The Characterization of Residential Impedences and Noise Sources for Power Line Communications

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THE CHARACTERIZATION OF RESIDENTIAL
IMPEDANCES AND NOISE SOURCES FOR
POWER LINE CARRIER COMMUNICATIONS

by
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THE CHARACTERIZATION OF RESIDENTIAL IMPEDANCES AND NOISE SOURCES FOR POWER LINE CARRIER COMMUNICATIONS

by

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A thesis submitted to the Graduate Faculty of North Carolina State University at Raleigh in partial fulfillment of the requirements for the Degree of Master of Science

DEPARTMENT OF ELECTRICAL ENGINEERING

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Approved by:

________________________________________

Chairman of Advisory Committee
ABSTRACT

VINES, ROGER M. The characterization of residential impedances and noise sources for power line carrier communications. (Under the direction of Dr. R. J. Trussell)

Residential impedances on the distribution transformer secondary and noise output of appliances from 5 to 100 kHz were investigated. Impedance measurements were made of distribution transformer secondary windings, electrical lines, electrical loads, and at four residences. Voltage and current spectra generated by typical residential devices were observed; and the noise output of two of these, the universal motor and the incandescent light dimmer, was measured and analyzed.

The impedance seen from the residence is determined by the distribution transformer, residential loads, and connecting lines. It was found to be resistive and inductive with a positive slope for increasing frequency at the lower frequencies. Resonances were observed at the higher frequencies.

The noise spectrum generated by the universal motor is flat with spectral lines whose frequencies are proportional to motor speed. The universal motor is a good current source so that the magnitude of the voltage spectrum is proportional to the power circuit impedance. The light dimmer produces 60 Hz harmonic noise. Since the light dimmer circuit consists of the dimmer, a lamp, and the 60 Hz power circuit in
series, the magnitude of the voltage is determined by voltage division between the power circuit impedance and the lamp and light dimmer filter impedances.
BIOGRAPHY

Roger Mack Vines was born December 19, 1952, in Richmond, VA. He attended primary and secondary school in Richmond and graduated from J. R. Tucker High School in 1971. He attended Virginia Polytechnic Institute and State University for one year, served three years in the U. S. Army Security Agency, and returned to VPI and SU to receive his bachelor's degree in electrical engineering in 1978. In that year he began employment with Western Electric Company in Burlington, NC. In 1980 and 1981 he attended evening classes in electrical engineering at North Carolina A. and T. State University in Greensboro, NC. In 1981 he resigned from Western Electric Company and entered graduate school at North Carolina State University in Raleigh, NC. Along with taking coursework he instructed an electrical engineering undergraduate problem session and worked as a research assistant for NCSU before accepting part time employment with Carolina Power and Light Company.

The author is married to the former Sharon Gail Pauls and has one daughter, Maury Anne.
ACKNOWLEDGEMENTS

The author wishes to thank Dr. R. J. Trussell and the other members of the power line carrier research group at N. C. State University; Kay Clinard, Lou Gale, and the other members of Distribution Engineering Design Research at Carolina Power and Light Company; Gene Hayden, Tony Pennisi, Barry Poteat, and Ken Shuey of Westinghouse Electric Corporation; and Dr. J. B. O'Neal, Jr. of N. C. State University for their support of this research.
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LIST OF SYMBOLS

Hz  Hertz
kHz Kilohertz
PLC Power Line Carrier
EMC Electromagnetic Compatibility
nF Nanofarad
kvolt Kilovolt
KVA Kilovolt-Amp
kohm Kilohm
AWG American Wire Gauge
Zo Characteristic Impedance
L Inductance
C Capacitance
AC Alternating Current
uH Microhenry
hp Horsepower
uF Microfarad
m Meter
f Frequency
pi 3.14159...
LISTN Line Impedance Stabilization Network
rms Root Mean Square
FFT Fast Fourier Transform
dB Decibel
DC Direct Current
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<td>rpm</td>
<td>Revolutions Per Minute</td>
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<tr>
<td>dBE</td>
<td>Decibel Referenced to an Engineering Unit</td>
</tr>
<tr>
<td>dBV</td>
<td>Decibel Referenced to One Volt</td>
</tr>
<tr>
<td>dBA</td>
<td>Decibel Referenced to One Amp</td>
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<tr>
<td>dBOHM</td>
<td>Decibel Referenced to One Ohm</td>
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<tr>
<td>SCR</td>
<td>Silicon Controlled Rectifier</td>
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<tr>
<td>msec</td>
<td>Millisecond</td>
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<tr>
<td>V</td>
<td>Volt</td>
</tr>
<tr>
<td>usec</td>
<td>Microsecond</td>
</tr>
<tr>
<td>mV</td>
<td>Millivolt</td>
</tr>
<tr>
<td>sec</td>
<td>Second</td>
</tr>
<tr>
<td>≈</td>
<td>Approximately Equals</td>
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<tr>
<td>δ</td>
<td>Dirac Delta Function</td>
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<tr>
<td>∞</td>
<td>Infinity</td>
</tr>
<tr>
<td>j</td>
<td>Square Root of -1</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
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<tr>
<td>H</td>
<td>Henry</td>
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<tr>
<td>mH</td>
<td>Millihenry</td>
</tr>
<tr>
<td>Re</td>
<td>Real Part of Impedance</td>
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<tr>
<td>Im</td>
<td>Imaginary Part of Impedance</td>
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1. INTRODUCTION

Power line carrier (PLC) communication over distribution feeders involves placing transmitters and receivers at many points within the feeder network. An important location is the residence and is on the secondary side of the distribution transformer. Receivers and transmitters located at the residence can be part of a system which will provide functions such as load shedding and remote meter reading.

The characterization of the residential secondary circuit is a necessary step in understanding the communication channel between the residence and any other point on the feeder. The loads, lines, and noise sources of the residences constitute the network into which the transmitter and receiver are placed. The noise voltage generated at the power circuit by a noise source operating into that power circuit depends on the impedance of the power circuit. Knowledge of the residential network should lead to improved performance of PLC systems.

The frequency range into which most distribution PLC systems fall is from 5 kHz to 100 kHz with emphasis in recent years toward the lower frequencies. For this reason the impedance and noise measurements made cover this range, with more detail in the range of 5 kHz to 20 kHz.

This paper presents the methods and results of investigating the residential network. First, impedance measurements of distribution transformers, electrical lines, residential loads, and four residences are presented. Then, typical residential noise sources are characterized including an analysis of two common ones: the universal
motor and the incandescent light dimmer. Finally, the results of the residential impedance and noise measurements are presented, and conclusions of this investigation drawn. Appendix B describes the filters used to couple into the power circuit, and Appendix D lists the household devices used in this investigation.
2. IMPEDANCE MEASUREMENTS AND ANALYSIS

Impedance is an important characteristic to understand from the viewpoint of both Electromagnetic Compatibility (EMC) and Power Line Carrier (PLC) communications. For EMC, the impedance of the source of noise, input and output of the channel, and receiver of the noise as well as other characteristics of the source, channel, and receiver need to be known in order to analyze the network and predict the signal at the receiver [3],[12]. For PLC communications, the impedance at the residence is the driving point impedance into which the transmitter operates. By measuring impedances of the loads and knowing the transmission characteristics of the conducting paths between loads and the network configuration, impedances at any point in the network can be determined.

The network in this case is everything on the secondary side of the distribution transformer, i.e. on the secondary circuit. The loads include the secondary of the distribution transformer, and various resistive and reactive loads (which could be household appliances). The conducting paths are the cable which connects the distribution transformer to the house and the house wiring or whatever connects the loads together. For residences, the elements of the network can sometimes be readily determined. Since some devices are 120 volt devices and others are 240 volt devices, measurement of both 120 volt and 240 volt power circuits is of interest.
Impedance measurements of distribution transformer secondaries were made on five distribution transformers of different sizes with varying resistive loading. Measurements were also made of lines and loads commonly found in residential circuits. Finally, 120 volt and 240 volt impedance measurements were made at three houses and one apartment with different loads switched off and on.

The impedance measurements were made by forcing a voltage (through a filter) across two conductors of the secondary circuit and measuring the voltage across and current into the filter. The two conductors were line and neutral for the 120 volt measurements, and line and line for the 240 volt measurements. The elements of the filter were then "subtracted out" to give the true driving point impedance looking into the two conductors. This is discussed further in Appendix C. Frequency was stepped from 5 kHz to 20 kHz in 1 kHz steps and then to 50 kHz and 100 kHz for a total of eighteen discrete frequencies. The data has been plotted and each curve, representing one measurement, consists of sixteen closely spaced points (the impedances at 5 kHz to 20 kHz in 1 kHz steps) followed by the other two points (the impedances at 50 kHz and 100 kHz). Refer to Appendix C for more details on the impedance measurements. Since the residential measurements were made on residences in use, the impedances seen there were changing constantly as loads were switched on and off. Measurements of specific load effects were repeated to insure that the effects measured were of the load in question and not of an unknown load having been switched on or off during or between measurements. Single phase loads were used for the
120 volt measurements, and balanced 240 volt loads were used for the 240 volt measurements.

The results are that the impedances observed at the residences can be determined or explained by considering the elements in the secondary circuit. The distribution transformers of the residences could not be disconnected and examined unenergized, and access to each residence on the secondary circuit as well as knowledge of the loads in each house on the secondary circuit could not be obtained. Thus, the impedances seen could not be exactly predicted; however, a survey of the impedances of transformers, motors, televisions, etc., allow the observed impedance behavior to be understood.

To summarize the results, the impedance of a normally loaded distribution transformer is generally a few ohms with an angle greater than 60 degrees at 10 kHz, and its magnitude increases with frequency. Inductive motors have a high impedance so that they do not load the circuit. Resistive heating loads the circuit with resistance plus inductance of the elements and connecting wire. Some television receivers contain capacitance on the order of 50 nF which affects the impedance at high frequencies. The inductance of lines tends to isolate loads at higher frequencies.
2.1 TRANSFORMERS

Secondary driving point impedance measurements were made on five pole-mount distribution transformers of different sizes. The impedance measurement equipment with 120 volt filter was used, and different resistive loads were connected to the primary as shown in Figure 2.1. All transformers had 13.2 kvolt primary windings. Table 2.1 lists each transformer, the manufacturer, and the figures in which the impedances are plotted.

Figure 2.2 shows the 240 volt secondary impedance for four different values of resistive load connected to the primary of a 10 KVA distribution transformer. Normally, the impedance that a distribution transformer sees looking out of its primary would be less than 10 kohms so that the 10 kohms represents a practical upper bound on primary impedance [20]. The lower bound is 0 ohm (short circuit). Generally, the curves of distribution transformer secondaries have a positive slope for increasing frequency and lie in the first quadrant for kilohertz frequencies. This impedance is often dominant in influencing the impedance seen at a residence.

Figures 2.3 through 2.6 show the 240 volt secondary impedances (for the same four resistive primary loads) of the other four transformers. The shapes of the curves are similar but have distinctive characteristics. For example they all have a positive slope for increasing frequency, but the 25 KVA transformer's reactance is negative at the lower frequencies while the 50 KVA transformer's impedance
Figure 2.1 Test Configuration.
Table 2.1 Transformer Information.

