protection. The most common three phase transformer (or transformer bank) is delta connected on the transmission side (source) and wye connected on the primary distribution (load) side with the neutral grounded. Only radial distribution circuits will be considered here. Primary networks will not be considered at this time because of their complexity and the difficulty of determining the predominant current supply paths. As most residential customers are connected single phase, only a single phase circuit need be analyzed. A slightly simplified diagram of such a single phase distribution system is shown in Figure 1. T_{D_1} is the distribution transformer at the point chosen for a communications signal source while ΣT_{D_n} represents a composite of all the other transformers and customer loads on this particular single phase distribution circuit.

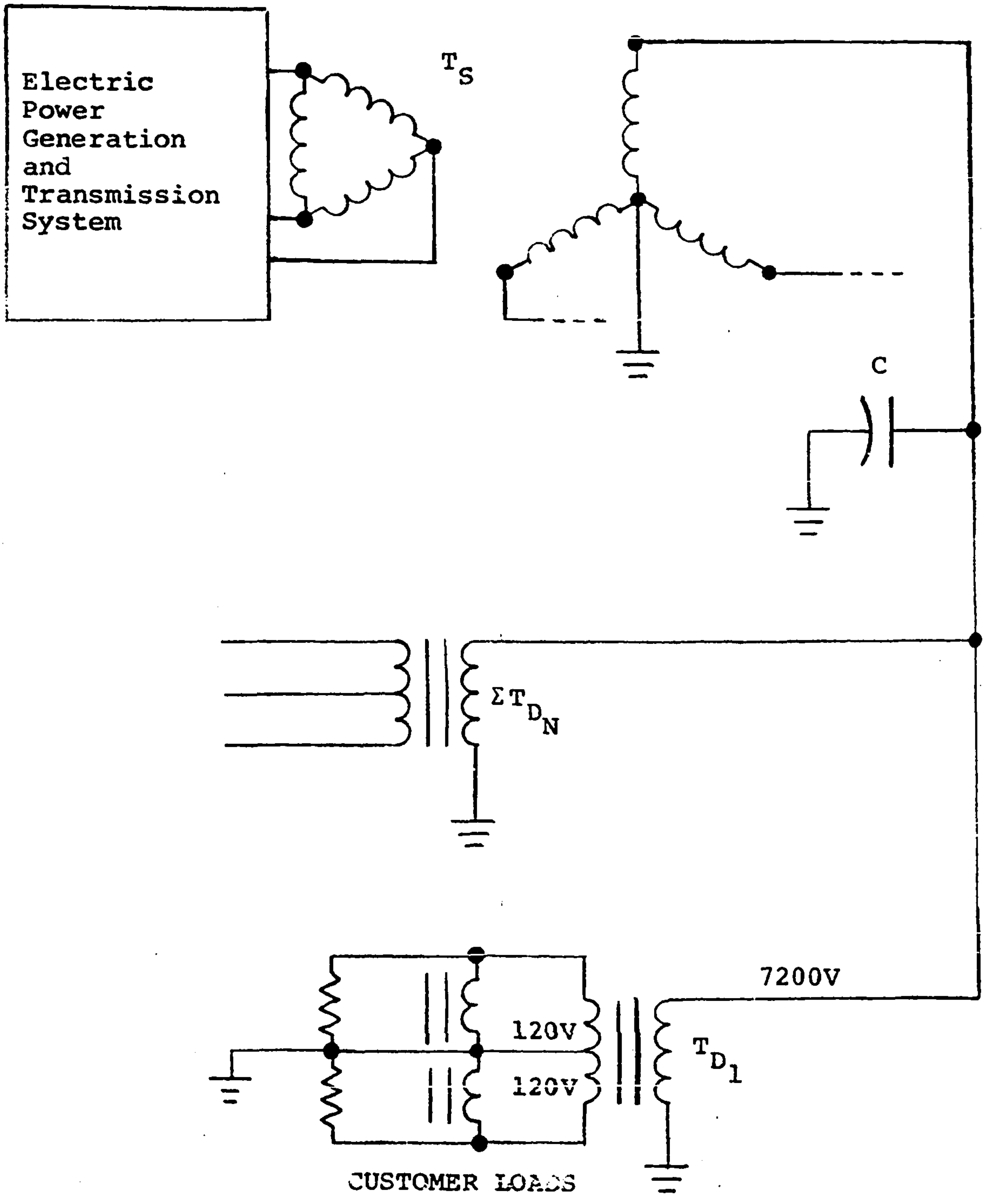

Figure 1. A single phase electric power distribution system

Normally there will be some power factor correcting capacitors, C, on such a circuit. T_S is the three phase delta-wye substation transformer.

Were it not for the presence of the power frequency energy, the system of Figure 1 would be quite good for audio frequency communication since the losses are quite small and the effective bandwidth of the system is limited on the low frequency end by the transformers themselves and on the high frequency side by the phase correcting capacitors and the leakage impedances of the transformers. The low frequency limit depends directly upon the signal level. For a transformer winding, the voltage rating at a constant peak flux is directly proportional to the frequency of the applied voltage (28). An extremely low cut-off is of no consequence since for asynchronous data transmission the lowest frequency component present is the character rate itself. The upstream data communications technique proposed later in this dissertation requires a low frequency band limit of 4 Hz. Unfortunately for general communications, such a low loss set of conductors and transformers exists mainly to supply 60 Hz energy to customers and can never be usurped solely for communications purposes. Thus any communications to be carried out on the power system must be performed in spite of the 60 Hz power present.

In order to make best use of the winding and core materials in transformers, the cores are operated as near to absolute saturation as loss economics will allow. The saturation of the transformer cores induces odd harmonic currents in the system (26). Loads of various natures introduce other harmonic and nonharmonic currents in the power system (1, 12, 13, 19, 27). The nonlinearities of the transformers mix the harmonic and nonharmonic currents to produce a wideband noise spectrum on the system. Corona and arcing produce additional noises that radiate with a spectrum limited only by the sensitivity of the receivers used to test for it.

For good voltage regulation to the electric customers, the source impedance is designed to be less than a tenth of the impedance of the system's maximum rated load. Thus the low source impedance minimizes the signal voltage rise found in the system when a signal current is injected but at the same time maximizes the current transfer from any load point to the source. For this reason any signal current injected at any load point (assuming a reasonably linear system) will be practically undiminished (by other than the expected transformations) in the source current.

It is readily (and improperly) assumed that one could superimpose a signal voltage at the peripheral signaling point and then isolate that signal voltage as a component of the power source voltage. However, the power source impedance presents an extremely low impedance to the signal voltage and reduces the signal voltage amplitude to an unusable level. If the signal voltage were isolated from the power source by a suitable filter and if the signal voltage source were protected from power frequency energy by a similar filter, signaling by voltage could be accomplished nearly as easily as on a dedicated circuit. Such filters are not in keeping with this dissertation's topic of a low cost upstream communications system that does not require substantial modifications of the power distribution system.

When signaling by current, the signal current can be conveniently found in the transformer secondary current since the source is transformer coupled. Further, when the substation transformer is connected delta-wye, the single phase current is not transformed to the primary transmission line (2).

Thus the necessary components for a communication path on the distribution system are a source of signal current and a current sensitive receiver sampling the current at the substation secondary neutral. The latter is easily accomplished with a current transformer and suitable power frequency rejection filters. The former is easily provided by any signal current source that is not affected by the power frequency voltages at its output terminals. If one were to use a suitable filter to prevent the application of power frequency energy to the current source terminals, any current source of suitable current rating would suffice. A simple one might have an output stage made of transformer coupled bipolar transistors with or without current feedback. If the filter were left out, to reduce the cost of the transmitter, the signal current source terminal voltage would be that of the power system while the current would be that of the signal. In an ordinary amplifier, maximum current corresponds to minimum device voltage. With voltage and current having different frequencies, maximum voltage and maximum current can coincide causing large levels of power dissipation in the output devices.[1] With vacuum tubes in the output stage this might possibly be practical but semiconductors have thermal time constants short compared to a half cycle at the power frequency and destruction is most probable.

The combined communications and power system circuit is shown in Figure 2 and an equivalent circuit for Figure 2 is shown in Figure 3. For a numerical example, assume the distribution transformer T_{D_1} is rated at 15KVA with an impedance of 3 percent, so that $Z_P \simeq Z_S \simeq 50$ ohms on a 7200 volt base. Let n = 100, that is a total of 101 similar

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[1]See Appendix A.

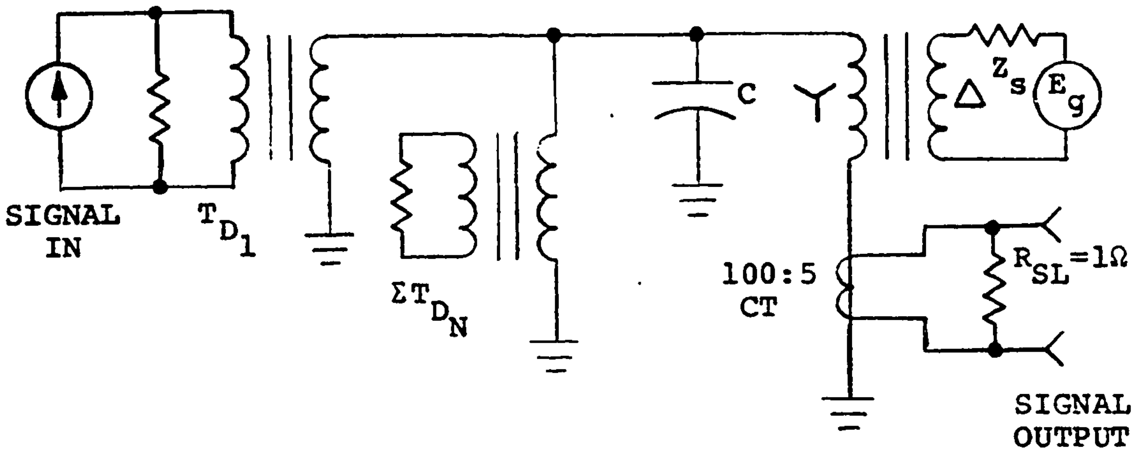

Figure 2. A single phase signal transmission path

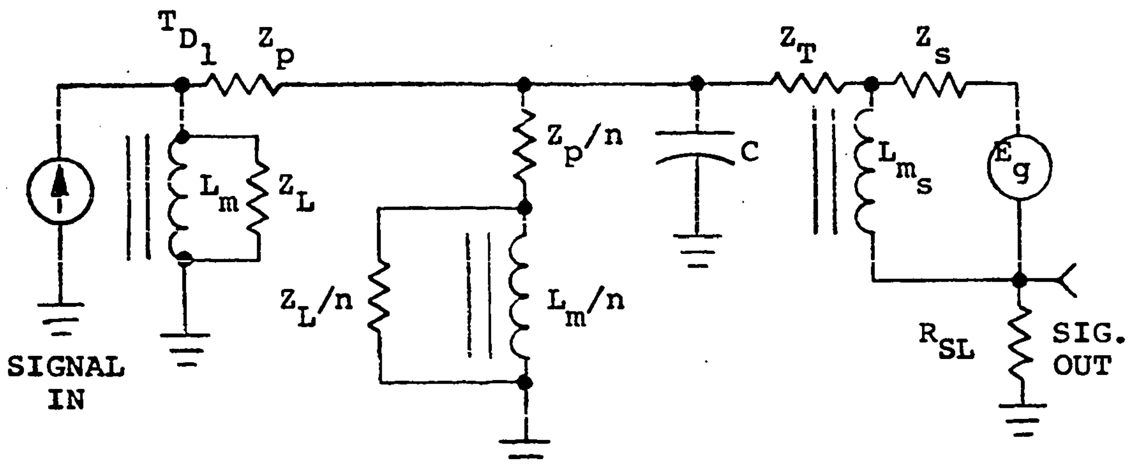

Figure 3. An equivalent circuit for Figure 2

transformers and loads (Z) are connected to the system. If the substation transformer has a three phase load rating of 3MVA and a three percent impedance, then Z_T for both positive and zero sequence voltages is about 1.5 ohms. With these numbers and with some circuit simplification the circuit of Figure 3 simplifies to Figure 4.

