directly attached sensors for measuring voltage and current on conductors. A Tektronix P2015 voltage probe was used for the measurement of voltages at potentials up to 15 kV. A Model P201D voltage probe was used to measure voltages at secondary levels below 440 V. A Tektronix CT5 current probe was used to measure current in conductors.

Table 3-1 gives a simplified set of guidelines to determine if a sensor is located in the near or distant zone of a source. λ is the wavelength of the signal being measured.

Table 3-1

NEAR- AND DISTANT-ZONE GUIDELINES

Distance Source to Sensor	Zone	Sensor
λ or larger	Distant	Either E or B
$\lambda/6$ to λ	Mixture	E and B
$\lambda/6$ or less	Near	E and B

The entire measurement system was calibrated in IEEE defined MKS units. The electric-field amplitude of measured data are expressed in volts per meter (V/m), the magnetic field in tesla (T), voltage in volts (V), and current in amperes (A). The amplitude of signal and noise components in all spectral views presented in this report are calibrated in root-mean-square (rms) values. Oscilloscope views are calibrated in peak voltage. Values of sine wave components scaled from oscilloscope views can be converted to rms units by multiplying by 0.707.

A 7-track analog magnetic tape recorder (Ampex Model 300) was used during early measurements to record the output of sensors in parallel with the real-time processing of data from any selected sensor. A 2-track cassette recorder (Sony Model TC-D5M) was also available for the analog recording of sensor outputs at frequencies from 60 Hz to 19 kHz. The limited dynamic range of these recorders prevented the permanent recording of much useful data. Late in the measurement period, a Sony digital recording system with a dynamic range of more than 90 dB was added to the measurement system. This recorder provided a means to record two channels of data with sufficient dynamic range to analyze many pertinent signal and noise situtations.

3.3 MOBILE MEASUREMENT SYSTEM

The instrumentation described in Section 3.2 was installed in a

small van for mobility and convenience in making measurements at remote locations. A trailer containing a motor-driven generator for electrical power was added to the van. Figure 3-2 shows an exterior view of the van and its power trailer. Figure 3-3 shows a partial view of the interior of the van and some of the instrumentation. Some of the auxilary equipment required to integrate the instrumentation into an operating system is also shown.

Flexibility in making various kinds of field measurements was achieved by adding the capability to switch and interconnect the instrumentation in a variety of configurations. Figure 3-4 is a block diagram of the primary interconnect features of the van equipment for measuring signals and noise at frequencies from 10 Hz to 300 kHz. A total of six separate data channels were used to connect the instrumentation in the van to any combination of six sensors. Line amplifiers whose gain could be adjusted in 10-dB steps were added to each data channel so that signal levels for each analaysis channel could be adjusted to uniform levels. The channelized or scanning analyzers could be connected to any data channel with a rotary coaxial switch.

All sensors, line amplifiers, and low-level signal-handling components were battery powered to minimize introducing 60-Hz-related effects through power supplies and to avoid ground loop effects in low-level circuits and cables. In addition, the van system was operated from its own power source to avoid unwanted ground loops and the radiation of 60-Hz electromagnetic fields from van's power cables. The motor generator was operated at 64 Hz so that low-level residual electric and magnetic fields from the van instrumentation power source could be distinguished from 60-Hz effects and harmonics of 60 Hz.

A total of six separate data channels were provided. Line amplifiers in each channel permitted adjusting the channel gains in 10-dB steps to set channel signals to a common level for processing. The channelized or scanning analyzers could be connected to any desired data channel with a rotary coaxial switch.

The power wiring in the van was isolated from ground, and special filters and grounding techniques were used to isolate the instrumentation from outside electrical effects. External and internal grounds were established on the van body to terminate common-mode and ground currents on either the external or internal surface of the van body.