<table>
<thead>
<tr>
<th>Transformer Size</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Voltage</th>
<th>Figures That Contain Plots</th>
<th>Serial Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 KVA</td>
<td>Allis-Chalmers</td>
<td>24940GDY/</td>
<td>14400-120/240</td>
<td>2.2</td>
<td>2527661</td>
</tr>
<tr>
<td>15 KVA</td>
<td>Westinghouse</td>
<td>24940YZ/</td>
<td>14400-120/240</td>
<td>2.3, 2.7</td>
<td>73AB16357</td>
</tr>
<tr>
<td>25 KVA</td>
<td>McGraw-Edison</td>
<td>22860YZ/</td>
<td>13200-120/240</td>
<td>2.4, 2.8</td>
<td>81ND207-069</td>
</tr>
<tr>
<td>37.5 KVA</td>
<td>Allis-Chalmers</td>
<td>24940YZ/</td>
<td>14400-120/240</td>
<td>2.5, 2.9</td>
<td>5874953</td>
</tr>
<tr>
<td>50 KVA</td>
<td>General Electric</td>
<td>24940YZ/</td>
<td>14400-120/240</td>
<td>2.6</td>
<td>K972591Y73AA</td>
</tr>
</tbody>
</table>
Figure 2.2 240 Volt Secondary Impedance of a 10 kVA Distribution Transformer.
Figure 2.3 240 Volt Secondary Impedance of a 15 KVA Distribution Transformer.
Figure 2.4 240 Volt Secondary Impedance of a 25 KVA Distribution Transformer.
Figure 2.5 240 Volt Secondary Impedance of a 37.5 KVA Distribution Transformer.
Figure 2.6 240 Volt Secondary Impedance of a 50 KVA Distribution Transformer.
becomes no larger than 18 ohms at 100 kHz. Figures 2.7 through 2.9 show both 120 volt (phase to ground) and 240 volt secondary impedances of three of the distribution transformers for a 10 kohm primary load. It is clear that the two 120 volt impedances are in general not equal which is probably due to the asymmetry of the transformer secondary winding and that the 240 volt impedance is not equal to the simple sum of the 120 volt impedances.

In summary, distribution transformers have distinctive impedance curves at kilohertz frequencies which is transformer particular. Generalization over manufacturer or electrical size cannot be made from the data presented here.
Figure 2.7 240 Volt and 120 Volt Secondary Impedances of a 15 KVA Distribution Transformer With 10 Kohms on Primary.
Figure 2.8
240 Volt and 120 Volt Secondary Impedances of a 25 KVA Distribution Transformer with 10 Kohms on Primary.
Figure 2.9 240 Volt and 120 Volt Secondary Impedances of a 37.5 KVA Distribution Transformer With 10 Kohms on Primary.
2.2 LINES

The lines which connect the various loads of the secondary circuit are usually two, three, or four conductor wires or cables. For example, triplex cable may connect the distribution transformer to the entrance head of each house, AWG 12/2 wire may connect each 120 volt load to the service panel, AWG 12/3 wire may connect the hot water heater to the service panel, etc. If the electrical parameters (e.g. the capacitance and inductance per unit length) of the different types of lines can be found, then the lines can be represented by suitable elements in the secondary circuit.

Capacitance measurements were made on various wires and cables using a Doric C-Meter, model 130A. The results are listed in Table 2.2. Impedance measurements were made on various lines connected to resistive loads. Table 2.3 lists the configurations, the resulting calculated inductances, and the figures which contain the corresponding plots. A characteristic impedance can be assigned to each line using

\[ Z_0 = \text{square root of } \frac{(L/C)}{ \text{ } } \]

where \( L \) is in \( \mu \text{H/ft} \), and \( C \) is in \( \text{pF/ft} \). The characteristic impedances for these lines range from 70.2 ohms for the triplex cable (line to ground) to 98.2 ohms for the AWG 12/2 wire (line to neutral).

Since the wavelength at PLC frequencies is large compared to the length of conductors found in the secondary circuit, a lumped rather than a distributed network is adequate to represent the lines. Looking at the range of capacitances listed in Table 2.2, the effective
### Table 2.2 Line Capacitances.

<table>
<thead>
<tr>
<th>LINE AND MEASUREMENT CONFIGURATION</th>
<th>CAPACITANCE</th>
<th>CAPACITANCE/FT</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ft of extension cord (16/3), line to neutral</td>
<td>3320 pF</td>
<td>33.2 pF/ft</td>
</tr>
<tr>
<td>33 ft of 12/2, line to neutral</td>
<td>1815 pF</td>
<td>21.9 pF/ft</td>
</tr>
<tr>
<td>37 ft of 12/3, line to line</td>
<td>1800 pF</td>
<td>20.7 pF/ft</td>
</tr>
<tr>
<td>61 ft of Al 1/0 triplex, line to ground</td>
<td>1300 pF</td>
<td>21.3 pF/ft</td>
</tr>
<tr>
<td>61 ft of Al 1/0 triplex, line to line</td>
<td>990 pF</td>
<td>16.2 pF/ft</td>
</tr>
</tbody>
</table>

### Table 2.3 Line Inductances.

<table>
<thead>
<tr>
<th>LINE AND MEASUREMENT CONFIGURATION</th>
<th>INDUCTANCE</th>
<th>INDUCTANCE/FT</th>
<th>FIGURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ft of extension cord (16/3) with 5 ohms connected line to neutral</td>
<td>21.6 uH</td>
<td>0.216 uH/ft</td>
<td>2.10</td>
</tr>
<tr>
<td>33 ft of 12/2 with 5 ohms connected line to neutral</td>
<td>17.5 uH</td>
<td>0.211 uH/ft</td>
<td>2.11</td>
</tr>
<tr>
<td>37 ft of 12/3 with 4 ohms connected line to line</td>
<td>16.2 uH</td>
<td>0.186 uH/ft</td>
<td>2.11</td>
</tr>
<tr>
<td>61 ft of Al 1/0 triplex with 2 ohms connected line to ground</td>
<td>6.4 uH</td>
<td>0.105 uH/ft</td>
<td>2.12</td>
</tr>
<tr>
<td>61 ft of Al 1/0 triplex with 4 ohms connected line to line</td>
<td>7.3 uH</td>
<td>0.120 uH/ft</td>
<td>2.12</td>
</tr>
</tbody>
</table>
Figure 2.10 Line to Neutral Impedance of 16/3 Extension Cord Terminated in 5 Ohms.
Figure 2.11 Line to Neutral Impedance of AWG 12/2 Wire Terminated in 5 Ohms and Line to Line Impedance of AWG 12/3 Wire Terminated in 4 Ohms.
Figure 2.12 Line to Line and Line to Ground Impedances of Triplex Cable Terminated in 4 Ohms and 2 Ohms, Respectively.
capacitive reactance can be seen to be small compared to the low impedances normally encountered on the secondary at PLC frequencies. Thus the lines may be represented by inductances and resistances in series, with the inductive reactance and resistance increasing with frequency.
2.3 LOADS

The loads of the secondary circuit are the distribution transformer, household appliances, lighting, heating and cooling systems, and could even include 240 volt power factor correction capacitors. The distribution transformer has already been discussed. The other loads constitute reactive and resistive loads.

Residential resistive loads include incandescent lighting and resistive heating. Typical values of resistance for 120 volt loads could range from 240 ohms (nominal) for a 60 watt incandescent lamp to 13.7 ohms (nominal) for a 1050 watt toaster. Typical 240 volt resistive loads are electric hot water heaters, clothes dryers, ranges, and electric heating. These resistances could range from 12.8 ohms for a 4500 watt hot water heater to 5 ohms for a 11500 watt electric furnace.

One method of measuring the impedance of these devices while energized is to power them with a ferro-resonant isolation transformer which presents a relatively high impedance to the device at kilohertz frequencies. The impedance looking into the two terminals is then the device impedance shunted by the impedance of the ferro-resonant transformer. Figure 2.13 shows the impedance of a toaster (13.7 ohms nominal) not energized by AC power, the impedance of the toaster energized through the ferro-resonant transformer, and the impedance of 100 ft of AWG 16/3 extension cord in series with the toaster energized by the ferro-resonant transformer. The first curve shows the relatively constant resistance of the toaster elements and the increasing positive
Figure 2.13 Impedances of Three Configurations of the 1050 Watt Resistive Load (Toaster).
reactance for increasing frequency due to the inductance of the appliance cord and toaster elements. The value of 12 ohms real is also lower than the calculated 13.7 ohms because of the positive temperature coefficient of nichrome [16]. The second curve shows a higher resistance than the first, closer to the calculated 13.7 ohms. It also does not have the same shape as the first curve due to the shunting effects of the ferro-resonant transformer. By looking at these two curves, it can be seen that the toaster may be represented by a 13 ohm resistor and a 5.1 uH inductor. The third curve shows the impedance of the load and the shunting effects of the ferro-resonant transformer as well as the reactance and resistance of the extension cord.

Loads such as induction motors and universal motors have impedances much higher than the impedance of the secondary circuit. For example, a 3/4 hp utility (induction) motor was found to have an impedance of 192 ohms with an angle of 78 degrees at 5 kHz by measuring it's impedance while powered with the ferro-resonant transformer. Another method of determining impedance of devices is to measure the normal secondary impedance with the load off and then again with the load on, noting the difference in the two impedance curves. Using this method it was verified that the induction motors which power dishwashers, washing machines, fans, blowers, etc. have an impedance so much higher than the secondary circuit that no difference in the impedance curves could be detected.
Measurements of television receivers have shown that they can have capacitance approaching 0.1 uF between the conductors of the power cord. This capacitance will resonate with the inductance of the distribution transformer at frequencies in which the 120 volt inductive reactance of the distribution transformer is equal to the reactance of the capacitor. An examination of the distribution transformer impedances shows that this would not occur below 50 kHz.
2.4 RESIDENCES

120 volt (phase to neutral) and 240 volt (phase to phase) impedance measurements were made at three houses and one apartment to determine the impedances normally encountered at a residence and their causes. The houses are labeled House No. 1, No. 2, and No. 3.

House No. 1 is connected by 130 ft of overhead triplex cable to a 37.5 KVA Allis-Chalmers pole-mount distribution transformer. Four neighbors' houses are also connected with their own triplex cable to the distribution transformer. One phase of one of these four houses, connected by 120 ft of cable, was also used for impedance measurements, and this house will be designated Neighbor 1. In addition to the five houses listed above, there are three more houses connected to the distribution transformer in the following way. The three houses each have triplex cable connecting them to a pole where they are attached to a three-wire overhead run of 190 ft to the distribution transformer. One phase of one of these three houses, connected by 100 ft of cable, was also used in making measurements, and this house will be designated Neighbor 2.