To take transformer core saturation into account, more detailed information is needed. Despite requests to several manufacturers for transformer data none has been made available. Therefore values have been approximated. From transformer design experiences and references (3, 26) a maximum flux density of 1.5 Teslas (97,000 lines per square inch) is assumed. The excitation current of a Westinghouse 3KVA transformer with a silicon steel core was measured over a range of supply voltages. When plotted, the curve of this data was experimentally fitted to the curve for 0.012 inch grain oriented silicon steel as given on page 33 of the Arnold Engineering Company catalog (3). The data taken at rated voltage corresponds to a maximum flux of 1.6 Teslas. A pair of C cores were chosen from the Arnold catalog that appear to be suitable for a shell form 15KVA distribution transformer. For the AA-564 indicated in the catalog as popular, the 7200 volt primary would require 5141 turns. The design would be complete after computing insulation requirements, losses, and adjusting core size, conductor size

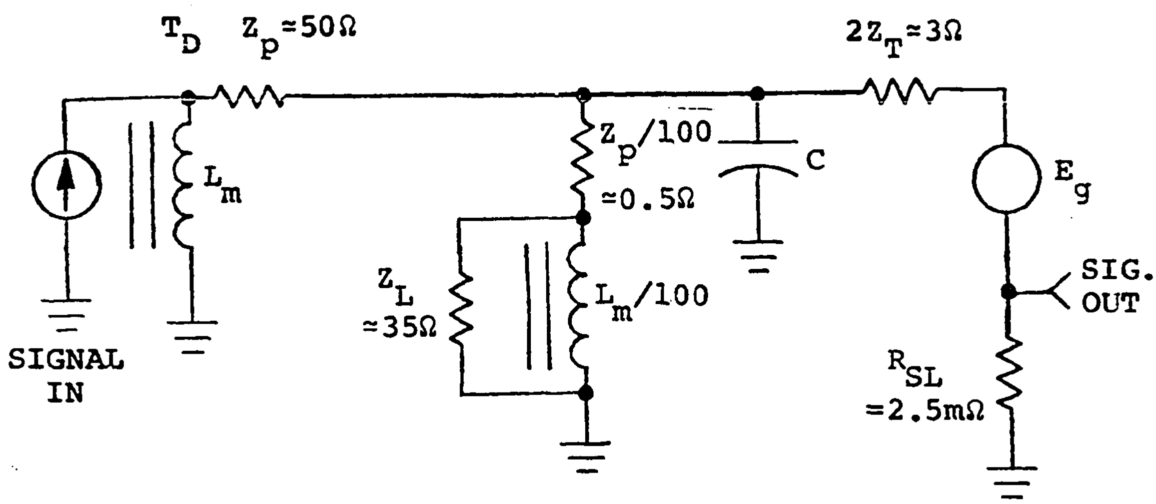

Figure 4. A simplified equivalent circuit for Figure 2 (7200 volt base)

and configuration, and maximum flux density in order to minimize cost and losses. As only approximate data is required for the purpose of this analysis and production is not contemplated the refinements were not pursued.

From Ryder (24) a transformer with a grain oriented silicon steel tape wound core would have an incremental inductance

$$L_i = \frac{aAB_nN^2}{\ell} \operatorname{sech} \frac{aNi}{\ell} + \frac{cAN^2}{\ell} \text{ Hy}$$

where $B_n = 1.0075 \times 10^8$ amp-Hy/m^2, $a = 6.93 \times 10^{-3}$ m/amp, $c = 7087$ Hy/m, N is the number of turns, ℓ = magnetic path length in meters, A = the cross sectional area of the core in square meters and i is the current in the winding. For the AA-564 core pair, on a 7200 volt base,

$$L(i) = 892.9 \operatorname{sech} 49.9i + 9.06 \text{ Hy.}$$

Thus if the core is saturated (current arbitrarily large) the incremental inductance would be about 9 Hy. As a check on this formula, The Arnold Engineering Company catalog (3) indicates that the exciting current for a 7200 volt winding on a pair of AA-564 cores when operating at a peak (symmetrical) flux density of 1.8 Teslas is 0.5 ampere. A linear

38 Hy inductor would draw a similar current. A 9 Hy inductor would have an impedance of 5100 ohms at 90 Hz in T_{D_1} and about 51 ohms for the equivalent of all the other distribution transformers. Compared to the 3 ohms of the source, even distribution transformer saturation will divert little signal current from the substation transformer. Thus the effect of saturation of distribution transformers on the signal can be neglected.

For quite some time, the author's upstream communications designs were based on the use of a phase shift keyed 90 Hz or 150 Hz carrier.[1] Kudashov (16) gives a method of computing the effects of circuit saturation providing a transfer function for the circuit can be derived. The low source impedance of the distribution circuit minimizes the effect of distribution transformer saturation, therefore data distortion due to circuit nonlinearities was not computed.

Use of a Saturated Distribution Transformer for Signal Generation

As a corollary to the above discussion of saturation, one might suspect that the distribution transformer could be used as a magnetic amplifier in order to produce signalling

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[1]See Appendix A.

currents. That is, if a sufficiently large unbalanced direct current were drawn through the secondary winding, the operating point of the core will be removed from the origin of the B-H curve. Then because of the nonlinearity of the magnetic material, the B-H loop will be asymmetric and will cause the excitation current to be asymmetric as well, as is readily discerned from Figure 5.

The result of an experiment to test this corollary is shown in Figure 6. It was found that the operating point in the B-H plane does not shift to the limit of the unbalance immediately but requires many cycles to complete the shift. When fully shifted by a large halfwave rectified secondary current, the peak value of the excitation current is greater than the primary current required to supply the secondary current but the time duration for the excitation component is much shorter so that the energy contained in the excitation component is much smaller than the energy contained in the halfwave rectified component. Furthermore the two currents are of opposite polarity and thus tend to reduce the signaling effectiveness of the other. Half sines were found to be more effective so the use of transformer saturation as a signal generator was dropped and the half sines concept was pursued with the results to be shown in the following sections of this dissertation.

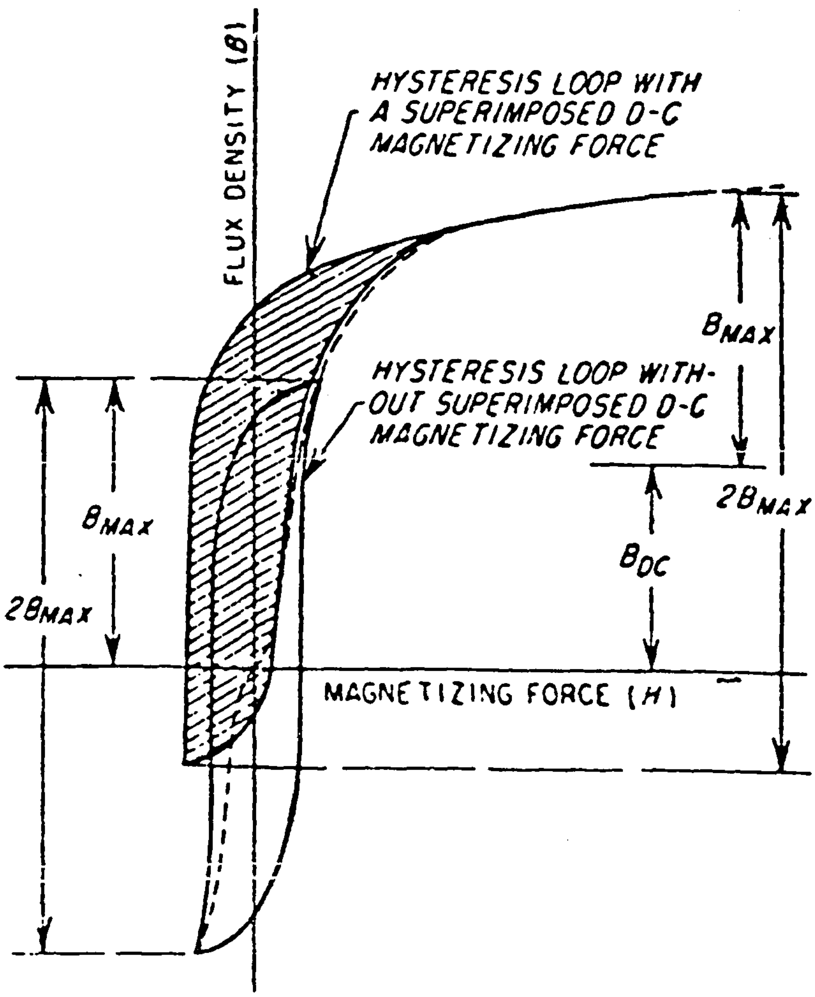

Figure 5. Hysteresis loops with and without a superimposed d-c magnetizing force

From Landee et al. (18, Figure 14.5)

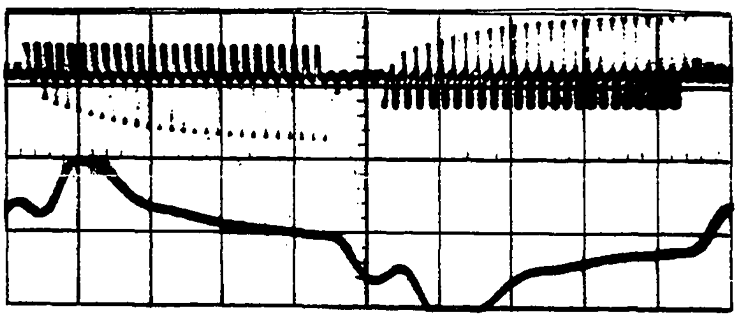

Figure 6. Waveforms from the circuit of Figure 11

Upper trace: Distribution transformer primary current with a large half wave rectified load. Half sines are due to load, sharp peaks are due to saturated core material. Sweep speed is 0.1 sec per division.
Lower trace: Upper trace after 9 Hz 4-pole Butterworth low pass filter. Due to the large signal level, the amplifiers were being driven to saturation causing considerable distortion.

A TECHNIQUE FOR TRANSMITTING DATA UPSTREAM ON A DISTRIBUTION SYSTEM

Data can be transmitted upstream on the distribution system either by transmitting the data directly or by using the data to modulate a suitable carrier and transmitting that modulated carrier. Either process is fraught with the difficulties caused by the stiff voltage regulation (low source impedance) of the power system.