3.4 PORTABLE INSTRUMENTATION SYSTEM

A simple battery-operated portable instrumentation system was provided as a supplement to the van instrumentation system. It consisted of a single sensor (either a field sensor or a directly connected sensor), a line amplifier, and a cassete recorder (Sony Model TC-D5M). A battery-operated SSB receiver (modified Sony Model 2001D) replaced the line amplifier when signals above 10 kHz were

Figure 3-2. Exterior View of Instrumentation Van

Figure 3-3. Interior View of Instrumentation Van

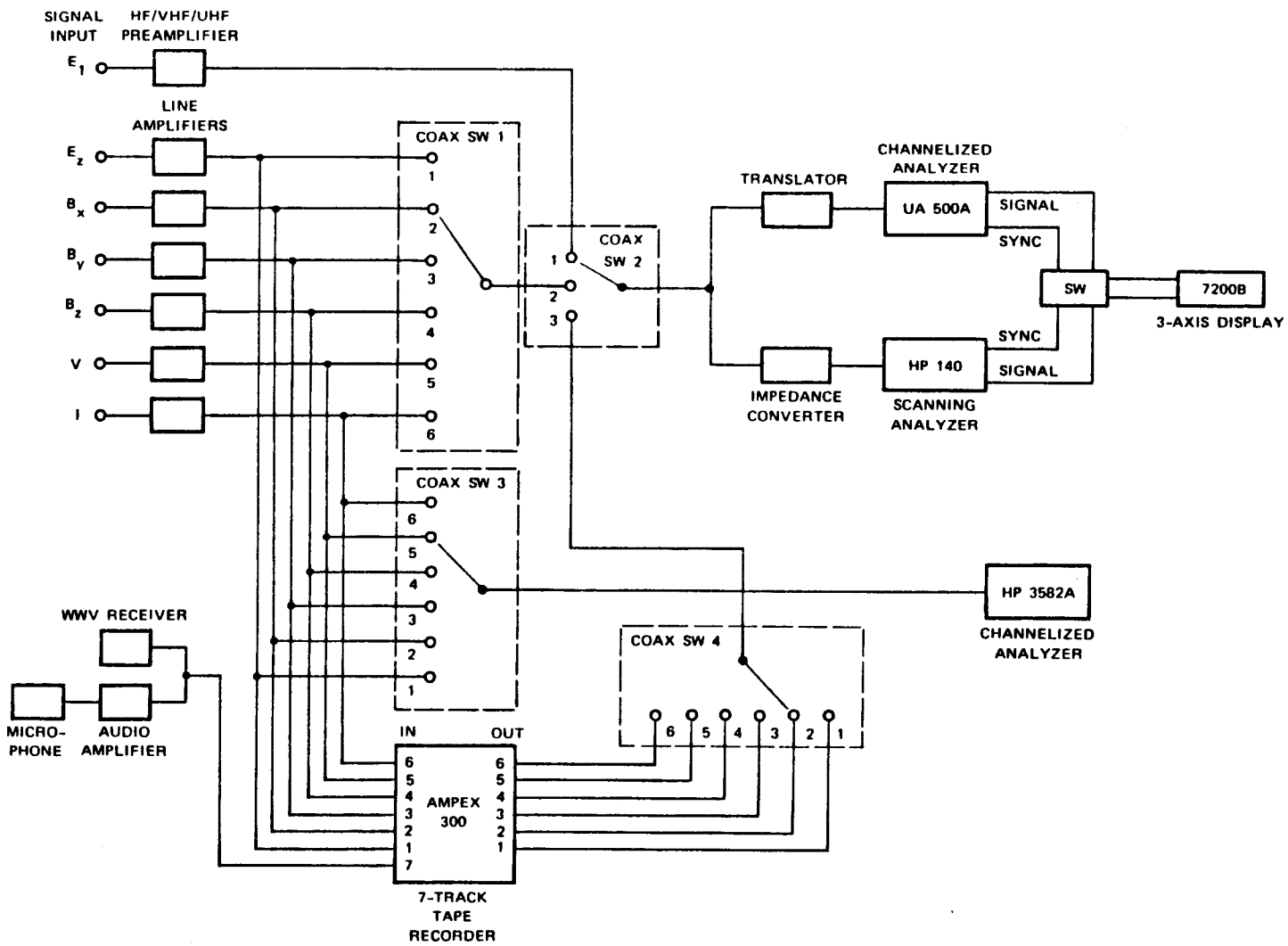


Figure 3-4. Block Diagram of Van Instrumentation System

examined. Figure 3-5 is a block diagram of the portable measurement system.