House No. 2 is connected by 40 ft of triplex cable to a pole where triplex cable from another house joins it and goes 175 ft to a 50 KVA pole-mount distribution transformer. Three other houses are connected to the distribution transformer in the following way. One house is connected by 150 ft of triplex cable from the distribution transformer to a pole and then by 75 ft more to the house. Access for connecting
loads to this house was gained, and it will be designated Neighbor A. The second house is connected by 150 ft of triplex cable from the distribution transformer to a pole and then by several more feet to the house. The third house is connected by triplex cable paralleling Neighbor A's triplex cable to the pole, and then the cable continues to the house. Atop this pole is a 240 volt power factor correction/voltage regulation capacitor, probably installed because of this neighbor's air conditioner.

House No. 3 is connected by an estimated 220 ft of underground cable to a 37.5 KVA pad-mount transformer along with four other neighbors.

The apartment is connected by an estimated 35 ft of underground cable to three other apartments at a junction box which is connected along with three other junction boxes to a 100 KVA pad-mount distribution transformer by an estimated 80 ft of underground cable.

The impedances of both phases, A and B, of the secondary circuit of House No. 1 were measured and are shown in Figure 2.14. The impedance of phase B with the 1050 watt load plugged into the circuit at the point of measurement is also shown. This impedance should be the phase B impedance shunted by 13 ohms plus the reactance of 5.1 uH (the impedance of this appliance). Calculations show that this is the case. This figure also shows the impedance of phase B with the 1050 watt load connected using the AWG 16/3 extension cord which should be the phase B impedance shunted by the appliance impedance in series with the
Figure 2.14 Four Impedances at House No. 1.
inductive reactance and resistance of the cord shown in Figure 2.10 minus 5 ohms. Calculations also show that this is the case.

Figure 2.15 shows the impedance of phase B unloaded, loaded with the 1050 watt load at the point of measurement, and loaded with the 1050 watt load at another point in the house but on the same phase. It can be seen here that the inductance of the wires connecting the load tends to reduce the loading effect, especially at higher frequencies, in the same way that the AWG 16/3 cord does for the load in Figure 2.14.

Figure 2.16 shows the impedance of phase B measured directly and indirectly through the AWG 16/3 cord. The impedance measured indirectly is the sum of the impedance measured directly plus the impedance of the cord. This indirect method of measurement was used to measure impedances long distances from the measurement equipment.

Phase B of Neighbor 1 and phase A of Neighbor 2 were measured, and the results are shown in Figure 2.17. At the time of measurement Phase B of Neighbor 1 appears to be loaded resistively because of the shape of the impedance curve. The spacing between points of phase A of Neighbor 2 indicates a large inductance is an element comprising its impedance. The spacing of wire for the 190 ft overhead run which connects Neighbor 2 with the distribution transformer is estimated to be about 12 in. and the radius of the wire 0.158 in. so that the inductance per meter is

\[ L = 0.92 \log(12 \text{ in.}/0.158 \text{ in.}) = 1.73 \text{ uH/m}. \]

Using the length of line which is 58 meters, the inductance of the line is found to be about 100 uH. This value of inductance gives a spacing between points of about 0.6
Figure 2.15 Three Impedances at House No. 1.
Figure 2.16 Direct and Indirect Impedance Measurements of Phase B at House No. 1.
Figure 2.17 120 Volt Impedances of Neighbors 1 and 2.
ohms/kHz as in the low frequency section of the impedance curve. The shape of the curve indicates that there is a parallel resonance followed by a series resonance between 20 kHz and 50 kHz. The source of the capacitive loading necessary for resonance is not exactly known but is believed to be capacitance of loads such as television receivers. Loading of phase A at Neighbor 2 with the 1050 watt load did not alter the impedance of phase A seen at House No. 1. On one occasion, the impedance of phase A of House No. 1 temporarily exhibited a parallel and a series resonance like the impedance described above, but the parallel resonance was just above 50 kHz and the series resonance just below 100 kHz.

240 volt impedance measurements of House No. 1 were made and are shown in Figure 2.18. One curve is the unloaded impedance seen from the dryer outlet, and the other is the impedance with the circuit loaded by the range, an estimated 7 ohms. The effect of loading is to decrease the magnitude of the impedance for all points as was the case for loading of the 120 volt circuits. Since the range is on its own electrical circuit, the load it presents at the service panel is the resistance and inductance of the range and connecting wire.

For House No. 2, 240 volt and 120 volt impedance measurements were made. The loaded (with the range) and unloaded 240 volt impedances seen from the dryer outlet are shown on Figure 2.19. The unloaded impedance curve is almost a vertical line of closely spaced points for low frequencies to be contrasted with the impedance curves of the distribution transformers (Figures 2.2-2.6) or the 240 volt curve of
Figure 2.18 240 Volt Impedances at House No. 1.
Figure 2.19 240 Volt Impedances at House No. 2.
House No. 1 (Figure 2.18). The vertical portion of the curve suggests a series RLC circuit in which the resistance and inductance are those of the triplex cable, and the capacitance is that of the 240 volt power factor correction capacitor located at a neighbor's house. The reactance is approximately equal to $2\pi f L$ close to and above resonance which gives a value of $L = 47 \text{ uH}$, looking at Figure 2.19. This is the same value of inductance obtained by multiplying the length of triplex cable connecting House No. 2 to the capacitor by the line to line inductance of triplex cable. But the whole circuit including the distribution transformer must be considered in order to account for the complete impedance curve shown in the figure. Loading with 8000 watts at Neighbor A changed the 240 volt impedance at House No. 2 only slightly by decreasing the real part of the impedance a fraction at each point. The 120 volt impedances for House No. 2 have the usual shape as those of House No. 1 from 5 kHz to 20 kHz. At 50 kHz both impedances had angles greater than 60 degrees which then dropped to below 22 degrees at 100 kHz, giving the impedance curve a semicircular shape.

The 240 volt impedance of House No. 3 which is connected with underground cable to its transformer is shown in Figure 2.20, loaded and unloaded, and is similar to the impedance of House No. 1 in that its real and imaginary components continue to increase to 100 kHz. The 120 volt impedances had the usual shape of those of House No. 1 except that their curves started to bend downward at about 50 kHz and approached the real axis (resonance) at 100 kHz, similar to the 120 volt impedances of House No. 2.
Figure 2.20 240 Volt Impedances at House No. 3.
All of the impedance curves of the apartment were similar to those made at House No. 1. An example of loading by an adjacent apartment is shown in Figure 2.21. Here it can be seen that the load, although not in the same apartment, is close enough electrically to the point of measurement to alter the impedance.

From the data presented here, it is evident that the distribution transformer, the cable connecting the distribution transformer to the residence, residential loads, and 240 volt power factor correction capacitors determine the impedance seen at the residence. In the absence of large resistive loads and 240 volt capacitors, the impedance seen is determined by the connecting cable and the distribution transformer. The inductance of small runs of triplex is small so that the impedance seen at the residence under these conditions is that of the distribution transformer.
Figure 2.21 240 Volt Impedances at Apartment.
3. NOISE MEASUREMENTS AND ANALYSIS

Noise measurement is a difficult and often confusing task. One of the main concerns in the area of electromagnetic compatibility (EMC) is noise measurement. Noise and its measurement for EMC generally fall into two categories: conducted and radiated. Efforts to simplify the characterization of noise and the interference produced through the use of "quasi-peak" measurements and the line impedance stabilization network (LISN), to name two, show the desire for a relatively easy way to handle a complex problem [14].

The noise measurements made here were made by direct measurement of steady-state conducted voltages and currents generated by commonly used household devices. A Nicolet FFT spectrum analyzer was used to measure and record the voltage and current spectra from 0 to 100 kHz. (Refer to reference [21] or the Nicolet operating manual for a complete description of the annotations of the spectral plots.) High-pass filters were used to limit the low-frequency signals so that a high dynamic range (i. e. low noise floor) could be achieved for better observing the high-frequency noise components. The instrumentation used in the measurements is somewhat different than that normally used in a laboratory in that low-frequency, high power and voltage are present while small, high-frequency voltages and currents need to be measured. This requires special consideration for equipment saturation, equipment damage, and operator safety. Appendix A describes the techniques used in making the noise measurements. An available 120 volt power circuit whose impedance was known was used in these measurements and will be
referred to as the "60 Hz power circuit". This power circuit was not located in any of the residences.

In addition to the 0 to 100 kHz plots, expansion plots were made about a center frequency of 12480 Hz with a width of 1280 Hz so that resolution would be greatly improved allowing details of the noise spectrum to be observed. Using this expansion mode, 60 Hz harmonic lines could be discerned. Concerning rms representation and density normalization, all of the spectra were computed with the analyzer in the "rms" mode so that the spectrum amplitudes are indicated in rms values. The analyzer can also express amplitude in rms spectral density ("per Hz" values) which shifts the spectral plot by a certain number of dB depending on the frequency range setting. For the 0 to 100 kHz plots using a 2K FFT, the shift is -21 dB (-10 log{256 kHz sampling frequency/2K points}), and for the expanded plots the shift is -2 dB (-10 log{3277 Hz effective sampling frequency/2K points}). Concerning "leakage" effects on the spectrum, a Hanning squared window was used on the data so that the frequency side lobes are negligible.

Many residential devices use universal motors which generate high levels of random, impulsive noise. The light dimmer is also a common device that generates a large amount of 60 Hz impulsive noise. Detailed measurement and analysis were performed on these two items for these reasons. Other noise sources were also studied under controlled conditions.
A device which is used to measure the amount of conducted noise generated by electrical equipment is the LISN. This a network which can supply low-frequency power to the electrical equipment so that the equipment will operate and can couple high-frequency noise into a controlled impedance so that the noise can be observed. There are several problems with this approach, one of which is that all power circuits do not have the same impedance so that the LISN cannot possibly match every one. Another problem when observing noise under 100 kHz is the frequency response and impedance of the LISN. The 5 uH LISN impedance is close to a measured mean power line impedance only above 150 kHz, but LISN's have been designed for lower frequencies. Design difficulties arise as the corner frequency of the LISN impedance approaches the power line frequency [4],[10]-[11].
3.1 UNIVERSAL MOTORS

Universal motors are small series-wound motors which can operate on AC or DC voltage. Their light weight makes them ideal for small appliances, especially hand-held ones. Appliances which use this type of motor include vacuum cleaners, mixers, blenders, sewing machines, and portable hand-held sanders, drills, and saws. Like DC motors, universal motors contain brushes, and their performance is similar to that of DC series motors: when a load is placed on the motor, the speed decreases and when the voltage to the motor is increased, the speed increases. A series connected variable resistor can be used to obtain a continuously variable speed from the motor, and changing the field winding can be used to obtain different discrete speeds. Some appliances now use solid state switching devices to control their speed. Typical maximum speeds under full load range from 3500 rpm to 10000 rpm [13],[15]-[17]. The noise generated by motors with brushes has been described as having random amplitude and frequency and can cause radio interference [19],[22].

The current into a typical small appliance (blender) universal motor operating at the highest speed is shown in Figure 3.1. This figure was obtained by connecting a Fluke Model 601-800 current probe around one wire of the appliance cord and looking at its output in real time. The current is in phase with the 60 Hz voltage driving the motor shown in Figure 3.2. Looking at Figure 3.1, it can be seen that the output current is composed of a 60 Hz fundamental frequency component, harmonics of 60 Hz which give the waveform its triangular shape, and
Figure 3.1 Current Into a Universal Motor.