Since there is a large source of energy connected to the power system it is an erroneous assumption that one could impress an additional source of energy on the system for upstream communications purposes. (Many of the author's attempts to do this have resulted in damaged apparatus.)[1] Rather the author realized that appropriate nonlinear loading can be applied in a manner that approximates the desired upstream communications signal. One could transmit information upstream (towards the power source) using a data-controlled current sink rather than having to have an independent data-controlled signal source. A basic circuit for this is shown in Figure 7. This circuit connects the resistor, R_L, to the line only when the polarity of the line and the bipolar data are the same by means of the logical EXCLUSIVE-OR and the relay.

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[1]See Appendix A.

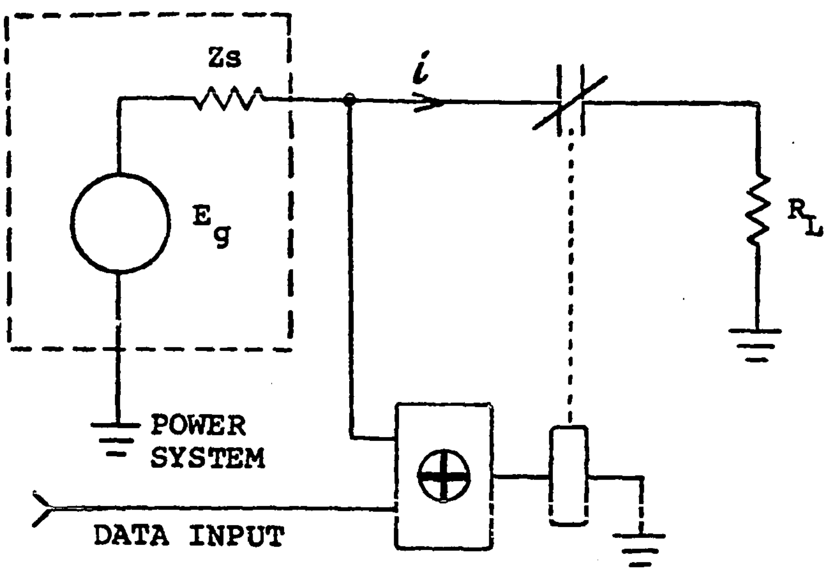

Figure 7. A circuit of a conceptual data-controlled current sink

The data-controlled current sink can be used for communication in the system of Figure 8 because it can be used to approximate any upstream communications signal that can be propagated on the power line. The signal may be simple data, multiplexed data, or data modulated on a carrier. The upper frequency limit is, in practice, determined by the ability of the relay or its equivalent to interrupt the load current. The relay function can be readily implemented with solid state devices such as thyristors, provided certain operating conditions are satisfied. The most stringent condition is the necessity for the capability of stopping conduction in the thyristor. If the desired signal frequency is greater than the power frequency, auxiliary commutation (or "turn-off") circuits must be used. Such circuitry was experimentally tried but was dropped due to the complexity of the control logic and auxiliary circuits required.[1] In addition, these control logic and auxiliary circuits violated the original constraints of low cost and high reliability. Thyristors that can be turned-off with a low power gate control similar to that required for turn-on would be very useful in such a circuit.

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[1]See Appendix A.

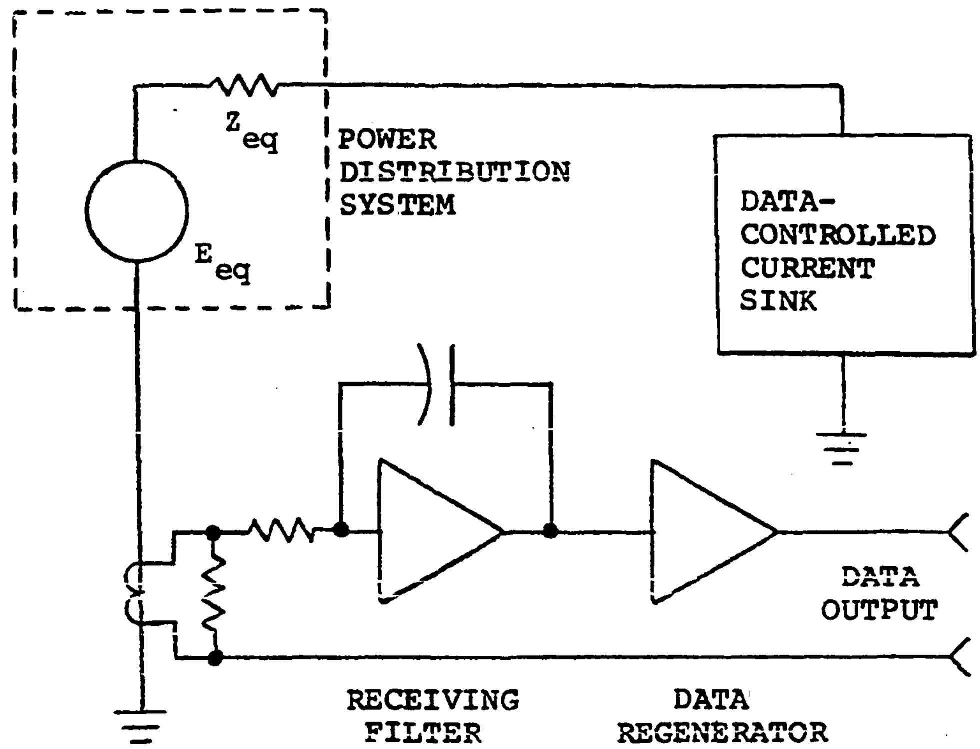

Figure 8. A power line communications system using a data-controlled current sink

Considerations for Simple Upstream Data Communications

At a data rate of 15 Baud, an alternating binary sequence (i.e., ----01010101010101010101010101010----) has a fundamental frequency of 7.5 Hz. That is, while there are higher frequency components present, all of the information is contained in the 7.5 Hz fundamental frequency. The minimum frequency present in random data is determined by the character length and is 4 Hz for a 7.5 unit character at 15 Baud. Repeating the calculation of the effect of saturation at lower frequencies will give similar results because the major portions of the transformer T equivalent series impedances are made up of leakage inductances which will maintain the same ratio to saturated magnetization inductance regardless of frequency of analysis. Since in a normally operating power system the transformers will not be run completely to saturation, the effects on the signal currents will be even smaller than computed above.

A Way to Use Natural Commutation

When thyristors are used in ac circuits commutation naturally occurs each time the current through the thyristor goes through zero. If gate drive is applied through the zero crossing, and the thyristor is bidirectional, such as a triac, then the thyristor will resume conduction a short time after the current has passed through zero. If the thyristor is a silicon controlled rectifier (SCR), the thyristor is reverse biased into a nonconducting state by the reversal of the line polarity.

A data rate of 15 Baud gives each bit a time duration equal to that of four cycles of a 60 Hz waveform. For data transmitted synchronously with the power frequency, natural commutation can be used and the waveforms and spectrum of Figure 9 developed. Natural commutation allows the use of thyristors for the switching with no requirement for forced commutation circuits.

For this communications experiment only the data components of the spectrum are of interest because that allows the use of a very simple receiver. The minimum receiver can be a suitable low-pass filter (Figure 8). Park (21) shows that a low-pass filter cut-off frequency slightly above the basic frequency present in the data is better for minimum receiver error. In this case, 9 Hz is suitable. A fourth order 9 Hz Butterworth low-pass filter has about 66 db attenuation at 60 Hz and a time response adequate for this application (30). In order to limit the 60 Hz voltage at the input of the filter, additional 60 Hz rejection is needed. Using these concepts a receiver was built that had the frequency response curve shown in

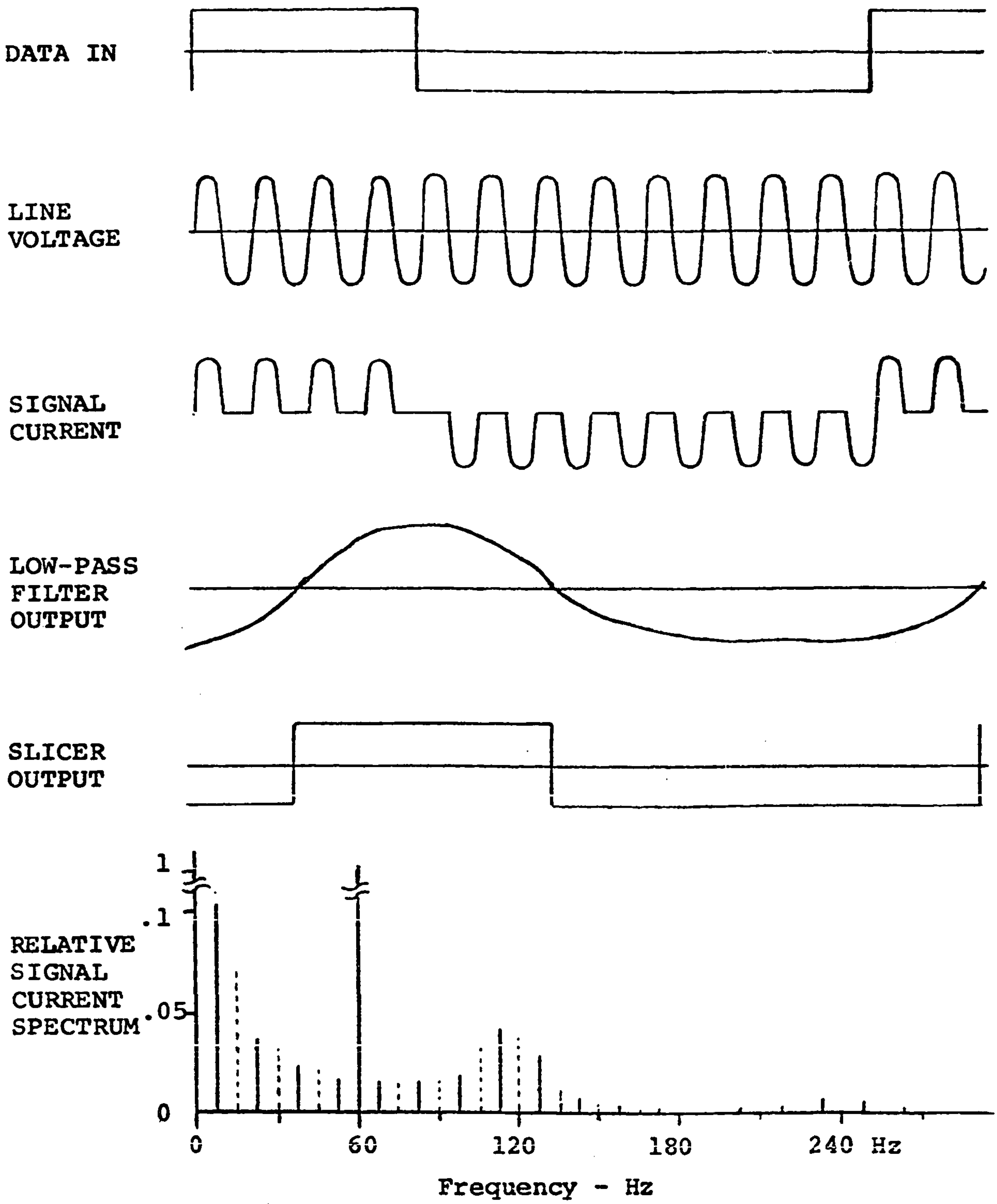

Figure 9. Waveforms and frequency spectrum for an approximation of 15 Baud data on a 60 Hz system

Figure 10. For data communications purposes it would be necessary to use a slicer or level decision circuit after the low-pass filter to convert the sinusoidal signal back to logic levels. A comparator or an operational amplifier set up for a gain of a few thousand would serve well. For a simpler experiment, the slicer need not be constructed.