Data recorded by the portable system were examined with the standard van instrumentation. Care was taken to operate the portable recorder at a gain setting at which the output signal level equaled the input signal level to simplify gain settings. The recorded data were then treated as if they came directly from the sensor employed in the portable measurement.

The portable system was useful for locating sources of noise and signals, tasks to diagnostic noise properties, and making measurements at locations inaccessible to the instrumentation van. The portable instrumentation was especially useful for tracing noise currents flowing in conductors and grounds.

3.5 SYSTEM CALIBRATION

All standard instruments in the system were calibrated in accordance with recommended manufacturers procedures. The electric- and magnetic-field sensors were devices designed especially for use with the instrumentation van. Calibration devices and procedures were developed to ensure that reasonable accuracy was obtained from the sensors themselves and when the sensors were used with the instrumentation van.

The electric-field sensors were first calibrated between two square plates (3.6 m x 3.6 m). The distance between the plates could be varied from 0 to 3 m. A second set of plates, circular in shape and 1 m in diameter, was constructed for general sensor checkout and testing. The distance between the plates could be varied from 0 to 1 m. The top plate could be replaced with a 1-m long bus to simulate conditions in which a sensor was located close to a bus or a wire conductor. A third electric- field calibration technique employed a long overhead wire whose distance above ground could be varied from 3 to 15 m. The entire van could be driven under the overhead wire or located at one side of the overhead wire to explore van the effects of the van's proximity on the performance of the sensors.

The magnetic-field sensors were calibrated by dual coil solenoids that were 0.35 m in diameter and spaced 0.23 m apart. Each solenoid consisted of ten turns of No. 28 wire. The two solenoids produced a uniform field over the sensor length and diameter. Secondary calibration devices were obtained by passing known currents at known frequencies through the bus associated with the 1-m diameter plate used for electric-field calibration and by passing a known current at a known frequency through the high overhead wire also used to calibrate electric-field sensors.

Attempts to calibrate the electric- and magnetic-field sensors in the laboratory were not successful because of stray electromagnetic fields in the laboratory and in other buildings. The calibration devices were always used in remote regions that were free of fields that would influence calibration procedures.

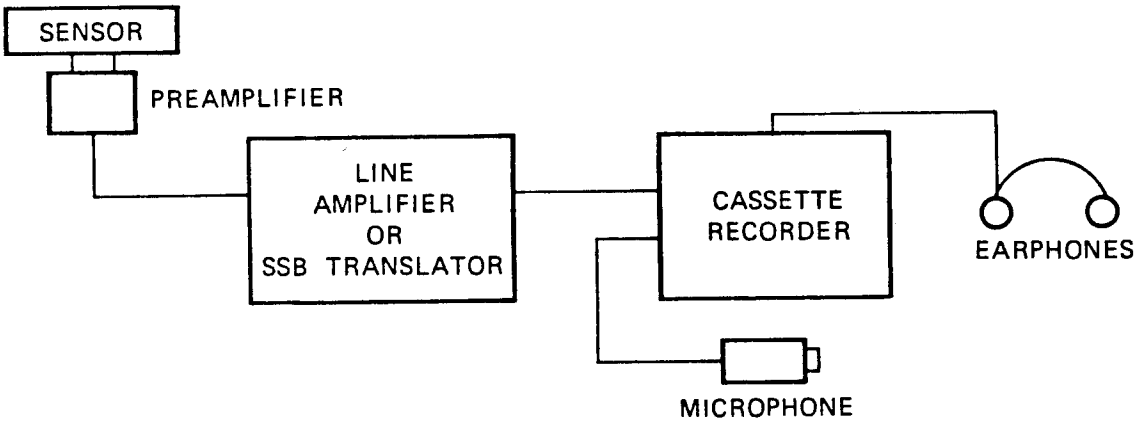


Figure 3-5. Block Diagram of Portable Instrumentation

3.6 MEASUREMENT CAPABILITIES

The instrumentation system could accomplish a wide variety of measurements. Examples of such measurements are

(A) Measurements of the amplitude of signals and noise such as peak value, rms value, average value, Vd, APDs, and quasi-peak value.