Figure 3.2 Voltage Across a Universal Motor.
high-frequency components which give the waveform its rough appearance. The high frequencies are attenuated somewhat by the Fluke current probe so that the high-frequency components are actually slightly larger than shown in the figure.

The high-frequency components were best observed by connecting a Tektronix Model P6021 current probe around one of the appliance cords and connecting the output of the probe through a high-pass filter to the Nicolet FFT Spectrum Analyzer as diagrammed in Figure 3.3. For some of the larger motors a current shunt was used in order to insure that the current probe was not saturating. The resulting spectrum from 0 to 100 kHz for one hundred averaged spectra is shown in Figure 3.4. Figure 3.5 shows the current spectrum with the device operating at the lowest speed. The speed change in this particular motor is effected by changing the field winding. In both figures the top line is the 0 dB reference line where E has been set to equal amperes, so the top line represents 0 dB A or one ampere. The scale is 10 dB per vertical division and 10 kHz per horizontal division.

In Figure 3.4 one can observe a gradually decreasing spectrum for increasing frequency out to 100 kHz, and there are also distinct peaks occurring at 6 kHz and its harmonics. In Figure 3.5 one can observe a slightly lower spectrum in general, and the peaks have shifted to a lower frequency. (The first peak at 4 kHz is actually higher in amplitude than its counterpart at 6 kHz.) Loading the motor and lowering the 60 Hz AC voltage slightly, both of which lower the operating speed of the motor, also causes each peak to shift to a lower frequency
Figure 3.3 Current Spectrum Measurement Set-Up.
Figure 3.4 Current Spectrum of the Universal Motor Operating at High Speed for 0 to 100 kHz.

Figure 3.5 Current Spectrum of the Universal Motor Operating at Low Speed for 0 to 100 kHz.
indicating that their position is related to motor speed. Considering
the operation of the motor, the position of the first peak should be the
same as the frequency of brush opening and closing with the rotor
contacts.

The high-frequency current output is practically independent of the
load resistance that the motor "sees". This is demonstrated by driving
the universal motor as shown in Figure 3.6. The motor is connected to a
ferro-resonant isolation transformer which supplies 60 Hz power to the
motor but presents a high impedance at kilohertz frequencies.

Resistances (such as incandescent lamps or other high voltage resistive
loads) can be connected in parallel to provide real impedances into
which the motor will operate. The results are that for resistances of
144 ohms to 13.7 ohms the high-frequency current is the same.

On the other hand if the voltage is measured for different values
of load resistance per Figure 3.6, it is found to be proportional to the
resistance and the current. For computing the voltage spectrum,
consider the equation

\[ V = I \times R. \]

Taking 20*log of both sides gives

\[ \text{Voltage(dBV)} = \text{Current(dBA)} + \text{Resistance(dBOHM)}. \]

The result is that the voltage spectrum should be the current
spectrum increased by the resistance seen by the motor, all in dB units.

This is shown in the four curves of Figure 3.7. Curve (a) is the
high-frequency voltage spectrum for the universal motor operating into
Figure 3.6 Current and Voltage Spectrum Measurement Set-Up.
144 ohms. It is $20 \log(144) = 43$ dB above the current curve of Figure 3.4. Similarly the curves (b), (c), and (d) are approximately 34, 29, and 23 dB above the curve of Figure 3.4 for resistances of 48, 29, and 13.7 ohms, respectively.

The voltage spectrum of Figure 3.8 was produced by operating the universal motor into the 60 Hz power circuit whose impedance is known. This voltage spectrum (in dBV) can be calculated by adding the current (in dBA) to the magnitude of the impedance of the 60 Hz power circuit (in dBOM). For example, using the current spectrum from Figure 3.4 and the power circuit impedance obtained earlier from impedance measurements, the voltage is calculated for four frequencies as follows:

- $-47$ dBA + $17$ dBOM = $-30$ dBV @ 12 kHz
- $-69$ dBA + $21.8$ dBOM = $-47.2$ dBV @ 20 kHz
- $-77$ dBA + $30.7$ dBOM = $-46.3$ dBV @ 50 kHz
- $-88$ dBA + $42.7$ dBOM = $-45.3$ dBV @ 100 kHz

These calculated voltages agree with the voltage spectrum in Figure 3.8.

Figure 3.9 is an average of thirty-two 0 to 10 kHz current spectra of the universal motor. The structure of the first peak of Figure 3.4 can be seen in Figure 3.9 to be composed of several spectral lines located at 6 kHz and spaced 120 Hz apart. Although these particular lines are 120 Hz apart, they are not located at harmonics of 60 Hz. An expanded spectral plot shows these spectral lines more clearly. The lines move instantaneously because the speed of the motor continuously varies (even when the motor is not being loaded). Averaging several spectra will result in the lines widening to become tens of Hertz wide.
Figure 3.7 Voltage Spectra for the Universal Motor Operating Into Various Resistive Loads.

a=144 ohms  
b=48 ohms  
c=29 ohms  
d=13.7 ohms

Figure 3.8 Voltage Spectrum for the Universal Motor Operating Into the 60 Hz Power Circuit.
Solid state devices such as SCR's are sometimes used in series with universal motors to control their speeds [8]-[9]. An example of this is a portable electric drill. Figure 3.10 is a plot of current vs. time for the drill at high speed, and Figure 3.11 is a plot of current vs. time for the drill at medium speed. (The DC level in this plot is zero because the probe is an AC instrument.) An even lower speed reduces the time the device is on to less than half of a cycle. Figure 3.12 shows the high-frequency current generated by the motor for high and medium speeds. Viewing the expanded spectrum of this motor operating at medium speed reveals a spectrum much like that of Figure 3.9.

In order to present a survey of the noise produced by universal motors, Figures 3.13 and 3.14 show the current spectra produced by six different appliances. Figures 3.15 and 3.16 show the voltage measured with the same six appliances operating into the 60 Hz power circuit as well as the background noise on that particular circuit.

To summarize, universal motors produce impulsive high-frequency currents whose spectrum consists of a relatively flat spectral density and instantaneously moving spectral lines proportional to motor speed. The voltage seen across the output depends upon the product of the current and impedance. The largest voltage spectral density was observed to be produced by the vacuum cleaner as indicated in Figure 3.15.
Figure 3.9 Current Spectrum for the Universal Motor for 0 to 10 kHz.

Figure 3.10 Current Into a Universal Motor Operating at High Speed.
Figure 3.11 Current Into a Universal Motor Operating at Medium Speed.

Figure 3.12 Current Spectra of an SCR Controlled Universal Motor at Two Speeds.
Figure 3.13 Current Spectra for Three Appliances.

Figure 3.14 Current Spectra for Three Appliances.
Figure 3.15 Voltage Spectra for Three Appliances Operating Into the 60 Hz Power Circuit.

Figure 3.16 Voltage Spectra for Three Appliances Operating Into the 60 Hz Power Circuit.
3.2 LIGHT DIMMERS

A popular residential electrical device which generates high levels of harmonic noise is the solid-state light dimmer. It is normally used with up to 600 watts of incandescent lighting to provide continuously variable lamp brightness. The dimmer is wired in series with the incandescent lights and controls lamp brightness by switching on and off rapidly through the use of SCR's or triacs. The National Electrical Manufacturers Association has established limits on allowable noise as a function of frequency, but the lowest frequency specified is 500 kHz. The noise generated by this device is a function of the device and the elements of the switched network [5],[7],[18].

Figure 3.17 shows the typical configuration of a light dimmer, incandescent light, and 60 Hz power circuit, including a functional diagram of the dimmer itself. A test set-up identical to this configuration was constructed, and the voltage and current measured during operation of the dimmer switch. This particular light dimmer uses a triac for switching and an L-C type filter for noise suppression. The resonant frequency of the L-C low-pass filter is 134 kHz.

Voltage (V) and current waveforms for operation with a 100 watt (144 ohm) lamp are shown in Figures 3.18 through 3.21 for minimum and maximum brightness settings of the dimmer. It can be seen from Figures 3.20 and 3.21 that the switch (triac) closes early in the first half-cycle for maximum brightness and late in the first half-cycle for minimum brightness, and then opens during the zero crossing. This
Figure 3.17 Light Dimmer Configuration.
Figure 3.18 Voltage Across Power Circuit With Dimmer Set for Minimum Brightness.

Figure 3.19 Voltage Across Power Circuit With Dimmer Set for Maximum Brightness.
Figure 3.20  Current Through 100 Watt Lamp With Dimmer Set for Minimum Brightness.

Figure 3.21  Current Through 100 Watt Lamp With Dimmer Set for Maximum Brightness.
repeats for the second half-cycle. The high-frequency voltage $V$ of Figure 3.17 is a damped oscillatory waveform with natural resonant frequency of approximately 125 kHz [6]. Note that when the dimmer is adjusted for maximum brightness, voltage is not applied to the lamp during the complete cycle so that sharp leading edges are still present in the current waveform. Also when the dimmer control is turned completely counterclockwise, the triac does not switch at all.

Referring to Figure 3.17 the voltages and currents of the circuit are produced in the following way. Since the switching of the triac $(\frac{dv}{dt} = 100v/\text{usec})$ [5] is much faster than the change in 120 volt 60 Hz excitation voltage, the excitation can be considered to be a DC voltage $V_i$ of whatever value the instantaneous excitation voltage is at the time of triac switching. With the switch (triac) open, the circuit is that of Figure 3.22 which is the same as Figure 3.23 where the open switch has been replaced by the voltage source $V_i$. When the switch closes, the circuit is that of Figure 3.24 which is the same as that of Figure 3.25. Using superposition, Figure 3.25 is seen to be the sum of Figure 3.23 and Figure 3.26. Thus the switch circuit has been reduced to a superposition of two circuits with voltage sources [1]. The currents $i_1$ and $i_2$ can be solved for in these two figures and added together to give $i$ of Figure 3.25, the current through the lamp. Since $i_1 = 0$, $i = i_2$; and the circuit solution is that of Figure 3.26.
Figure 3.22 Light Dimmer Circuit Before Switching.

Figure 3.23 Light Dimmer Circuit Before Switching.

Figure 3.24 Light Dimmer Circuit After Switching.
Assuming the switch (triac) closes instantly (actual triac \(dv/dt = 100v/\text{usec}\)) and since the triac switches every half-cycle, the high-frequency voltage \(V_i(t)\) can be approximated by a series of step functions; and since the 60 Hz applied voltage waveform is bipolar and the triac switches when the voltage is plus and minus, the steps are of alternating sign spaced approximately \(1/120\) sec apart. The largest possible magnitude of the step function is the peak value of the excitation voltage (170 volts) and occurs when the duty cycle is one half. For this case \(V_i(t)\) is a square wave shown in Figure 3.27. It can be represented by a Fourier series and written

\[
V_i(t) = 170(2/\pi) \sum_{n} (1/n)\sin(2\pi*60*n*t) \text{ for } n \text{ positive odd.}
\]

\(V_i(t)\) contains odd harmonics of 60 Hz.