An Upstream Communications Test Unit

The test circuit as implemented in the laboratory is shown in Figure 11. The resistor labeled R_{static} was necessary to prevent the complete floating of the transmitter circuit due to stray capacitances and leakage in the transformer. Without that resistor, voltage to ground was great enough to endanger insulation of the output transformer in the audio oscillator. The circuit commons were not directly connected in order to preclude stray signal ground currents. SCRs were used for switching elements because of their ease of natural commutation, simple gate drive circuits, and because the distribution transformer provides voltages of both polarities. The two diodes connected in parallel with the gate terminals of the SCRs allow the floating audio generator output to drive the gates in pushpull. R_N is a load whose value was varied to provide a normal load on the distribution circuit while R_L is the load resistor that is

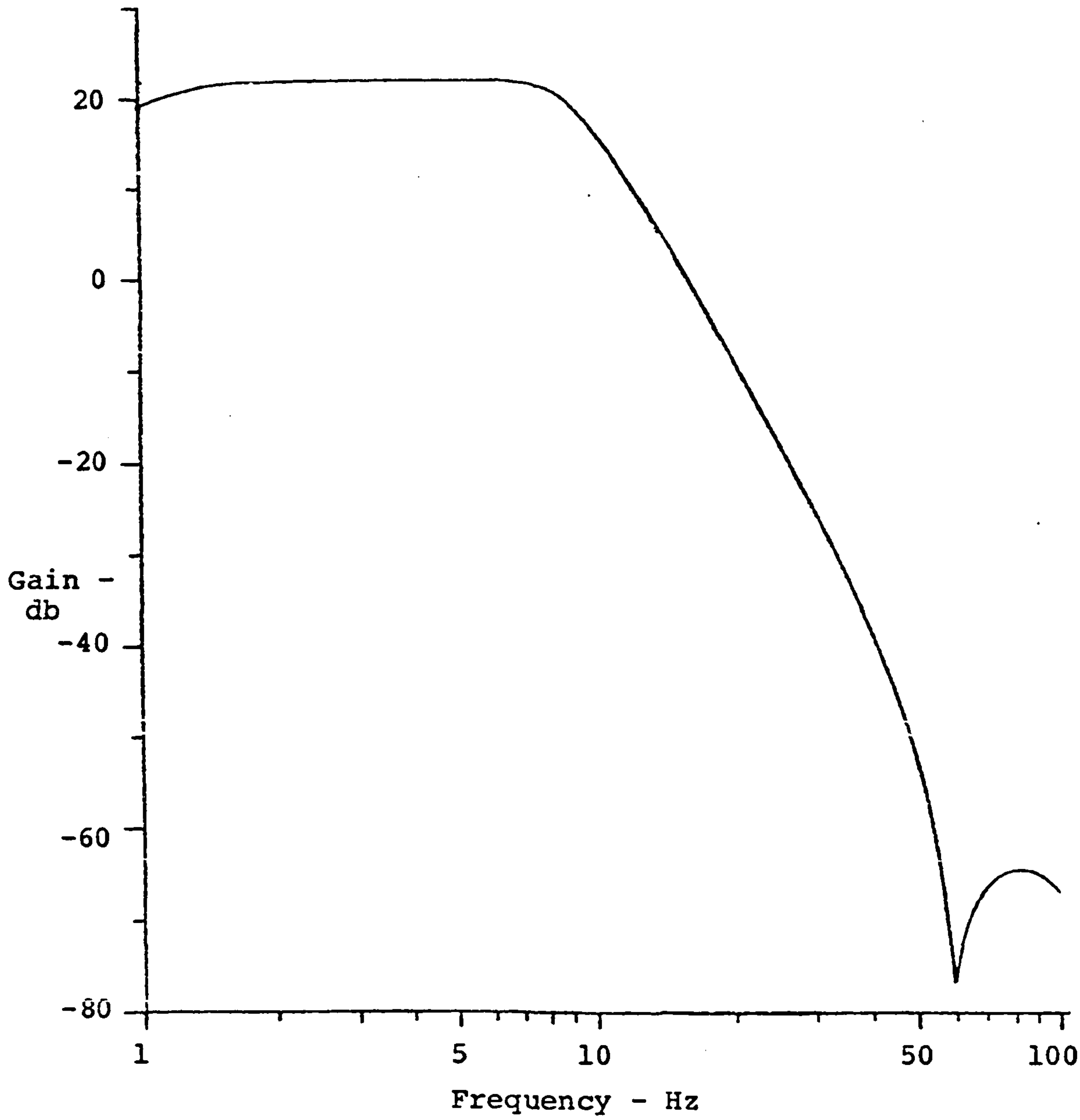

Figure 10. Frequency response of the receiving filter

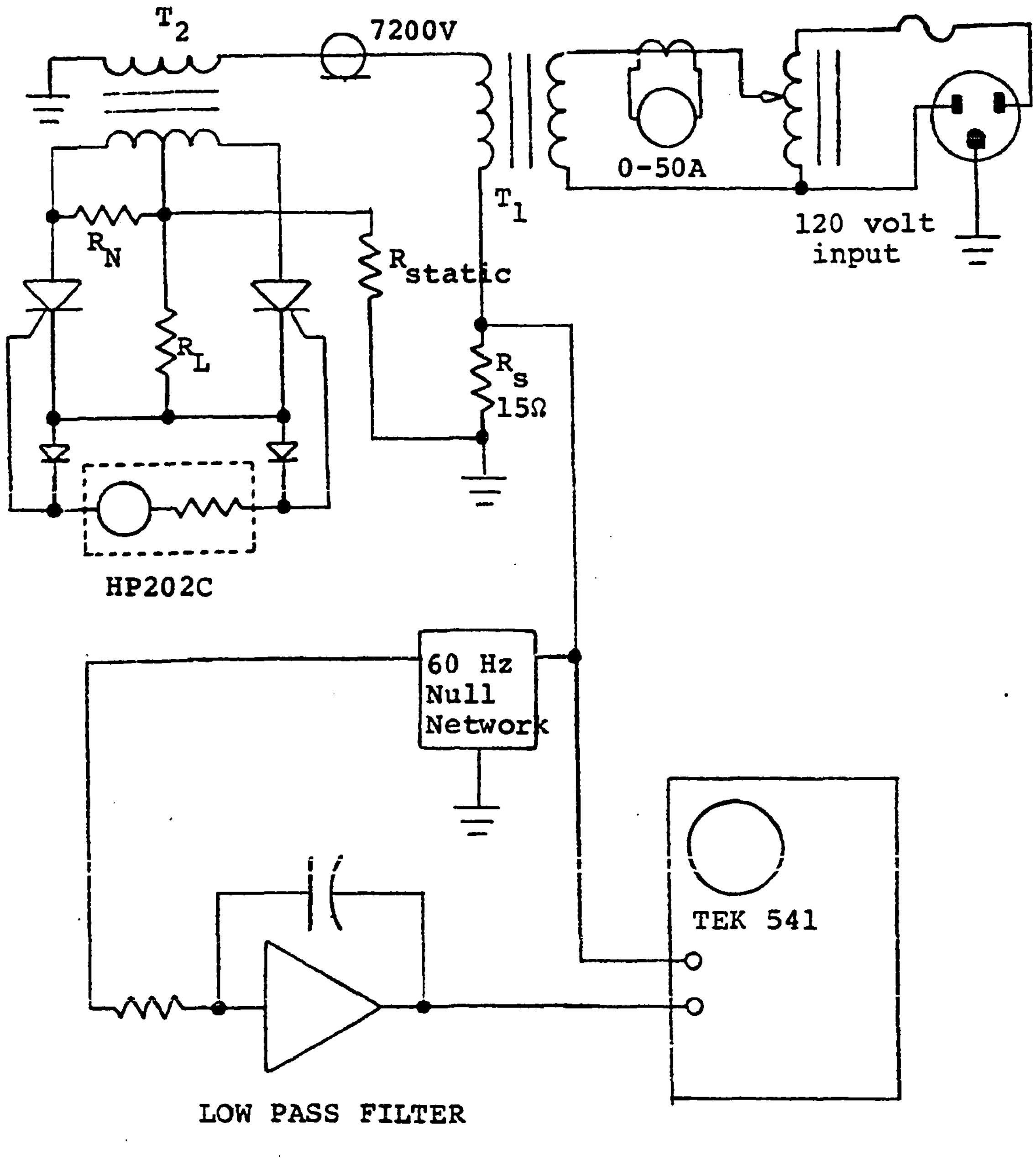

Figure 11. An experimental circuit for upstream data communications

T_1 and T_2 are Westinghouse 3 KVA 7200/240/120 volt distribution transformers. The distribution circuit (7200 V) is in 15 KV cable with a concentric neutral. The SCRs are Motorola type HEP-306.

switched in order to generate a communications signal. Due to the back leakage currents of the SCRs when forward biased, large values of R_L resulted in signal currents smaller than expected. The largest value successfully used for R_L in this experiment was 7150 ohms. Larger values doubtlessly could have been successfully used if the back leakage currents of the SCRs were blocked with diodes. The poorest signal to noise ratio experienced was with R_L = 7150 ohms and R_N = 11.5 ohms (a 1320 watt heater). At that point the signal out of the filter was composed of about 20 mv peak to peak of 7.5 Hz with 5 mv of 60 Hz ripple and 10 mv of low frequency random noise. The voltage into the filter was about 8 volts peak to peak and on the oscilloscope appeared as purely 60 Hz (Figure 12). The 20 mv p-p output of the filter requires 1.6 mv of signal into the filter so the signal to noise ratio before the filter is $(1.6 \times 10^{-3})/8 = 2 \times 10^{-4} = -74$ db. (See Table 1.)