(B) Measurements of the amplitudes of power-line harmonics (both voltage and current).

(C) A means of investigating subfundamental signals on power lines.

(D) Measurement and definition of the spectral and temporal characteristics of signals and noise examined by electric-field sensors, magnetic-field sensors, voltage probes, or current probes.

(E) Measurement and definition of the spatial characteristics of electric- and magnetic-fields in the near zone of a source.

(F) A graphic presentation of time variations of the spectral properties of signals and noise.

(G) A means of graphically presenting and evaluating nonstationary signals and noise.

(H) A means of graphically presenting and evualuating nonfrequency-flat noise.

3.7 DATA FORMATS

The measurement system could be adjusted or switched into four different configurations for analyzing signals and noise. Each configuration produced data in a somewhat different format. The formats are described in this section for each configuration. The measurement configurations were as follows:

(A) HP140 scanning analyzer and 3-axis display

(B) UA500A channelized analyzer and 3-axis display

(C) HP3582A channelized analyzer and its internal display.

(D) Standard oscilloscope.

3.7.1 Configuration A

The format for for the presentation of data from Configuration A (the HP140 scanning analyzer and the 7200B 3-axis display) is the most complex because scan time is employed to define the temporal properties of broad-band signals and noise in addition to the conventional means of presenting data from a scanning analyzer. Figure 3-6 illustrates the format for presenting the most frequent data obtained with Configuration A. The single filter of the analyzer (the IF bandwidth) is moved from the lowest frequency to the highest frequency with a linear scan process. The data from this scan are entered into the bottom scan line of the 3-axis display. When the next scan of the analyzer is completed, the bottom line of the 3-axis display is moved up to Line 2 and the new scan is entered in the bottom line. This orderly process continues until all 60 lines of the display are filled. At this time, new data continues to enter the bottom line as old data are pushed off the top line and discarded. The moving display provides a continuous real-time view of all signals and noise contained in the band of frequencies under observation. The latest scan is on the bottom line of the 3-axis view and the oldest scan line is on the top line of the 3-axis view.

The width of the frequency scan can be changed at any time to observe signals and noise in any block of frequencies within the range of the scanning analyzer rf head. The width of the IF filter can be changed (within the normal limits permitted with a scanning analyzer) to change the frequency resolution or impulse response time of the analyzer. The scan time can be changed at any time as long as it is consistent with the normal IF-response limitations of a scanning analyzer. The 3-axis display is fully locked to the operation of the scanning analyzer and faithfully displays 60 successive scans of data from the analyzer without modification or distortion.

Adjusting the scan-time of the scanning analyzer is important when examining repetitive impulsive noise such as that generated by switching devices sychronized to a power-line voltage waveform. The scan time must be set at a value larger than several periods of the impulses. This permits the amplitude of several impulses to be examined during each scan of the analyzer, and the display provides impulse amplitude versus frequency on each line as well as the time between impulses.

The orderly and precise scan-time process and the period of the impulsive signals or noise are not synchronized, although they may by chance be nearly identical for some signals. The difference in the time base of the analyzer and the impulsive signals cause the impulsive signals to appear as slanting lines across the 3-axis view while discrete frequency signals appear as straight lines parallel to the time axis of the 3-axis view. This distinctive separation of repetitive signals and discrete frequency signals in the 3-axis views is very useful for analyzing complex mixtures of the two types of signals.

The display controls are used to enhance a particular feature of the mixture of signals under study. For example, the display amplitude can be compressed to emphasize the temporal features of

repetitive impulsive noise in a 3-axis view, or the amplitude compression can be removed and the vertical control adjusted to show amplitude versus frequency of the impulsive noise and of all discrete frequency signals. Two views of the same set of data are often shown to show both the temporal and spectral aspects of received signals and noise. All views containing both spectral and temporal data have dual scales of the horziontal axis. The frequency limits of the scanning process are provided, and the scan-time values are provided.