Utilizing network analysis, the voltages and currents of the network can be calculated for any frequency as follows. Using the Fourier coefficients for the magnitude of the input voltage, values of \(L, C,\) and \(R\) found in Figure 3.17, and measured wall circuit (source) impedances, \(V'\) and \(V\) were found for \(f = 5, 10, 20, 50, \) and \(100\) kHz. Table 3.1 lists the frequencies, source impedances, and calculated peak \(V'\) and \(V\). As an example of this calculation for \(f = 5\) kHz, \(n = 83\) and the peak value of the 83rd harmonic of 60 Hz is \(170(2/\pi)(1/83)\). Multiplying this by \([\text{SOURCE IMPEDANCE}/(R + \text{SOURCE IMPEDANCE})][Z'/Z'']\) gives \(V = 28.8\) mV peak which is 20.4 mV rms or \(-33.8\) dBV. Table 3.1 also lists the measured harmonic levels which are, taking into consideration the insertion loss of the coupling filter used in the measurements, about 1.5 dB less than but track the calculated values
Figure 3.25 Light Dimmer Circuit After Switching.

Figure 3.26 Light Dimmer Circuit for Calculating $i_2$.

Figure 3.27 The Square Wave, $V_i(t)$. 
from 5 kHz to 100 kHz. Figure 3.28 shows the high-frequency spectrum of 
$V'$ and $V$ from 0 to 100 kHz where the resolution does not allow each harmonic to be perceived. (dBE is dBV for this figure.) The magnitude of the harmonics of $V$ actually rises for frequencies approaching 100 kHz because the wall circuit (source) impedance increases so rapidly in that region and the L-C filter of the light dimmer is nearing resonance. The voltage levels of Figure 3.28 are approximately 3 dB above the measured harmonics because there are approximately two harmonics per FFT point.

The above analysis assumed that the square wave was half wave symmetric which led to the production of odd harmonics of 60 Hz. This is not the case in general. The asymmetry of the waveform actually generated by the dimmer was observed to produce both odd and even harmonics as described below.

Considering the operation of the triac and the wall circuit impedance, and observing the spectrum of $V$ of Figure 3.28, the high frequency line to neutral voltage, $V(t)$, seen at the wall circuit can be approximated by a series of impulses, alternating plus and minus, in the time domain. The time between two impulses of the same sign is $1/60$ second. The generation of harmonics can be explained by interpreting the impulses as a sum of two sets of impulses, one set positive and one set negative. Let the positive set be given by

$$
\sum_{k=-\infty}^{\infty} \delta(t-kT) \quad \text{and the negative set by} \quad -\sum_{k=-\infty}^{\infty} \delta(t-kT-tau)
$$

where $T = 1/60$ second, $tau \approx 1/120$ second, and $\delta$ is the Dirac delta function. The sum is then

$$
V(t) = \sum_{k=-\infty}^{\infty} \delta(t-kT) - \sum_{k=-\infty}^{\infty} \delta(t-kT-tau),
$$
as shown in Figure 3.29. Taking the Fourier transform of both sides gives

\[ V(f) = \frac{1}{T} \sum_{n=-\infty}^{\infty} \delta(f-n/T) - \frac{1}{T} \left[ \exp(-2j\pi f \tau) \right] \sum_{n=-\infty}^{\infty} \delta(f-n/T) \]

\[ = \frac{2j}{T} \left[ \exp(-j\pi f \tau) \right] \sum_{n=-\infty}^{\infty} \delta(f-n/T). \]

\[ |V(f)| = \frac{2}{T} |\sin(\pi f \tau)| \sum_{n=-\infty}^{\infty} \delta(f-n/T) \]

Letting \( \tau = (T/2) + (T/2) \cdot \text{del} \) where \( \text{del} = [\tau-(T/2)]/(T/2) \), a normalized difference,

\[ |V(f)| = \frac{2}{T} \left\{ \sum_{n \text{ odd}} |\cos(n\pi \text{del}/2)| \delta(f-n/T) + \sum_{n \text{ even}} |\sin(n\pi \text{del}/2)| \delta(f-n/T) \right\}. \]

From this expression it can be seen that there can be both odd and even harmonics present in the spectrum. The envelope of the magnitude of the odd harmonics is \( |\cos(f\pi \text{del}/T)| \), and the envelope of the magnitude of the even harmonics is \( |\sin(f\pi \text{del}/T)| \), and is in quadrature with the odd envelope. If \( \text{del}=0 \), the even harmonics are all zero (half wave symmetry).

For the light dimmer tested \( \tau \) varies from 8.36 msec for the dimmer at minimum brightness to 8.54 msec for the dimmer at maximum brightness, resulting in a \( \text{del} \) of from 0.0032 to 0.0248. The resulting envelope frequency ranges from 0.0838 radians/\( \text{kHz} \) to 0.649 radians/\( \text{kHz} \) respectively. (Note that \( \text{del} \) is never zero resulting in only odd harmonics.) Figure 3.30 shows the high frequency spectrum of \( V \) for minimum \( \text{del} \) and Figure 3.31 for maximum \( \text{del} \). (dBE is dBV for these figures.) In both of these figures the odd and even harmonic envelopes
### Table 3.1 Calculated and Measured Voltages of 60 Hz Harmonics.

<table>
<thead>
<tr>
<th>FREQUENCY (kHz)</th>
<th>IMPEDANCE (OHMS)</th>
<th>CALCULATED ( V' ) (PEAK)</th>
<th>CALCULATED ( V ) (PEAK)</th>
<th>CALCULATED ( V ) (RMS)</th>
<th>MEASURED ( V ) (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.58 + j3.14</td>
<td>1.31 V</td>
<td>28.8 mV</td>
<td>-33.8 dBV</td>
<td>-35.2 dBV</td>
</tr>
<tr>
<td>10</td>
<td>0.79 + j6.10</td>
<td>651 mV</td>
<td>27.6 mV</td>
<td>-34.2 dBV</td>
<td>-35.6 dBV</td>
</tr>
<tr>
<td>20</td>
<td>1.32 + j12.25</td>
<td>332 mV</td>
<td>28.0 mV</td>
<td>-34.1 dBV</td>
<td>-35.3 dBV</td>
</tr>
<tr>
<td>50</td>
<td>4.10 + j33.86</td>
<td>148 mV</td>
<td>33.3 mV</td>
<td>-32.6 dBV</td>
<td>-34.0 dBV</td>
</tr>
<tr>
<td>100</td>
<td>47.74 + j127.33</td>
<td>132 mV</td>
<td>77.8 mV</td>
<td>-25.2 dBV</td>
<td>-26.7 dBV</td>
</tr>
</tbody>
</table>

![Graph showing Spectra of \( V \) and \( V' \).](image_url)

**Figure 3.28** Spectra of \( V \) and \( V' \).

![Graph of impulses comprising \( V(t) \).](image_url)

**Figure 3.29** Impulses Comprising \( V(t) \).
Figure 3.30 Spectrum of $V$ for Minimum Del.

Figure 3.31 Spectrum of $V$ for Maximum Del.
can be seen, and the null points used to compute the envelope frequency calculated above using del. Figure 3.32 shows an expanded plot of the spectrum of \( V \) about 12480 kHz with del such that odd harmonics are present in the expansion frequency window, and Figure 3.33 shows an expanded plot with del such that even harmonics are present in the expansion frequency window. Figure 3.34 is another expanded plot with del such that the odd harmonics are increasing with frequency and the even harmonics are decreasing with frequency within the expansion frequency window.

The magnitude of \( V \) varies about 3 dB over the range of the dimmer control as might be expected by considering Figures 3.18 through 3.21. \( V(f) \) also varies with lamp load with the magnitude increasing and the spectrum becoming flatter from 0 kHz to 100 kHz as calculated using network analysis. For 400 watts of lighting the impulses are greater than 100 volts peak and generate harmonics each of which is up to 80 mV rms (-22 dBV).

In summary, the solid-state light dimmer produces 60 Hz harmonic noise whose odd and even components depend on the setting of the dimmer control. The noise amplitude is determined by the lamp load, the dimmer low-pass filter, the triac firing point with respect to the excitation voltage, and the power circuit impedance; and was observed to be up to 80 mV rms per spectral line for 400 watts of lighting.
Figure 3.32 Expanded Plot of the Spectrum of V About 12480 Hz Showing Odd Harmonics.

Figure 3.33 Expanded Plot of the Spectrum of V About 12480 Hz Showing Even Harmonics.
Figure 3.34 Expanded Plot of the Spectrum of $V$ About 12480 Hz Showing Both Odd and Even Harmonics.
3.3 OTHER NOISE SOURCES

The light dimmer and the universal motor are two examples of noise sources which generate relatively large amounts of harmonic and random impulsive noise, respectively. A sample of other appliances along with the kinds of noise they generate will be presented here. This sample is far from being a complete set of all possible noise sources. It includes a hair dryer, popcorn popper, razor, induction motors, radio and television receivers, and fluorescent lights.

The hand-held electric hair dryer and the hot air popcorn popper tested were very similar in that they both contained heating elements of around 1200 watts, and both had DC motors which were powered through full-wave rectifiers. Both generated noise similar to that which a low power universal motor would generate, and the heating elements of both loaded down the power circuit resulting in lower levels of measurable external noise. An electric razor, which used a DC motor powered through a full-wave rectifier which had a 0.009 uF capacitor across the rectifier input, produced very little conducted high-frequency noise compared to the other two appliances just discussed.

Various 120 volt induction motors ranging from 3/4 hp in size to a small shaded pole motor were tested. None of these generated any conducted high-frequency noise that could be measured. The results of testing small synchronous motors were the same.
Several radio receivers were tested, but no generated noise could be detected; however, the television receivers tested did generate appreciable noise between 0 and 100 kHz. A black and white receiver generated the voltage spectrum of Figure 3.35 operating into the 60 Hz power circuit. It shows the power centered about harmonics of 15734 Hz (the "line frequency") [2]. Figure 3.36 is an expansion about 47202 Hz which shows the structure of the video spectrum about one of the harmonics. This television receiver also had a capacitance of 55 nF across the power cord (even when turned off), so that its being connected to a circuit altered the circuit impedance. Figure 3.37 demonstrates this. One curve in the figure is the voltage spectrum generated by a universal motor operating into the 60 Hz power circuit, and the other curve is the voltage spectrum generated the same way except that the television receiver is plugged into (but turned off) the power circuit. This figure demonstrates the parallel resonance occurring at about 62 kHz. A color television was observed to generate a similar noise spectrum and cause a similar resonance but at a slightly lower frequency due to a value of capacitance of 87 nF. A second color television observed at House No. 2 generated 1 volt impulses synchronous with 60 Hz which resulted in 0.5 mV 60 Hz harmonics. This is thought to be caused by a solid-state switching power supply.

Eighty watts of fluorescent lighting was observed to generate very low levels of high-frequency noise. Figure 3.38 shows the current spectrum with the device operating into the 60 Hz power circuit. The source impedance is so high that the voltage spectrum was below the
Figure 3.35 Voltage Spectrum Generated by a Television Receiver.

Figure 3.36 Expanded Voltage Spectrum Generated by a Television Receiver From 46400 Hz to 48000 Hz.
Figure 3.37 Voltage Spectra Generated by a Universal Motor Operating into the 60 Hz Power Circuit.