Prospective Performance on a Full-Scale Distribution System

In a 7.2/12.5 KV substation with a 3 MVA capability, the 60 Hz unbalance current in the neutral could be as high as 100 amperes. Thus a signal to noise ratio at the filter input of -74 db would require a signal current of 20 ma in the 7200 volt line which would be a signal current of 1.2 A

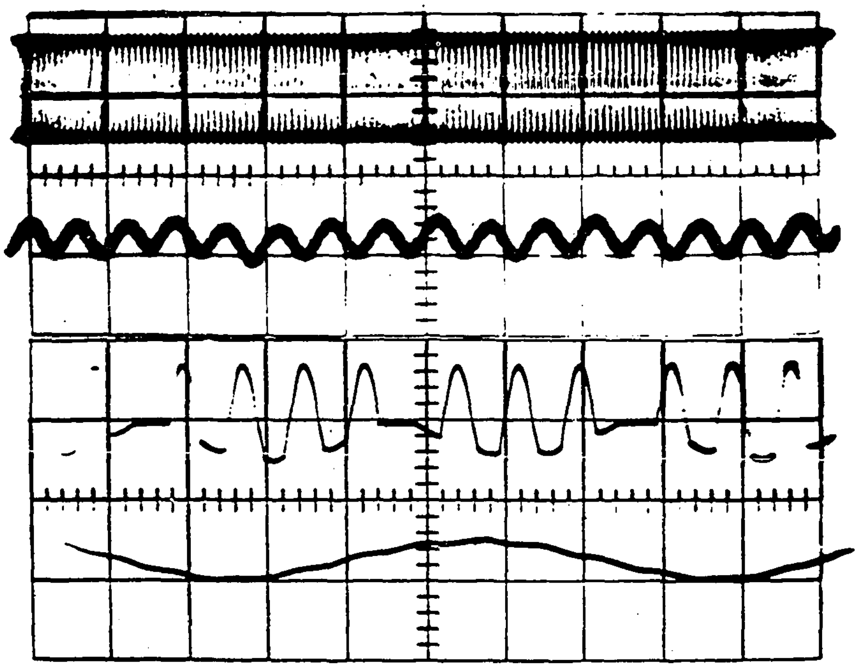

Figure 12. Waveforms from Figure 11.

R_N = 11.5 ohms. R_L = 7150 ohms.
R_S = 15 ohms.
Top trace: current in 7200 volt circuit. Sweep rate 0.1 second per division.
Second trace: output of low pass filter. Low frequency and 60 Hz noise are visible components. Vertical sensitivity = 0.05 volt per division. Sweep: 0.1 second per division.
Third trace: voltage applied to R_L. Vertical sensitivity = 200 volts per division. Sweep: 0.02 second per division.
Bottom trace: same as second trace with sweep at 0.02 second per division.

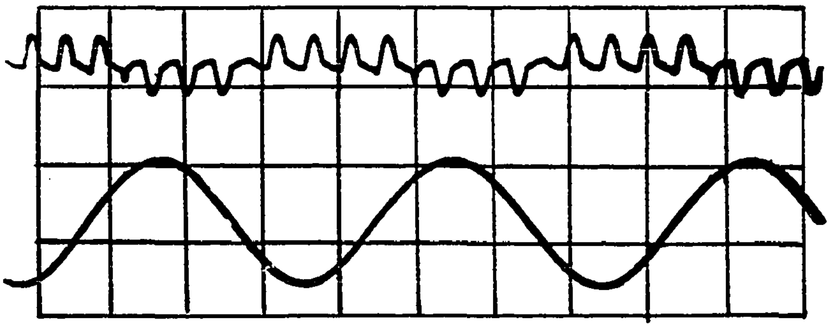

Figure 13. Waveforms from the circuit of Figure 11

Upper trace: Current in 7200 volt circuit with the effects of transformer excitation currents minimized. Half cycles are from 60 Hz current. R_N open circuit.
Lower trace: Low pass filter output. Same sweep speed as upper trace.

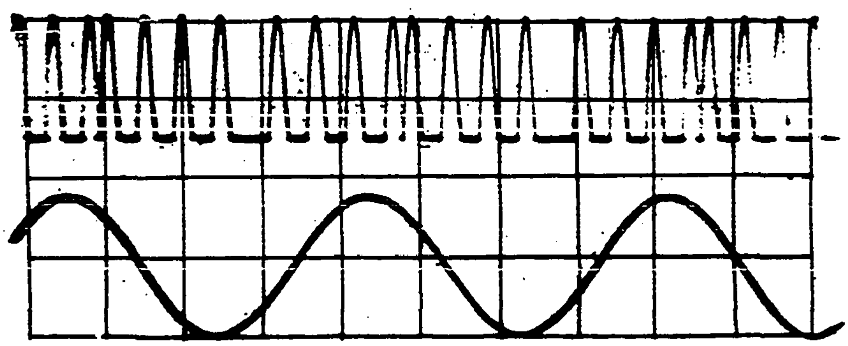

Figure 14. Waveforms from the circuit of Figure 11

Upper trace: current in R_L.
Lower trace: same as lower trace in Figure 13 above.

Table 1. Data taken in the circuit of Figure 11

R_L	R_N	R_S	I_{SUPPLY}	I_{7200V}	V_{LOAD}	V_{OUT} 7.5 Hz	V_{OUT} 60Hz	V_{OUT} Noise
270Ω	11.5Ω	2Ω	11.7A	.55Ap-p	110V_{RMS}	0.2Vp-p	--	--
630	11.5	2	11.6	.55	110	70mVp-p	--	--
3150	11.5	2	11.6	.55	110	12	--	--
3150	11.5	15	11.5	.53	110	70	--	15mVp-p
7150	11.5	15	11.6	.55	110	20	5mVp-p	15
16000	11.5	15	11.6	.55	110	0	5	15

in the 120 volt line at the load. When the value of R_L in Figure 11 was set to 50 ohms, a 7200 volt line signal current of 80 ma was generated. With the 15 ampere SCR's used in this experiment two 11.5 ohm heaters were successfully switched in parallel and the output voltage from the filter drove the amplifiers to saturation at ±20 volts or 40 volts peak to peak. Obviously in a system with larger currents than in the laboratory system, a much smaller sampling resistor and lower filter amplifier gain would be adequate (and necessary). Signal recovery was similarly effective when the filter was connected across a 1 ohm burden replacing the ammeter in Figure 11. Except for the greater magnitudes of excitation components (for both transformers) all observed waveforms were the same as in the 7200 volt circuit.

There is a difficulty in transmitting data upstream in the above manner. It is not possible before testing a particular communications path to determine the polarity of the received signal. That is, mark and space will be of opposite polarity but it is not possible due to random distribution transformer and secondary service wiring polarity to predict, in advance, the sign of the receiver output that will correspond to mark. This difficulty can be overcome. One way of overcoming the difficulty is to test and adjust each installation as installed. Another way is by means of data coding. If the bit length of a mark, for example, were considerably longer than that of a space, random data would average out to a mark. The receiver logic could then use that long time average to determine the polarity for mark. A third method is to use a preamble on the transmitted data that consisted of a character with all bits marking and use that preamble to set the receiver polarity.

Operation in Power Distribution Systems Having Connections other than Wye

Upstream communications was designed for and tested in a wye connected distribution system because of the ease of analysis of a single phase of that system. It is common for wye connected systems to be supplied by a transformer with a delta connected primary. This delta-wye transformer connection has several purposes. The delta-wye connection confines zero-sequence currents and neutral shift to the distribution system. The delta connected windings provide a circuit for third harmonic currents so that such currents are not drawn from the transmission system even though these currents are present in the distribution system. The first feature very effectively interrupts upstream communications paths that use zero-sequence signals. Often this isolation effect can be put to good use to allow the use of the same communications frequencies in adjacent distribution systems with no mutual interference. This isolation is commonly used in ripple control systems for similar reasons.

Transformer and distribution system connections other than wye do not lend themselves to upstream communications as readily as the wye distribution already discussed. However, similar techniques can be used, generally at the expense of more complex receiving apparatus. For example, for a delta connected system, the analogous current transformer connection for single phase currents consists of three current transformers. The secondaries of the three transformers are connected in series to one receiver. The primaries are connected in each leg of the delta connected distribution transformer as shown in Figure 15. Since it is the normal practice of transformer manufacturers to connect the delta inside the transformer and only bring out the connected windings such a circuit would be difficult to add to a transformer in the field.

It is possible for the substation transformer secondary to be wye connected while some distribution transformers have delta connected primaries connected to the wye distribution. These distribution transformers will prevent upstream (or downstream) communications through them when the signaling is by zero-sequence currents (or voltages). Ways

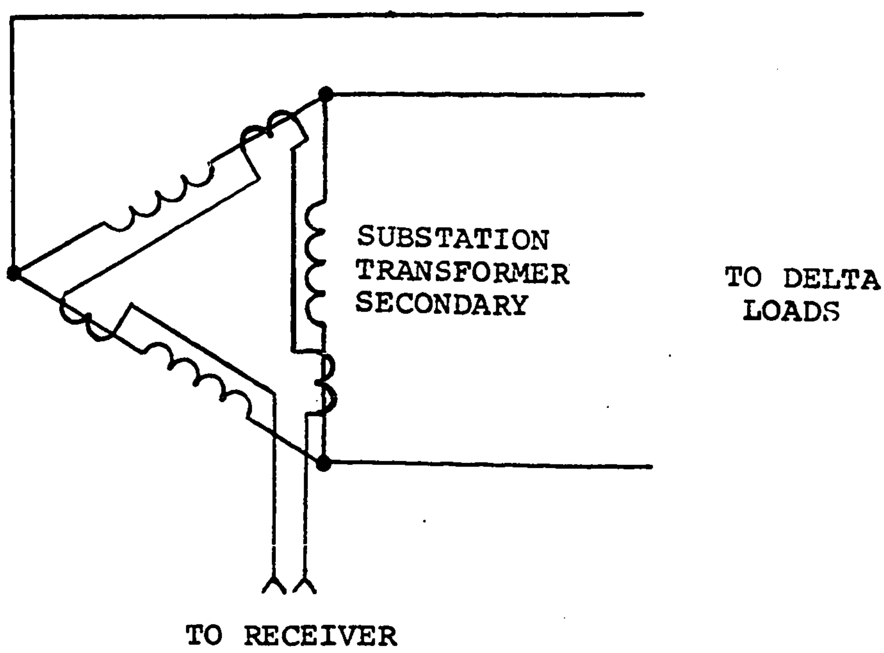

Figure 15. Current transformer connections for an upstream communications receiver on a delta connected distribution system

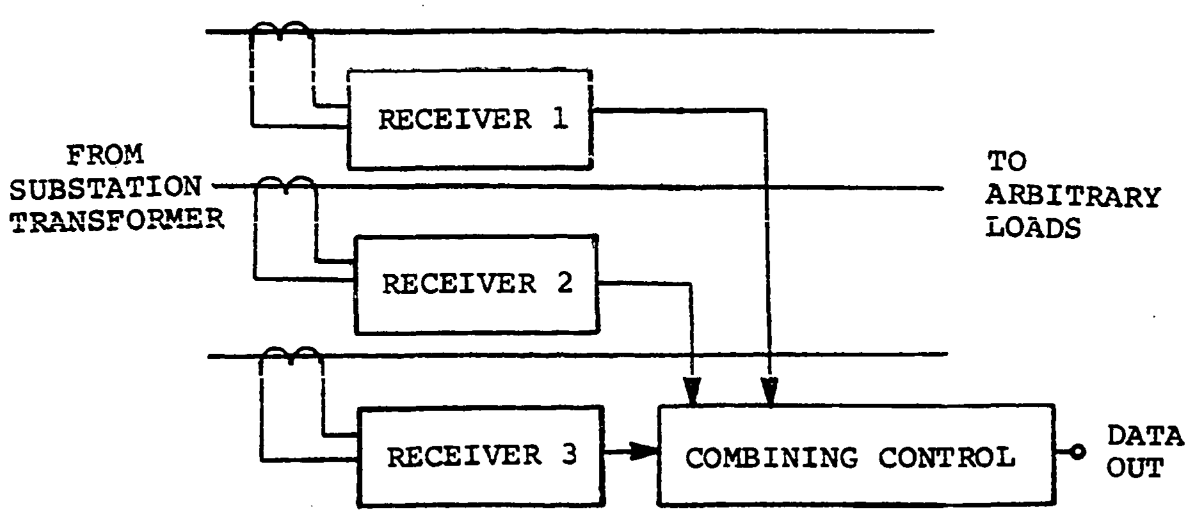

Figure 16. Connections of upstream communications receivers on distribution systems having mixed types of source and load connections

to communicate past them with low frequency signals as used in ripple control and the method of this dissertation include the use of single phase (line to line) signals and/or replacing the transformers with delta-delta or wye-wye connected transformers.