Variations in analyzer adjustment can be used to further enhance the observation of features of signals and noise. For example, the frequency scan process of the analyzer can be stopped while maintaining the time scan. This permits noise at a selected frequency and within the IF filter bandwidth to be examined. A detailed temporal view of repetive impulsive noise within a desired bandwidth is presented on the 3-axis display in this mode of operation. In views taken with the frequency scan process stopper, only the scan time value is shown of the horziontal axis of the view.

The scan-time process of the analyzer can be synchronized to the voltage waveform of the power line. This mode of operation aligns all impulses synchronized with the power-line voltage waveform parallel to the time axis. This type of view can often be used to portray the shape of impulses or to show fine-scale temporal detail. When using this mode, care must be taken to avoid confusion between discrete frequency signals and impulsive signals because they both are parallel to the time axis. The rapid switching of analyzer operation between the line synchronized mode and nonline synchronized mode will aid in separating discrete frequency signals from impulsive noise.

A disadvantage of the instrumentation in Configuration A is that a single filter is used to obtain the data shown in the two views. When the filter is at one frequency, it does not measure the instantaneous signal strength at another frequency, and the data shown in the two views are based upon a time- and frequency-sampling process.

When first encountered, the dual presentation of temporal and spectral data in a set of two views of the same data can appear confusing. After some famillarization with the technique, the value of the presentations in analyzing signals and noise becomes apparent and highly useful.

3.7.2 Configuration B

Configuration B consists of the UA500A spectrum analyzer and the 7200B 3-axis display. The UA500A spectrum analyzer simulates 500 narrow- bandpass filters spaced evenly over the spectral width selected by the operator. If a band of frequencies from 0 to 2000 Hz is being examined, the bandwidth of each filter is about 4 Hz. If the spectral width is set at 0 to 100 kHz, the bandwidth of each filter is 200 Hz. The spectral width setting of the UA500A analyzer and the related filter width (or frequency resolution) is then transferred to the horziontal axis of the 3-axis display. The UA500A analyzer samples all filters simultaneously and feeds the amplitudes

of signals and noise in all filters to the bottom line of the display. Each succeeding spectra is entered in the bottom line and pushes previous spectra up one line. The dead time between spectra is less than 2 us and can be ignored for most pratical situtations. The base spectral sampling rate of the UA500A is 20 spectra/s. The basic time-axis duration is then 3 s (20 samples/s x 60 lines). An auxilary control permits the display of all spectra, every second spectrum, every third spectrum, or any reduced rate up to every eighth spectrum. This control also increased the duration along the time axis by the same factor.

Additional controls on the UA500A analyzer permit terminating the spectral width at a value less than the analyzer setting. This process results in an increased spectral sampling rate and an increased bandwidth for each parallel filter. These controls are useful for the analysis of transients and other rapidly changing signal structures.

The UA500A analyzer and the 7200B display provide an excellent means to present the detailed spectral structure of signals and noise with modest time resolution. The combination of instruments is especially useful in analying transients and nonstationary noise conditions. A disadvantage of the UA500A analyzer is its limited dynamic range in amplitude of about 65 dB.

3.7.3 Configuration C

Configuration C consists of the HP3582A spectrum analyzer (also a channelized analyzer) operating as a stand-alone instrument. The instrument is often operated in parallel with the instrumentation in Configuration A and B. It provides increased dynamic range (80 dB compared to 65 dB for the older UA500 instrument) and increased operational convenience because of the automatic presentation of many instrument settings on its CRT display. The instrument has not been coupled to the 7200B display because of its low spectral production rate of 2 spectra/s. The spectral production rate is too low to follow changes in signals or noise with time. The instrument is primarily used to examine signals and noise that are stable with time.

3.7.4 Configuration D

Configuration D consists of a Tektronix Model 2213 dual channel oscilloscope operated in parallel with the other configurations. The oscilloscope is used as a general monitor of waveshapes and the temporal structure of signals and noise. The sweep of the oscilloscope is controlled by a 60-Hz crystal oscillator so that it is synchronized with the line frequency.