Figure 3.38 Spectrum of the Current Through Fluorescent Lights.
background noise of the 60 Hz power circuit. By powering the lights through the high impedance ferro-resonant transformer, the voltage spectrum could be observed to be composed of harmonic noise. Using Ohm's law, the voltage generated at the 60 Hz power circuit can be calculated and is found to be below typical background noise measured at the residences. The magnitude of the voltage is such that it would be only a fraction of the aggregate residential noise.
3.4 RESIDENCES

The voltage spectra generated by the universal motor observed at the four residences agree with the spectra calculated using the current spectrum and the measured impedances, except for the spectra observed at one house for frequencies of 20 kHz and below. In those spectra the voltage levels were up to 7 dB too low.

Measurements of the voltage generated by the light dimmer were made at three residences with 300 watts of lighting. The voltage spectra seen were like the ones generated under controlled conditions using the test set-up and 300 watts of lighting, except for reductions of up to 6 dB in voltage amplitude due to lower 60 Hz power circuit impedances. Solid-state light dimmers located permanently in the residence were observed at two residences. They produced 60 Hz harmonic noise also, but the amplitude of the noise spectra varied more as a function of frequency because of the secondary circuit configuration and the different locations of the light dimmer and measurement point.

Strong television video was evident after turning on a television receiver in the residence in which noise was being measured. Turning on local fluorescent lighting did not affect the noise spectrum appreciably.
4. SUMMARY OF RESIDENTIAL MEASUREMENTS

The impedance measurements made at the three houses and one apartment reveal that the impedance seen is determined by the distribution transformer, the loads connected to the circuit, and the lines connecting the different parts of the circuit. The impedance curves of the distribution transformer cannot be predicted exactly but are usually in the first quadrant with a positive slope. The effects of the line connecting the house to the transformer are usually small but may be great if the wires are not twisted together. Resistive heating loads cause the greatest change for lower frequencies, and their effect is to shunt the circuit with resistance and inductance. Loading from inductive motors does not change impedance at kilohertz frequencies because the reactance of the motor is so large. Lengths of line tend to reduce the effects of remotely located loads at higher frequencies because of the line inductance. A capacitive load can form a parallel resonant circuit with the inductance of the power circuit at the higher frequencies. This tends to make the impedance at the higher frequencies more unpredictable than at the lower frequencies unless the capacitive loading is known.

All of the residences had 240 volt impedances between 3 and 5 ohms, and 70 and 80 degrees (unloaded) at 10 kHz. Loading with the electric range lowered the impedance magnitude and angle, to between 2.7 and 4 ohms, and 55 and 66 degrees, respectively. The changes in magnitude and phase were 0.3 to 1 ohm and 12 to 18 degrees at 10 kHz. These are relatively small absolute changes when compared to the changes at 100
kHz. The 240 volt impedances at 100 kHz ranged from 12.5 to 25.5 ohms and from 17.4 to 55 degrees. The loaded impedances ranged from 6 to 13.9 ohms and from 27 to 73 degrees. The changes were from 6.5 to 11.6 ohms and from 1 to 34 degrees. From the shapes of the 240 volt impedance curves, it is obvious that there are resonances at the higher frequencies (above 20 kHz). The resonances are even more pronounced in the 120 volt measurements. The lowest observed parallel resonance was in the impedance of Neighbor 2 of House No. 1 which was at about 28 kHz.

A typical noise spectrum present on the 240 volt circuit is shown in Figure 4.1. Television video signals from neighbors are present, and the expanded spectrum shows the 60 Hz harmonic noise to be 10 to 30 dB above the flat noise spectrum. Loading the circuit by turning on resistive loads will lower the voltage over the entire observed spectrum.

The noise spectra of the universal motor and light dimmer observed at the residences were in agreement with spectra calculated using the analysis already presented. Since the inductance of lines tends to buffer the residences from each other, one would expect the noise measured far from the point of generation to be less than that measured at the point of generation. To illustrate this Figure 4.2 shows the 120 volt noise voltage at House No. 1 generated by the universal motor at two locations: at the point of measurement and at Neighbor 1. Figure 4.3 is the same except that Neighbor 1 has been replaced by Neighbor 2. It can be seen that for Neighbor 1, the observed noise is attenuated but
Figure 4.1  Typical Residential Background Noise Spectrum.

Figure 4.2  120 Volt Voltage Spectrum Observed at House No. 1 With a Universal Motor Operating at Two Locations.
has a relatively flat spectrum at high frequencies. For Neighbor 2 the noise is lower and has a resonance at about 28 kHz. The author believes this is caused by the resonance of capacitive loading and the relatively high inductance of the overhead run. A capacitance of 320 nF would resonate with the inductance of 100 uH from the overhead run to push the resonant frequency that low. Overall, the magnitude of the noise generated at a residence was observed at an adjacent residence to be less than if observed at the point of generation and to be frequency sensitive, but by no means are the residences completely isolated from each other. This is illustrated by Figure 4.4 which shows the voltage spectrum measured on one phase of House No. 2 with the light dimmer and 300 watts of lights connected to that phase at House No. 2 and at Neighbor A.

In general the 240 volt background noise was up to 6 dB greater than the 120 volt background noise as might be expected since the secondary winding of the distribution transformer is center tapped. For the case of locally generated 120 volt noise, this was not the case. The 120 volt noise measured at the point of generation was greater than the 240 volt noise. The 120 volt noise measured on the other phase was even less. Both the 240 volt noise and the 120 volt noise on the other phase varied as a function of frequency compared to the 120 volt noise measured at the point of generation.
Figure 4.3 120 Volt Voltage Spectra Observed at House No. 1 With a Universal Motor Operating at Two Locations.

Figure 4.4 120 Volt Voltage Spectra Observed at House No. 2 With a Light Dimmer Operating at Two Locations.
5. CONCLUSIONS

This paper has examined the residential power circuit in terms of impedance and noise for frequencies from 5 to 100 kHz. Impedance measurements were made on typical loads, lines, and transformers, and at four residences. The following conclusions can be drawn from the results:

1. The 240 volt impedance observed at a residence is determined by the network whose elements are the distribution transformer, (large) resistive loads, electrical lines, capacitive loads, and upon occasion 240 volt power factor correction capacitors.

2. With large resistive loads turned off and short runs of triplex connecting the residence to the distribution transformer, the 240 volt impedance is primarily determined by the distribution transformer at the lower frequencies.

3. Normally loaded distribution transformers generally exhibit a 240 volt RL circuit impedance in that the impedance increases with frequency and has a large angle.

4. Resonances (parallel first, then series) can occur at the higher frequencies (usually 50 kHz and above) in the residential network, making the impedances at higher frequencies more unpredictable than those at lower frequencies.
5. The inductance of connecting wires can tend to buffer elements of the network from each other at higher frequencies because of the increase in reactance of the wires.

6. Capacitive loads such as televisions may cause resonance, usually above 50 kHz.

7. The impedance of induction motors is much larger than the normal circuit impedance.

Conducted noise measurements were made on several appliances under controlled conditions and at the residences. Using the results of these measurements several conclusions can be made:

1. Residential background noise generally consists of random, spectrally smooth noise and 60 Hz harmonic noise. Usually there is television video noise also.

2. Universal motors are high-frequency current sources. The universal motor operating into a 60 Hz power circuit generates a flat noise spectrum that can be up to 30 dB above the normal background noise for a large motor.

3. Incandescent light dimmers produce 60 Hz harmonic noise due to the transients of switching the load. The level of phase to neutral noise produced can be up to 40 dB above normal background noise at 10 kHz for 400 watts of lighting. It can be even higher at higher frequencies.
4. Appliances with DC motors can generate noise similar to that generated by universal motors. Electronic appliances vary in the amount and type of impulsive noise generated.

5. Fluorescent lighting produces levels of noise lower than those mentioned above and is not a prominent source of conducted noise from 5 to 100 kHz.

6. Phase to neutral noise generated by a 120 volt source is usually 0 to 10 dB above the measured phase to phase noise.

It may be desirable to consider several areas for future investigation. More measurements of transformers may be made in order to obtain a more complete survey of the many sizes and manufacturers of transformers in use as well as the 120 volt to 240 volt transfer characteristics. Other appliances which generate noise may be investigated, especially those using solid-state devices and power supplies and those which generate radio frequency conducted electromagnetic interference. With the apparent lack of control and concern over conducted interference for household devices in the 5 to 100 kHz range and the increase in the number of modern appliances in the home, residential noise levels in this range will probably increase in the future. Understanding the residence more clearly in terms of the passive elements of the network and noise sources should allow more effective PLC communication systems to be designed.
LIST OF REFERENCES


APPENDICES
APPENDIX A. NOISE MEASUREMENT TECHNIQUES

The 120 volt and 240 volt noise measurements were made using a Nicolet 6603 FFT spectrum analyzer. Coupling from the power circuit to the analyzer was accomplished using the 120 volt high-pass filter or the 240 volt high-pass filter whose characteristics are covered in Appendix B. Both filters are high impedance filters so that when they are connected across the power circuit, they do not load the circuit down but do allow the voltage to be measured. In the residential measurements the 120 volt filter input was plugged into 120 volt outlets, and the 240 volt filter plugged into 240 volt dryer or range outlets.

The 120 volt noise measurements were made from line to neutral which are the two conductors to which the 120 volt device under consideration is connected. Inside the filter, the neutral is connected through to the chassis ground of the analyzer while the line voltage is filtered and fed to the input of the analyzer. The analyzer itself generates noise, so it was plugged into a ferro-resonant isolation transformer and a 4 uF capacitor connected across the analyzer side of the transformer. This lowers the analyzer noise injected back into the 60 Hz power circuit, but still presents a high impedance to it. In order to avoid two grounds in the circuit, the analyzer's safety ground was lifted at its power plug so that it received its ground only through the filter's ground which is connected to the power circuit neutral as explained above. Normally in residences both the neutral wire and safety ground wire are connected to the earth ground at the service
panel. Safety was assured by measuring 60 Hz voltages with a multimeter to determine whether the power circuit was properly wired before connecting the noise measuring equipment.

The 240 volt noise measurements were made using the 240 volt filter which is a high pass filter whose input is the 240 volt line to line voltage and whose output is a voltage referenced to the neutral. The output is connected to the Nicolet analyzer in the same way as for the 120 volt filter. Again, the safety ground of the Nicolet analyzer was lifted at its power plug so that its chassis ground was received through the filter from the power circuit neutral. Multiple grounds should be avoided because they change the residential network configuration.
APPENDIX B. FILTERS

Two different high impedance high-pass filters were used in making noise measurements, and two different low impedance high-pass filters were used in making impedance measurements.

Figure 7.1 shows the schematic diagram of the 120 volt high impedance high-pass filter. This filter was used to couple the Nicolet spectrum analyzer (high impedance) to 120 volt power circuits. Switch S1 allows either the voltage from line to ground or neutral to ground to be observed. By using an adapter which connects neutral to ground, the line to neutral voltage can be observed. Switch S2 switches in 20 dB of attenuation. There is an unfiltered output in addition to the filtered output which is 27 dB down. Figure 7.2 shows the voltage transfer function of the filter with S2 in both positions. The input impedance of this filter is greater than 10 kohms within the passband.