Delta connected loads on wye distribution present difficulties to upstream communications also since the delta load cannot possibly generate signals in the neutral. Signals generated in the distribution transformer secondaries will, however, be present in the distribution line currents. If the phases that supply a particular single phase delta connected load are known, only one receiver is required for reception of communications from that load. The current transformer can be connected in either phase conductor feeding that load. Three separate receivers are needed for full coverage since the single phase current in one line conductor will be exactly out of phase with the single phase current in another conductor serving that load. For operation without advance knowledge of the load phase connections, the logic outputs of the three individual receivers would have to be compared and the data taken from those two receivers whose outputs were out of phase. Such a connection (shown in Figure 16) can be used for arbitrary source and load transformer connections so long as the desired communications path is not interrupted by delta-wye transformers. This connection does not take any advantage of the system balance in the neutral or of the three current transformers in the delta source connection to reduce the 60 Hz input to the receiver filter. Thus more effective 60 Hz rejection filters may be required. Simple 60 Hz rejection filters with over 100 db attenuation ($V_{out} = 10^{-5} V_{in}$) have been constructed in earlier parts of the author's research (12).

POTENTIAL APPLICATIONS

There are numerous applications for a reliable and inexpensive upstream communications path from the periphery to a central point on the electric power distribution system. One is the remote metering of utility customer meters for billing. Such a system could combine ripple control techniques (5, 7, 12, 15, 17, 25) for sending "read" commands to a particular meter and then use the system of this dissertation to transmit the meter number and meter reading to the substation where the data could be recorded or sent to the billing computer by other means. Several modes of operation are possible. One might broadcast a command to all meters causing them to store the meter reading at that instant for later retrieval and then gather the stored readings one at a time. For a simpler meter, one might not put any storage in the meter and simply take the data available at the instant of transmitting the reading. This would not allow a precise time of day for all customer readings. A precise time of day for all customer readings is desirable for meter reading applications where multiple or "time of day" rate schedules are being used. The logic designs for either design can be realized with hardware that is on distributors' shelves at no great expense per unit. For large quantity systems the logic could be fabricated in custom integrated circuit at low cost for either design. The logic required is very similar to the logic in computer peripherals using common data and device code busses. Westinghouse Electric meter division has constructed watthour meters with logic built in for the major functions required in a remote meter reading system (6). At the last inquiry such a meter was not available for sale separate from their remote metering system.

When using ripple control to switch power factor correcting capacitors, it is useful to verify that the switch operation has actually occurred. Some potential purchasers of remote metering equipment desire additional functions to the system, mainly the capability of remotely disconnecting and reconnecting the customer service. The logic required for such additions is minimal but the cost of the switch itself would be significant.

A communications system that reaches into virtually every home, office, and hideaway could be useful for "big brother" surveillance activities so long as the authority was satisfied with the digital data and the rate capabilities of this system. Of course since the power system is actually shared between many homes, only a limited number on a given system could be observed closely or only a very limited amount of data could be obtained from many. Or more practically, such a surveillance capability could be used for security purposes such as detection of forced entries, fires, and medical emergencies. A cable TV installation near Phoenix, Arizona, with a two way capability is offering these services in addition to potentials for remote meter readings (4). That cable system's developer foresees extension to such functions as remote control of lights, sprinkler valves, and motors as well as the more sophisticated functions of shopping, education, banking, and opinion polling. All of the proposed capabilities of two way television cable can be implemented on a power distribution system by use of the upstream communications technique of this dissertation in combination with ripple type downstream communications system having improved speed capabilities such as demonstrated in the author's prior research (12).

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APPENDIX A: UPSTREAM DATA TRANSMITTERS THAT DID NOT WORK OR DID NOT WORK WELL

The author's earliest attempts to impress a current on the power distribution system for communication involved the use of amplifier circuits optimized for the generation of currents. A circuit that was used is the Howland circuit shown in Figure 17. This circuit which was derived from an analog computation circuit is an excellent current source. However, after a short period of successful operation, both transistors of the output stage and the 1 ohm resistor in the positive feedback circuit were destroyed, and the power supply was saved only by its load fuse. In the search for simpler current sources, the Howland circuit was set aside. The Howland circuit requires a balancing adjustment of the positive and negative feedback paths to produce the desired current source effects. This adjustment, though not difficult to make, is not a desirable attribute of a simple production circuit. In addition, the amplifier in the Howland circuit provides all of the power that is dissipated in the positive feedback path, as well as the power supplied to the load from the current source. The overall result is a rather inefficient way of heating the resistors.

Another circuit that was used to inject a current into the ac line is shown in Figure 18. This circuit has fewer dissipative elements and therefore should have a greater

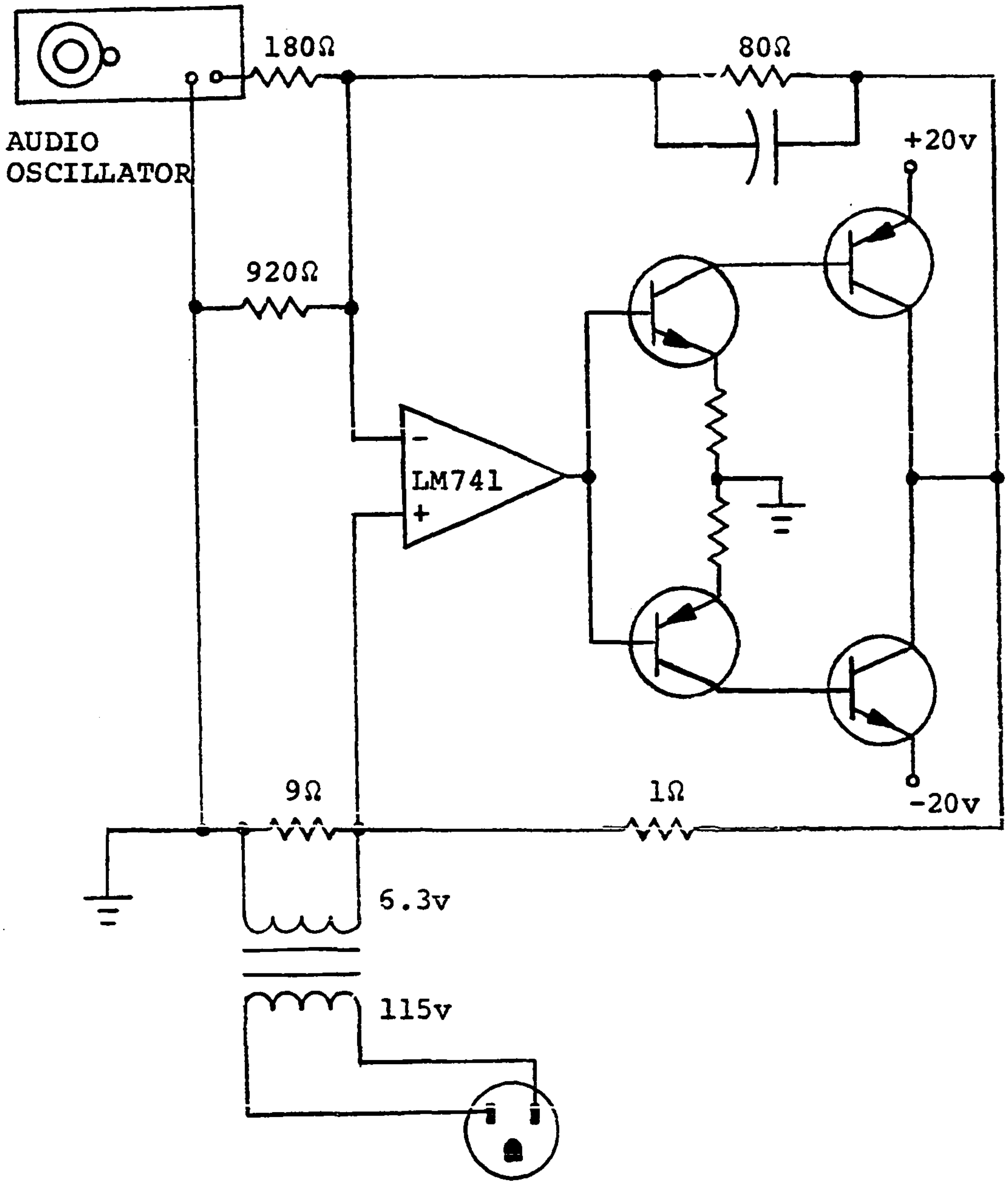

Figure 17. A power Howland circuit

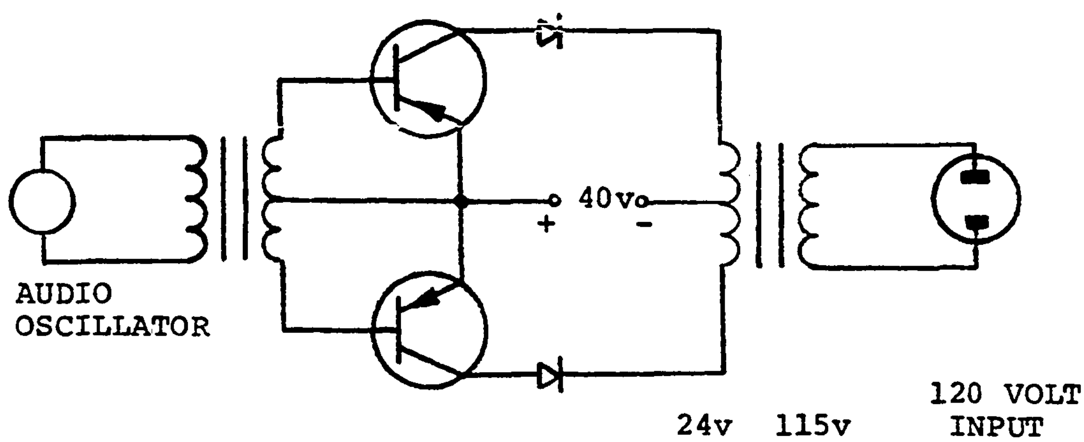

Figure 18. A direct collector current source

efficiency in converting dc power to signaling current. The operation of this circuit depends upon the inherent constant current nature of the collector of the bipolar transistor. It successfully produces a signal current with minimal 60 Hz current in the output circuit. The circuit is simple and there are no adjustments.