Section 4

MEASUREMENTS AT UTILITIES

4.1 GENERAL APPROACH

A series of planning and coordination meetings were held with EPRI personnel immediately after the start of the project in August 1981. These meetings were necessary to select host utilities, provide EPRI with time to contact the host utilities, permit the host utilities to select a coordinator and contact person, and allow SRI International personnel to contact the utility coordinator by telephone to coordinate the details of each utility visit. EPRI selected host utilities at locations throughout the United States to ensure that a wide variety of conditions were available for examination. Where possible, EPRI selected host utilities that had installed experimental DLC systems or were planning to install test DLC systems. In addition, utilities were selected with diverse environmental conditions that varied from open desert, midwestern farm land, coastal weather, suburban areas, and urban areas. A target goal was established of comprehensive measurements of signals and noise on ten distribution lines at ten utilities.

Because the instrumentation van was essentially ready for operation at the start of the project, preliminary field measurements were started as soon as initial planning and coordination efforts with utilities were completed. The project started with a brief series of measurements on distribution lines of the Pacific Gas & Electric Company (PG&E). These measurements permitted SRI International to test measurement techniques and become experienced in the processing and analysis of noise and signals associated with distribution lines with the full support of its laboratory facilities in Menlo Park, California. Minor modifications were made to the van's power system and instrumentation as a result of these local measurements. System changes were made such as replacing the gasoline generator with a diesel-powered generator for greater reliability, operating the motor generator at 64 Hz, adding additional signal channels, improving the sensor channel switching, improving the low-frequency deemphasis of sensors and probes, adding coaxial cable reels to simplify the handling of coaxial cables, and other similar items. These initial measurements also provided solid evidence that the analog magnetic-tape recorder in the van had insufficient dynamic range to provide a permanent record of complete temporal and spectral structure of all desired signal and noise conditions. The dynamic range of the recorder was about 55 dB compared with a real-time dynamic range of the processing equipment of more than 80 dB. This early finding emphasized the need to use real-time data processing and analysis along with Poloraid photographs of the 3-axis display for the primary data record. Late in the project, a Sony digital recording system with a dynamic range of more than 90 dB was installed in the van.

During the initial measurements at PG&E, coordination calls were made to the first three utlities selected by EPRI. These were San Deigo Gas & Electric (SDG&E), Arizona Public Service (APS), and Texas Electric Service Company (TES). Measurement details were arranged with the utility coordinator by telephone. Van travel schedules and operating personnel schedules were arranged to these three utilities. Additional coordination calls were made to other host utilities as the work progressed.

In the following subsections, the work accomplished at each utility is summarized. The subsections are listed in the time sequence of the work at the utilities.

Because of the large amount of data collected at each utility and the similarity of results from utility to utility, the technical details of the work have been integrated into a single section of the report (Section 5). A separate reporting of work accomplished at each utility would have resulted in an excessively large final report with an unwieldy presentation of the significant results and findings.

EPRI added a number of special work tasks to the project. These supplementary work tasks are briefly described in Section 4.12.

4.2 PACIFIC GAS & ELECTRIC COMPANY

The first utility selected for measurements was the Pacific Gas & Electric Company (PG&E). The main office of PG&E is located at 245 Market Street, San Francisco, California. Measurements were made at PG&E at several times during the duration of the projects. Primary measurements were made on 24 June 1981, 5 November 1981 through 23 November 1981, 2 December 1981, and on 15 March 1982. Mr. David Sharer was the PG&E coordinator for the measurements.

For the first measurement, Mr Sharer selected a 13.8-kV distribution line located between San Jose and Morgan Hill, both in California, for special attention owing to a large number of noise complaints from residents along the line. The source of the noise was not identified during the measurement periods; however, later in the project a review of the data from Morgan Hill showed that an RF-stabilized arc welder was being operated north of Morgan Hill. This welder was the source of severe radio noise and the cause of complaints by residents in the area. Three additional 13.8-kV distribution lines in the same general region were selected for study because of high gap-noise conditions on the lines. Seven additional distribution lines located in and around Pleasanton, California, were selected. These lines carried signals from a DLC system that PG&E was testing. DLC signals on PG&E distribution lines were measured extensively. A large number of other signals from customer- operated control systems were found on PG&E distribution lines that also carried DLC signals.