Figure 7.3 shows the schematic diagram of the 240 volt high impedance high-pass filter. This filter was used to couple the analyzer to 240 volt circuits. The switch S1 allows switching between filtered and unfiltered (-37 dB) outputs. Switch S2 allows 20 dB of attenuation to be switched in before the signal reaches the op-amps. The capacitors across the switch are high frequency compensation capacitors which help to give a flat filter response out to 100 kHz. Two unity gain op-amps with protective zener diodes at their inputs buffer the outputs of S2. The third op-amp sums the output of the other two op-amps and gives an output referenced to ground. The op-amps are powered by + and - 18
volts from four 9-volt batteries. Figure 7.4 shows the voltage transfer function of the filter with S2 in both positions. The input impedance of this filter (line to line) is greater than 10 kohms within the passband.

The 120 volt low impedance high-pass filter used in making 120 volt impedance measurements was designed and constructed by engineers at Westinghouse Electric Corporation in Raleigh, NC, and was used by them to make impedance measurements previously. Figure 7.5 shows the schematic diagram of the filter. It is driven by a low impedance amplifier, and the output is connected to the network whose impedance is desired. Nine volt zener diodes help to protect the input from large voltages. A sample of the voltage and current (using a current probe) is used to determine the impedance of the network in question. The 240 volt low impedance high-pass filter used in making 240 volt impedance measurements is a balanced version of the 120 volt filter. Its schematic is shown in Figure 7.6.
Figure 7.1 Schematic Diagram of 120 Volt High Impedance High-Pass Filter.
Figure 7.2 Transfer Function for 120 Volt High Impedance Filter.
Figure 7.3 Schematic Diagram of 240 Volt High Impedance High-Pass Filter.
Figure 7.4 Transfer Function for 240 Volt High Impedance Filter.
Figure 7.5 Schematic Diagram of 120 Volt Low Impedance High-Pass Filter.
Figure 7.6 Schematic Diagram of 240 Volt Low Impedance High-Pass Filter.
APPENDIX C. IMPEDANCE MEASUREMENT TECHNIQUES

The 120 volt and 240 volt impedance measurements were made using the equipment set-up shown in Figure 7.7. The HP 9825A desktop computer was programmed to control the network analyzer, synthesizer, and plotter, so that measurements could be made quickly and efficiently. The data points were plotted and stored on cassette tape for future reference. All of the equipment fit into one rack which could be rolled within the residence to access different power circuit outlets. Normally the equipment was powered through a ferro-resonant isolation transformer with the safety ground lifted so that the equipment received its ground from the circuit it was measuring.

The set-up allows impedances to be measured in the following way. The signal from the generator (synthesizer) drives the amplifier. The amplifier, which has a low output impedance, forces a voltage across the input of the filter. In the case of the 240 volt measurements, an isolating transformer was connected between the amplifier and filter. An attenuated sample of this voltage is fed into channel B of the network analyzer. The current into the filter is also measured by the current probe and current probe amplifier, and the resulting voltage is fed into channel A of the network analyzer. (The current probe amplifier is set for a gain of 0.1) The network analyzer divides (subtracts in dB) the magnitude of channel B by channel A and determines the phase difference. The result is $V/I = Z$, the driving point impedance looking into the filter.
The computer was programmed to step the generator from 5 kHz to 20 kHz in 1 kHz increments, and then to 50 kHz and 100 kHz for a total of 18 different frequencies. In order to avoid 60 Hz harmonic noise, the generator frequencies were actually chosen to be the odd 30 Hz harmonics closest to the desired frequencies. The intermediate frequency bandwidth of the network analyzer was set to 10 Hz. After the generator stepped to each frequency, the computer would have the network analyzer wait one second; and then it would read the network analyzer, giving Z. A slight magnitude and phase correction was implemented at each frequency to offset errors due to phase and magnitude characteristics of the system. This was done through the subroutine "OFFSET". The effects of the filter were "subtracted" by subtracting impedances or admittances of the elements of the filter to give the driving point impedance looking out of the filter into the unknown load, Zl. The values of Zl for each frequency were stored on tape in magnitude-phase form. Display prompts and printer messages let the operator know what had been measured and where it was stored. Data from ten measurements were stored in one tape file.

Figure 7.8 is a flowchart of the program which controls the equipment. After running the program from the beginning, it stops and the computer displays "PRESS SPECIAL FUNCTION KEY." The operator then presses one of the preprogrammed keys on the computer which will cause the program to start at one of the titles circled on the flowchart. That function will be performed, and then the computer will stop and wait for another key to be pressed. The programs, one for 120 volt
measurements and one for 240 volt measurements, are contained in Tables 7.1 and 7.2, respectively. The 120 volt program contains a subroutine for plotting admittance that the 240 volt program does not.

The accuracy of the measurement system was tested by connecting calibrated loads to the output and plotting the impedance curves obtained. Figure 7.9 and 7.10 show the impedance curves for the 120 volt filter and 240 volt filter, respectively, with various resistances and inductances connected alone and in series and parallel combinations. Load combinations whose impedances lie in the first quadrant were used because that is where most measured residential impedances were found to lie. The purely resistive values result in frequency independent resistive locations on the graph, and the parallel RL combinations yield semicircular curves. The series RL combinations result in relatively straight lines with a slight positive slope. This agrees with analysis when frequency dependent inductor losses due to core loss and skin effect are included.
Figure 7.7 Equipment Configuration For Impedance Measurements.
Figure 7.8 Flowchart For Impedance Measurement Program.
Figure 7.9 Impedance Calibration Curves Using 120 Volt Filter.

a = 10 ohms
b = 5 ohms
c = 1 ohm
d = 10 ohms + 47 uH
e = 5 ohms + 47 uH
f = 1 ohm + 47 uH
g = 47 uH
h = 5 ohms // 47 uH
i = 10 ohms // 47 uH
j = 20 ohms // 108 uH
Figure 7.10  Impedance Calibration Curves Using 240 Volt Filter.
Table 7.1 Program For Impedance Measurements Using 120 Volt Filter.

0: "Program to make Z measurements, 120V filter":
1: dim T$[10,100];strk 1
2: dim M[18,10], T[J8,10]
3:
4: "Load Keys":
5: 1ch 5
6:
7: "START":
8: for I=1 to 10
9: sfg 4
10: "BACK":
11: rem 7
12:
13: "Initialize 3330B Synthesizer":
14:
15: wrt 704,"L10.0>NO0.0<^X"
16: wait 1000
17:
18: "Initialize 3570A Net Analyzer":
19:
20: wrt 701,"CGJMT0"
21: lcl 7
22: stp ;dsp "CONNECT 10 OHM LOAD"
23: stp ;dsp "ADJUST NETWORK ANALYZER for 17.20dB & -14.30 deg"
24: rem 7
25: wrt 701,"CGJMT0"
26:
27: "Step Syn through freqs and read NA":
28:
29: fmt 2,"L",f,B,"="
30: stp ;dsp "Connect Load"
31: ent "TITLE?",T$[I]
32:
33: for N=5 to 22
34: gsb "FREQ-SET"
35:
36: wait 1000
37: wrt 701",""
38: fmt 1,2f,2;red 701.1,A,B
39: gsb "OFFSET"
40: gsb "FILTER"
41: M)M[N-4,1]
42: T)T[N-4,1]
43: next N
44:
45:
46: "KEY":
47: stp ;dsp "PRESS SPECIAL FUNCTION KEY"
48:
49: "CONTINUE":
50:
51: if flg4;goto 'BACK'
52: next I
53: stp ;dsp "STORE DATA ON TAPE"
54:
55: stp
56: end
57:
58: "FREQ-SET":jmp N
59:
60:
61:
62:
Table 7.1 (continued)

63: 5010 F; wrt 794.2, F; ret
64: 63030 F; wrt 794.2, F; ret
65: 69900 F; wrt 794.2, F; ret
66: 80100 F; wrt 794.2, F; ret
67: 90300 F; wrt 794.2, F; ret
68: 99900 F; wrt 794.2, F; ret
69: 101000 F; wrt 704.2, F; ret
70: 101000 F; wrt 704.2, F; ret
71: 101000 F; wrt 704.2, F; ret
72: 101000 F; wrt 704.2, F; ret
73: 101000 F; wrt 704.2, F; ret
74: 101000 F; wrt 704.2, F; ret
75: 101000 F; wrt 704.2, F; ret
76: 101000 F; wrt 704.2, F; ret
77: 101000 F; wrt 704.2, F; ret
78: 101000 F; wrt 704.2, F; ret
79: 101000 F; wrt 704.2, F; ret
80: 101000 F; wrt 704.2, F; ret
81: 101000 F; wrt 704.2, F; ret
82: "OFFSET": jmp N
83:
84:
85:
86:
87: A-.13 A B+.03 B; ret
88: A-.08 A B+.06 B; ret
89: A-.05 A B+.04 B; ret
90: A-.04 A B+.02 B; ret
91: A-.02 A B+.01 B; ret
92: ret
93: B-.03 B; ret
94: A+.01 A B-.07 B; ret
95: A+.02 A B-.11 B; ret
96: A+.04 A B-.15 B; ret
97: A+.06 A B-.13 B; ret
98: A+.07 A B-.21 B; ret
99: A+.07 A B-.25 B; ret
100: A+.07 A B-.28 B; ret
101: A+.08 A B-.29 B; ret
102: A+.09 A B-.35 B; ret
103: A+.06 A B-.38 B; ret
104: A-.07 A B-.72 B; ret
105:
106: "FILTER":
107:
108: 10<<((A+24-1)/20))C
109: C*cos(B)) X; C*sin(B)) Y
110: 1/2(F8.5e-6) D
111: Y*D) Y
112: atn(Y/X)) T
113: \((X^2+Y^2)) M
114: 1/M M1-1) T
115: Mcos(T)) X; Msin(T)) Y
116: 1/2(F6.25e-3) E
117: Y*E) Y
118: atn(Y/X)) T; \((X^2+Y^2)) M
119: 1/M M1-1) T
120: Mcos(T)) X; Msin(T)) Y
121: 1/2(F8.5e-6) H
122: 2(F2.4e-6) O
123: Y-H-O) Y; X-2.4) X
124: atn(Y/X)) T; \((X^2+Y^2)) M
125: ret
126:
127:
128: "STORE-ON-TAPE":
Table 7.1 (continued)