This circuit has the added possibility of being constructed with transistors having a sufficiently high voltage rating to allow direct connection to the ac line dispensing with the output transformer. Tests with the transformer coupled circuit produced currents a little less than 1A into the power line. However, like the Howland circuit, this circuit also had a short operating life. One transistor, its emitter resistor, and the power supply fuse were destroyed. Low cost transistors for construction of the direct coupled circuit were acquired but the circuit was not implemented once the reason for failure was understood.

Both of the above circuits fail for the same reason. The culprit is transistor dissipation. In an ordinary power amplifier circuit (such as shown in Figure 19) the load is of such a nature that when a transistor collector draws current, the collector voltage decreases, and the power dissipation in the transistor is relatively low. However, in the current sources driving an active load (Figure 19)

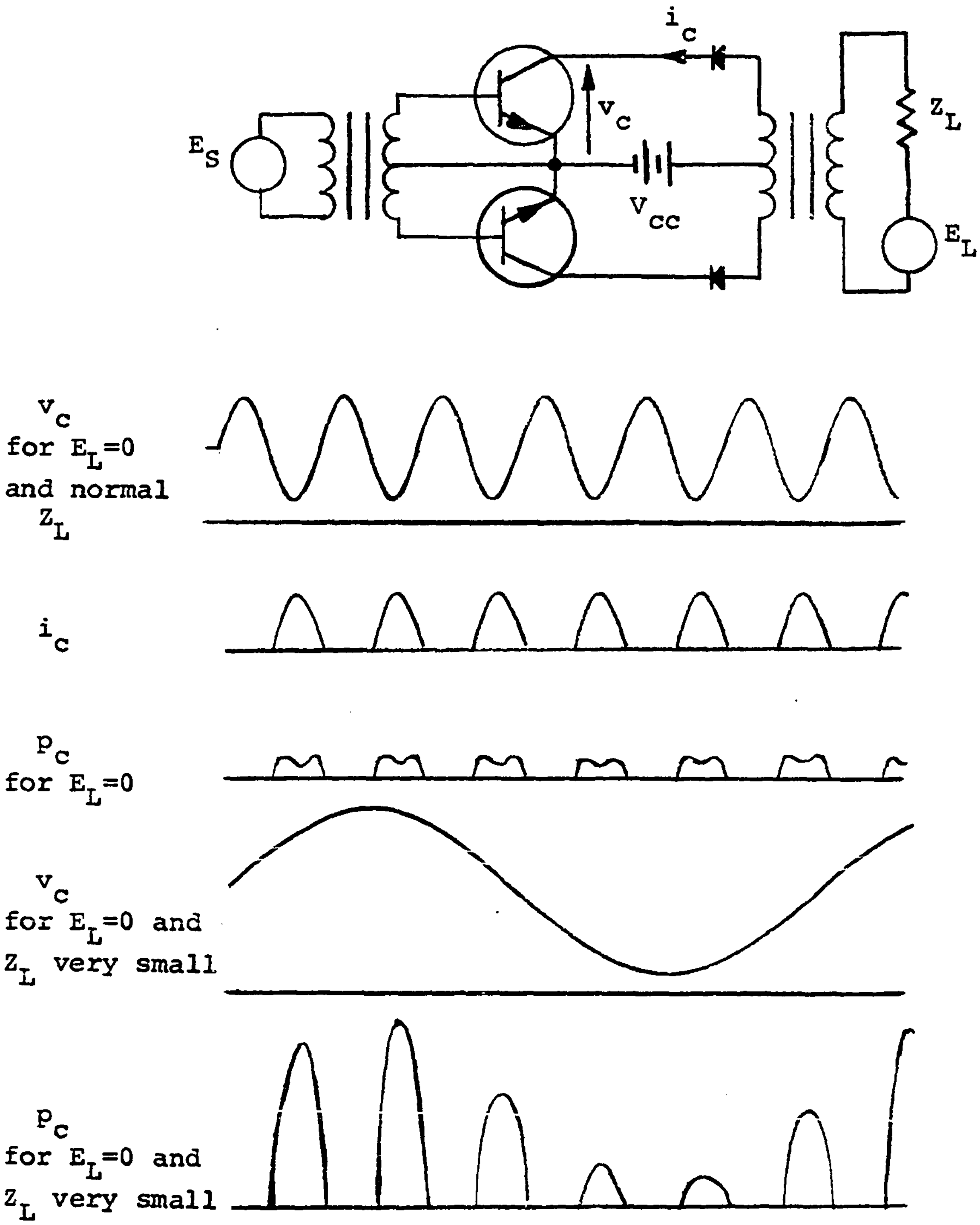

Figure 19. Waveforms and instantaneous collector dissipation (p_c) in a direct collector current source

the collector voltage is dependent only upon the active load voltage, while the collector current depends only upon the base current drive to the transistor.

With the current and the voltage having different frequencies, the result can be high power dissipation in the transistors. The experimental consequence of that high dissipation has continually been a melted junction in a power device, which almost always generates a short circuit. Then one must add a fuse to the power circuit to protect the rest of the distribution system from the blown transistor. Further investigation was made into circuits using low dissipation devices such as SCRs and reactive coupling circuitry in order to provide high reliability at low cost.

An experimental SCR inverter current source is shown in Figure 20. Between component failures, this circuit was capable of generating 90 Hz signal currents of up to 5 amperes. The 10 mfd capacitor and the 1 mhy inductor allow commutation of the SCRs. Circuit failures usually immediately followed failure to commutate caused by the 60 Hz voltage in the circuit upsetting the energy storage of the commutating capacitor. Fortunately the power supply was fused thereby limiting the effects of having both SCRs conducting continuously together. This circuit performed extremely well into passive loads. The 1 mhy choke was designed and constructed by the author with a dc current rating of 20A

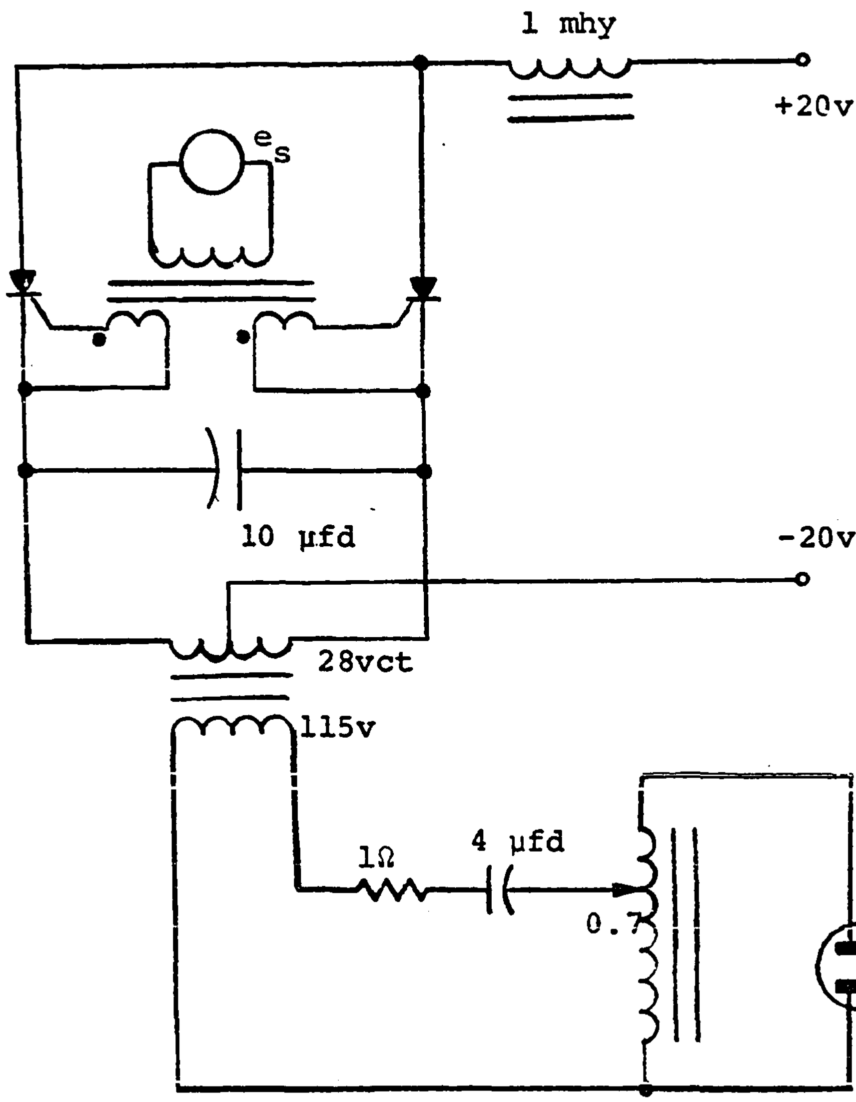

Figure 20. SCR inverter current source

but in operation the core heated excessively. It was found that the peak current was on the order of 50A; therefore the air gap in the core was increased and the excessive heating ceased to be a problem.

While testing the SCR inverter signal source, a small kilowatt-hour meter was connected in the signal line to determine the effects, if any, of the signal current on the meter indication. It was found for signal frequencies that were exact odd multiples of 30 Hz that the meter rotor was stationary but that as the signal frequency moved toward a multiple of 60 Hz (including 60 Hz) that the rotor would drift in one direction or the other. The KWH meter load did not include the dc power supply feeding the SCR invertor.

All work preceding that reported in the body of this dissertation was towards the use of a carrier frequency of 90 Hz for upstream communication. It was planned to transmit data with that 90 Hz carrier by means of Phase Shift Keying, that mode having been long proved to be most effective in the face of noise. When work was directed toward generating of communications signal by interrupted loading rather than by standard signal sources, the waveforms of Figure 21 were derived. Using a graphical Fourier analysis of the signal waveforms in Figure 21 it was ascertained that the 90 Hz component amplitude was about 40 percent the amplitude of

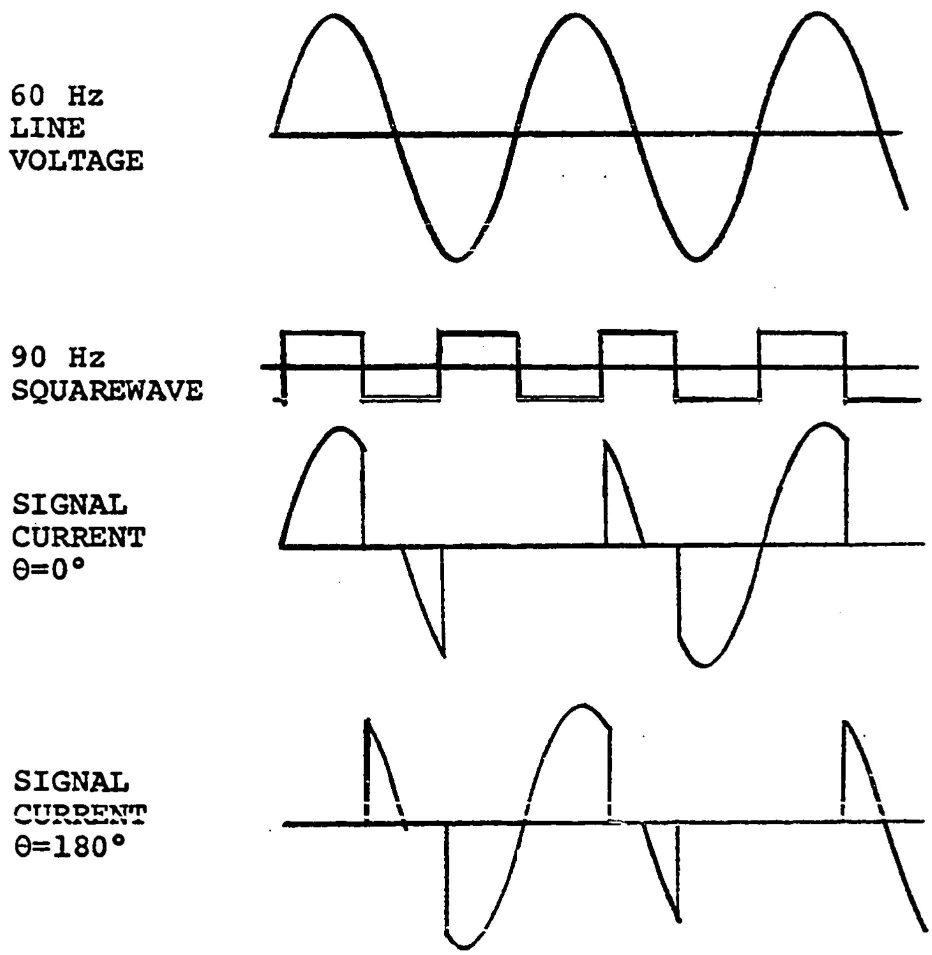

Figure 21. Waveforms for 90 Hz phase shift keying interrupted load

the 60 Hz component. Though such a signal could be generated by the circuit of Figure 7, implementation proved to be difficult while maintaining circuit simplicity. The major problem in using thyristors for switch was in getting the devices to stop conducting before the next zero-crossing of the line voltage waveform.

More recent experimental work used variations on an SCR chopper circuit to attempt to develop signaling currents on the power distribution system. The basic Jones chopper circuit (8) is shown in Figure 22. In this circuit (which is used for supplying pulses of dc to the load R_L) SCR is driven to supply dc to the load. To stop conduction in SCR 1, gate drive is removed from SCR 1 and SCR 2 is driven. SCR 2 uses the energy stored in the capacitor by SCR 3 to back bias SCR 1 and thus cause it to stop conducting. SCR 3 (triggered with SCR 1) charges the capacitor with a voltage developed across the lower portion of the auto-transformer by the rapid change in current when SCR 1 begins to conduct. In some variations of this circuit, the auto-transformer is allowed to saturate thereby limiting the voltage supplied to the capacitor and making the capacitor voltage less dependent upon the load current. To use this circuit for the relay of Figure 7, one could use two similar circuits constructed with opposite polarity. In order to minimize the use of large components, the author chose to

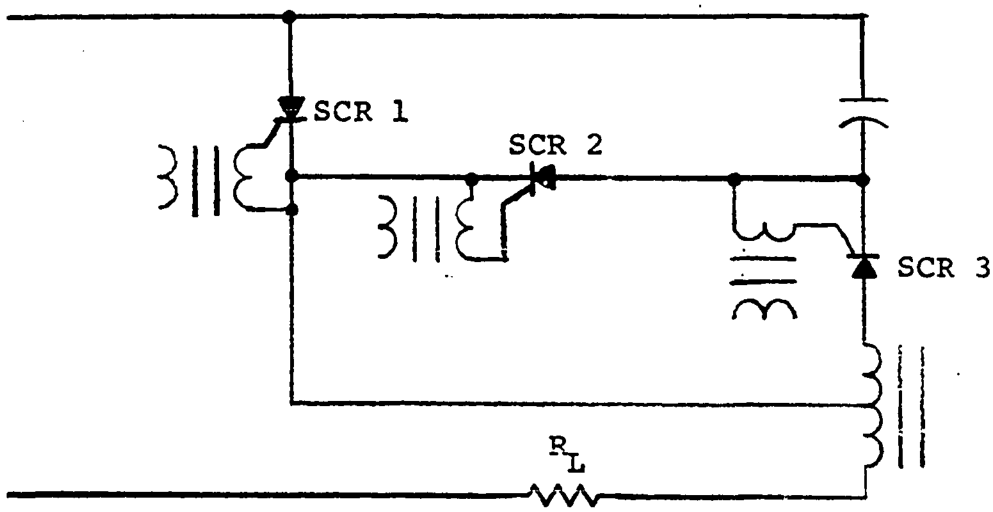

Figure 22. Jones chopper circuit

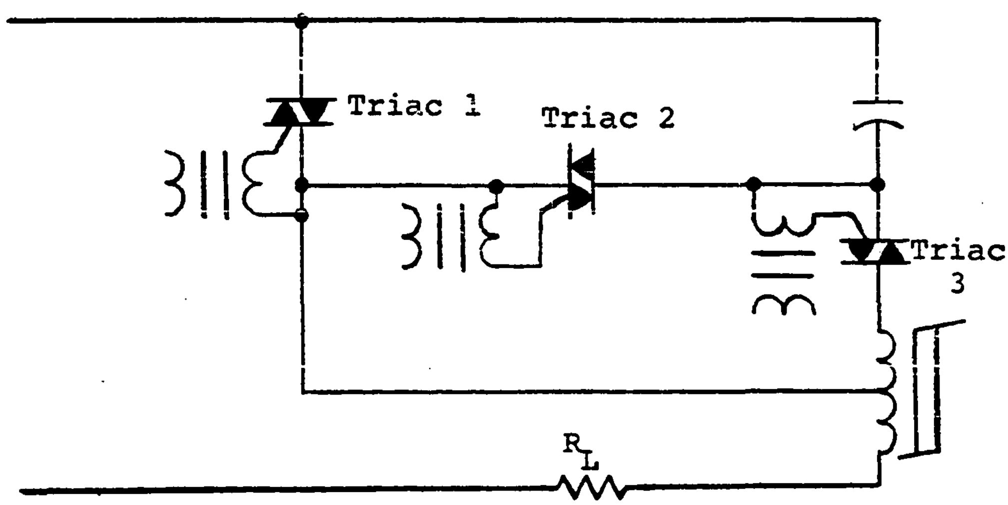

Figure 23. Bipolar modified Jones chopper circuit

convert the Jones chopper to ac by replacing all three SCRs with triacs which are essentially two SCRs having a common gate terminal with the main terminals connected in parallel with opposite polarity. With the ac supply, it was presumed that the ac voltage drop across the autotransformer could be used to charge the capacitor for commutation. It was found that if commutation (Figure 23) were desired during the half cycle that triac 1 and 3 were turned-on and if turn-on had not occurred at too low a voltage (in other words if there was a turn-on transient) that the circuit would commutate. Unfortunately, the waveform desired for communications as shown in Figure 21 required forced commutation generally only in half cycles where conduction began at a supply voltage zero-crossing where there was no turn-on transient current to charge the capacitor.

A circuit that partially overcame the commutation difficulty is shown in Figure 24. In this circuit, the triac is reverse biased through the 75 microhenry inductance to cause the triac to stop conducting. At each zero-crossing of the 60 Hz, the commutating capacitor is charged by SCR 3 or SCR 4 to provide the energy required to cause commutation of triac 1 if commutation is desired during that half cycle. The circuit was operated with a single floating power supply and, for commutations of that polarity, was successful. Since another floating power supply was not readily at hand

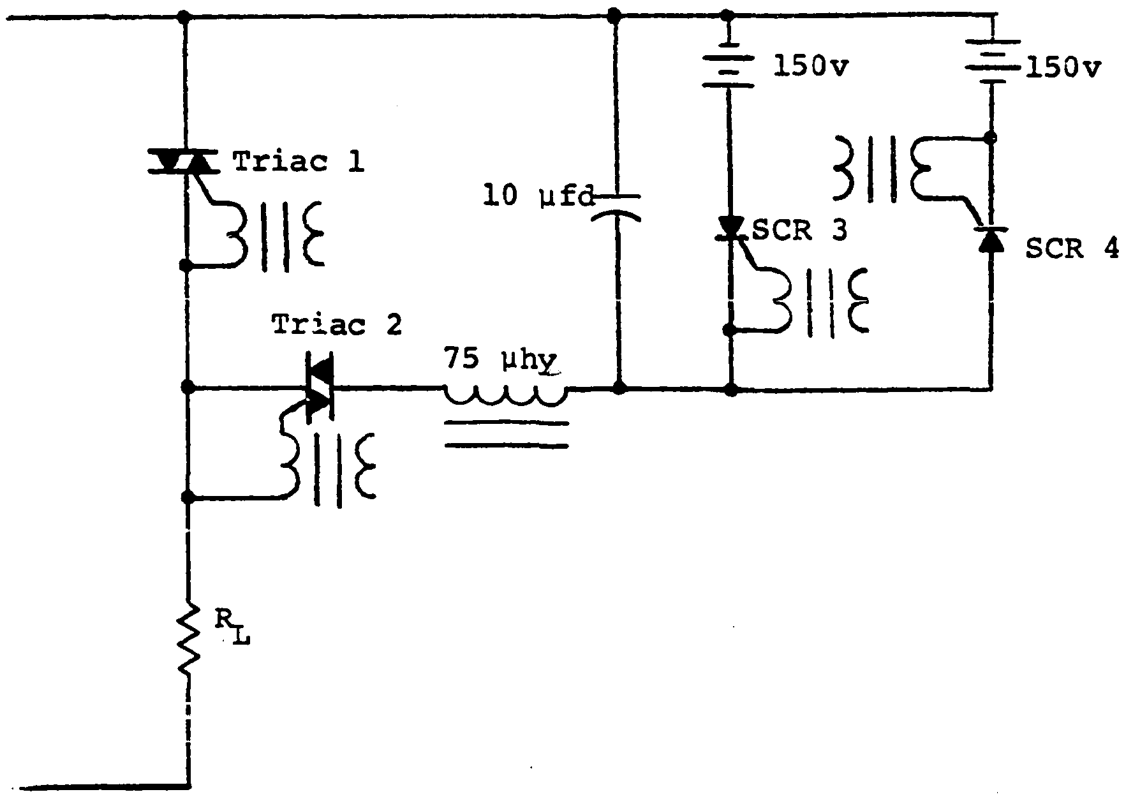

Figure 24. A triac forced commutation circuit

and because the single supply was supplying only commutating energy but was at its current limit of 0.5A, experiments with this circuit were discontinued. Another reason for discontinuance was the complexity of the control logic required. This circuit complexity was not in keeping with the simplicity desired of this research. The logic circuit that provided gate drive to the thyristors and provided for phase shift keying of the signal used: 6 Nand gates, 2 invertors, 2 EXCLUSIVE-OR gates, 3 toggle flip-flops, 1 divide by 6 three bit counter, 1 phase locked loop integrated circuit, 4 programmable unijunction transistors, and 7 individual transistors, as well as one 5 volt power supply. After this circuit was set aside, the circuit described in the main body of this dissertation was developed.