129: 130: trk 1
131: ldf 0,Q
132: rcf Q,Ts,M[*1],T[*]
133: O+1)Q
134: rcf 0,Q
135: trk 1
136: fxd 0; spc
137: pnt "DATA STORED IN FILE ",Q-1
138: fxd 2; spc
139: gto "START"
140:
141:
142: "PLOT-DATA":
143:
144: spc
145: pnt T$[I]
146: pnt "PLOTTEO"
147: spc
148: pcr; scl -3.25,13.416,-1,11;lim -1,10.5,-1,10.5
149: pen
150: for J=1 to 18
151: M[J,1]*cos(T[J,1])$X
152: M[J,1]*sin(T[J,1])$Y
153: wrt 705,"sm+
154: plt X,Y
155: next J
156: pen
157: gto "KEY"
158:
159:
160: "PLOT-SCALE6":
161: pcr; fxd 0
162: scl -3.25,13.416,-1,11
163: xax 0,1,0,10,1
164: yax -0,1,0,10,1
165: plt 0,10,1
166: plt 10,10,2
167: plt 10,0,2
168: pen
169: plt 4.35, -5,1
170: lbi "Re"
171: plt -.75,4.35,1
172: lbi "Im"
173: plt 1,10.6,1
174: plt; fxd 2
175: gto "KEY"
176:
177:
178: "PRINT-DATA":
179: spc
180: pnt T$[I]
181: for J=1 to 18
182: fxd 0
183: if J>16; jmp 3
184: pnt "kHz", J>4
185: jmp 2
186: pnt "kHz", (J-16)50
187: fxd 2; spc
188: pnt "ohms", M[J,1]
189: pnt "degrees", T[J,1]
190: spc
191: pnt "Re",M[J,1]*cos(T[J,1])
192: pnt "Im",M[J,1]*sin(T[J,1])
193: spc
194: spc
Table 7.1 (continued)

195:   next J
196:   gto "KEY"
197:   
198:   "PRINT-DATA-@-10kHz":
200:   spc
201:   prt T$/[I$
202:   prt "at 10 kHz"
203:   prt "ohms",M[I,6,I]
204:   prt "degrees",T[I,6,I]
205:   spc
206:   prt "Re",M[I,6,I]$cos(T[I,6,I])
207:   prt "Im",M[I,6,I]$sin(T[I,6,I])
208:   spc
209:   spc
210:   gto "KEY"
211:   
212:   "STORE":
214:   cfg 4
215:   fxn 0;spc
216:   prt T$/[I$," STORED AS MEASUREMENT ",I
217:   fxn 2;spc
218:   gto "KEY"
219:   
220:   "Y- PLOT-DATA":
222:   spc
224:   prt T$/[I$
225:   prt "Y- PLOTTED"
226:   spc
227:   pclr; scl -$325,1.3416,-1.1,1,1;lim -$1,1.05,-1.05,1
228:   pen
229:   for J=1 to 18
230:    1/M[I,J]$cos(-1*T[J,I])x
231:    1/M[I,J]$sin(-1*T[J,I])y
232:   urt 705, "sm+
233:   plt X,Y
234:   next J
235:   pen
236:   gto "KEY"
237:   
238:   "Y- PLOT- SCALES":
240:   pclr;fxn 1
241:   scl -$325,1.3416,-1.1,1,1
242:   xax -$1,1,0.1,1
243:   yax 0,$-1,1,0,1
244:   plt 1,-1,1
245:   plt 1,0,2
246:   plt 0,0,2
247:   plt .435,.02,1
248:   lbl "Re"
249:   plt -.075,-.45,1
250:   lbl "Im"
251:   plt .1,.08,1
252:   ptyp;fxn 2
253:   gto "KEY"
254:   
255:   +21299
Table 7.2 Program For Impedance Measurements Using 240 Volt Filter.

```
0: "Program to make 2 measurements, 240V filter":
1: dim T$(10, 100); trk 1
2: dim M[2, 10], r[18, 10]
3:
4: "Load Keys":
5: idk 5
6:
7: "START":
8: for I=1 to 10
9: sfg 4
10: "BACK":
11: rem 7
12:
13: "Initialize 3330B Synthesizer":
14:
15: wrt 704,"L10.6N00.0<X"
16: wait 1000
17:
18: "Initialize 3570A Net Analyzer":
19:
20: wrt 701,"CGJHTO"
21: let 7
22: stp ;dsp "CONNECT 10 OHM LOAD"
23: stp ;dsp "ADJUST NETWORK ANALYZER for 15.14dB & -35.85 deg"
24: rem 7
25: wrt 701,"CGJHTO"
26:
27: "Step Syn through freqs and read NA":
28:
29: fmt 2,"L",f,1,"="
30: stp ;dsp "Connect Load"
31: ent "TITLE?",T$(I)
32:
33: for N=5 to 2:
34: gsb "FREQ-SET"
35:
36: wait 1000
37: wrt 701,";"
38: fmt 1,2f,2;rd 701.1,A,B
39: gsb "OFFSET"
40: gsb "FILTER"
41: M$M[H-4,I]
42: T$T[H-4,I]
43: next N
44:
45:
46: "KEY":
47: stp ;dsp "PRESS SPECIAL FUNCTION KEY"
48:
49: "CONTINUE":
50:
51: if flg4;goto 'BACK'
52: next I
53: stp ;dsp "STORE DATA ON TAPE"
54:
55: stp
56: end
57:
58: "FREQ-SET": jmp N
59:
60:
61:
62:
```
Table 7.2 (continued)

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>63:</td>
<td>50 10 F; H 7</td>
</tr>
<tr>
<td>64:</td>
<td>60 30 F; H 7</td>
</tr>
<tr>
<td>65:</td>
<td>69 90 F; H 7</td>
</tr>
<tr>
<td>66:</td>
<td>70 10 F; H 7</td>
</tr>
<tr>
<td>67:</td>
<td>90 30 F; H 7</td>
</tr>
<tr>
<td>68:</td>
<td>99 90 F; H 7</td>
</tr>
<tr>
<td>69:</td>
<td>11 01 0 F; H 7</td>
</tr>
<tr>
<td>70:</td>
<td>12 03 0 F; H 7</td>
</tr>
<tr>
<td>71:</td>
<td>12 99 0 F; H 7</td>
</tr>
<tr>
<td>72:</td>
<td>14 01 0 F; H 7</td>
</tr>
<tr>
<td>73:</td>
<td>15 03 0 F; H 7</td>
</tr>
<tr>
<td>74:</td>
<td>15 99 0 F; H 7</td>
</tr>
<tr>
<td>75:</td>
<td>17 01 0 F; H 7</td>
</tr>
<tr>
<td>76:</td>
<td>18 03 0 F; H 7</td>
</tr>
<tr>
<td>77:</td>
<td>18 99 0 F; H 7</td>
</tr>
<tr>
<td>78:</td>
<td>20 01 0 F; H 7</td>
</tr>
<tr>
<td>79:</td>
<td>50 01 0 F; H 7</td>
</tr>
<tr>
<td>80:</td>
<td>99 99 0 F; H 7</td>
</tr>
</tbody>
</table>

81: "OFFSET": jmp N
83:
84:
85:
86:
87: A -.05 A; B -.25 B; ret
88: A -.04 A; B -.2 B; ret
89: A -.03 A; B -.15 B; ret
90: A -.01 A; B -.1 B; ret
91: A -.0 A; B -.08 B; ret
92: ret
93: A+.01 A; B -.04 B; ret
94: A+.02 A; B -.1 B; ret
95: A+.03 A; B -.15 B; ret
96: A+.04 A; B -.2 B; ret
97: A+.04 A; B -.27 B; ret
98: A+.05 A; B -.34 B; ret
99: A+.06 A; B -.41 B; ret
100: A+.06 A; B -.46 B; ret
101: A+.06 A; B -.52 B; ret
102: A+.06 A; B -.6 B; ret
103: A+.06 A; B -.7 B; ret
104: A+.06 A; B -.8 B; ret
105:
106: "FILTER":
107:
108: 10<((A+B)/20)) C; B+5.5 B
109: C; cos(B) X; C* sin(B) Y
110: 1/2 (F 6 e-6) D
111: Y+D) Y
112: atn(Y/X)) T
113: \( <X^2+Y^2) M
114: 1/M M -1 T) T
115: M* cos(T) X; M* sin(T) Y
116: 1/2 (F 6 e-2) E
117: Y+E) Y
118: atn(Y/X)) T; <(X^2+Y^2) M
119: 1/M M -1 T) T
120: M* cos(T) X; M* sin(T) Y
121: 1/2 (F 3.2 e-6) H
122: 2(F 1.9 e-6) O
123: Y+H-O) Y; X-2.3) X
124: atn(Y/X)) T; <(X^2+Y^2) M
125: ret
126:
127:
128: "STORE-ON-TAPE":
Table 7.2 (continued)

129: trk 1
130: ldf 0, Q
131: rcf Q, T$[-], T[+]
132: Q+=Q
133: rcf Q, 0, Q
134: trk 1
135: fx a 0; spc
136: prt "DATA STORED IN FILE ", 0-1
137: fx d 2; spc
138: goto "START"
139: spc
140: "PLOT-DATA":
141: spc
142: prt T$[I]
143: "PLOT-T":
144: spc
145: "PLOT-SCA":
146: pen
147: for J=1 to 18
148: M[J,I]=cos(T[J,I]) X
149: M[J,I]=sin(T[J,I]) Y
150: pen
151: for J=1 to 18
152: plt X, Y
153: next J
154: pen
155: goto "KEY"
156: spc
157: "PRINT-DATA":
158: spc
159: "RE":
160: spc
161: plt 4.35, -.5, 1
162: "IM":
163: plt -.75, 4.35, 1
164: spc
165: plt 1, 10, 2
166: plt 10, 2
167: spc
168: "OHMS":
169: "DEGREES":
170: spc
171: spc
172: spc
173: spc
174: spc
175: spc
176: spc
177: spc
178: spc
179: spc
180: spc
181: spc
182: spc
183: spc
184: spc
185: spc
186: spc
187: spc
188: spc
189: spc
190: spc
191: spc
192: spc
Table 7.2 (continued)

195:  next J
196:  gto "KEY"
197:  -
198:  
199:  "PRINT-DATA-0-10kHz":
200:  spc
201:  prt TS[I]
202:  prt "at 10 kHz"
203:  prt "ohms",M[6,I]
204:  prt "degrees",T[6,I]
205:  spc
206:  prt "Re",M[5,I]*cos(T[6,I])
207:  prt "Im",M[5,I]*sin(T[6,I])
208:  spc
209:  spc
210:  gto "KEY"
211:  
212:  
213:  "STORE":
214:  cfg 4
215:  fxd $;spc
216:  prt TS[I],"STORED AS MEASUREMENT ",I
217:  fxd 2;spc
218:  gto "KEY"
219:  
220:  *29431
APPENDIX D. LIST OF APPLIANCES

1. Blender, Oster, Model 847 LX.
2. Drill, 3/8 Inch Variable Speed, Rockwell, Model 4120 (74) Type 1.
5. Hair Dryer, Clairol, Son of a Gun.
6. Light Dimmer, Lutron, Model KDR-600PS.
7. Mixer, Large, Sunbeam Mixmaster.
10. Popcorn Popper, Hot Air, Presto Model 01/PNI.
11. Razor, Remington Electric, Model 300.
12. Sander, Black and Decker Orbital, Model 7420.
13. Sewing Machine, Wards Signature, Model UHT J227E.
14. Television, Black and White, Panasonic, 19 Inch, Model AN-609D.
15. Television, Color, Sharp, 19 Inch, Model 19F70.
16. Television at House No. 2, Color, Sears, Model 564.42101150.
17. Toaster, Presto, Model PT01D.
18. Vacuum Cleaner, Eureka, Model 736A.