Additional measurements were made on PG&E distribution lines later in the project when the instrumentation van was returned to the

West Coast. These measurements were made to investigate special noise and harmonic problems, test modifications in the instrumentation, and test new sensors and probes as they were developed. The close proximity of PG&E to SRI International, EPRI, and the home base for the instrumentation van (Los Altos Hills, California) permitted the rapid and efficient testing of instrument and measurement procedures.

4.3 SAN DIEGO GAS & ELECTRIC

San Diego Gas & Electric (SDG&E) was the second utility selected for measurements. The main office of SDG&S is located at 101 Ash Street, San Diego, California. Measurements were made from 4 January 1982 through 12 January 1982 and 8 February 1982 through 12 February 1982. Mr. H.E. (Bud) Wegner was the coordinator for SDG&E.

Mr Wegner selected ten distribution lines for measurement that were located in the urban and suburban areas east of San Diego. These distribution lines also carried signals from a DLC system that SDG&E was testing. Extensive noise surveys were made of the entire length of each of the selected distribution lines. Upon completion of the general noise surveys, measuring the DLC signals and noise levels was emphasized at locations at which poor remote DLC terminal operation was obtained. Signals and noise were measured at each selected remote location at and around the DLC carrier frequency. The temporal and spectral features of the noise were established at each location, and the noise was compared with received signal amplitude. The remote-location measurements were made with voltage and current probes that were attached to the input leads of the remote DLC receiver.

During measurements of DLC signals at SDG&S, an unexplained case of intermodulation of the DLC signal by the 60-Hz line frequency was found. The source of the intermodulation was a nonlinear device on the distribution line, and the source was not the DLC receiver. The exact source of the intermodulation was not located.

Signals from customer operated control systems were found on some of the SDG&S distribution lines. These signals were close to the DLC frequency employed by the SDG&E DLC system.

4.4 ARIZONA PUBLIC SERVICE COMPANY

The third utility selected for measurements was the Arizona Public Service Company (APS). The main office of APS is located at 2216 West Peoria Street, Phoenix, Arizona. Measurements were made on APS distribution lines from 30 March 1982 through 8 April 1982 and 18 April 1982 through 22 April 1982. Dr. Merwin Brown was the coordinator for APS. Dr Brown was assisted by Mr. Ron Durham for day to day coordination of the work.

Ten distribution lines were selected by APS during an initial

meeting, with the understanding that the selection could be changed as the work progressed. Several lines were selected in suburban and rural desert areas. Also, lines were selected that served heavy and light industrial complexes. For example, harmonics, signals, and noise generated by a large aluminum production plant were measured.

APS did not have a DLC system under test during the measurement period; therefore, no measurements were made of DLC signals.

During the measurement period, an APS solar-power-generation system located near the Phoenix airport was completed and placed into initial operation. The instrumentation van was used to troubleshoot noise problems in the array control system and to measure harmonics in the 13.8-kV distribution line connected to the solar system. Harmonics from the solar-power-generation plant inverter were quite low on the 13.8-kV distribution line connected to the plant, and they decreased to ambient harmonic levels about one block from the facility. No degradation was found in the quality of power delivered to the nearby customers or the airport facilities from test operation of the solar-power-generation system.

4.5 TEXAS ELECTRIC SERVICE COMPANY

The fourth utility selected for measurements was the Texas Electric Service Company (TES). The main office of TES is located at 115 West 7th Street, Fort Worth, Texas. Measurements were made at TES from 4 May 1982 through 14 May 1982. Mr. John McCoy was the TES coordinator.

Ten distribution lines were selected during an initial meeting with TES personnel. These lines included a 69-kV dedicated transmission line that provided power to alternating-current arc furnaces operated by a steel company located in the southern part of Fort Worth. Other lines selected included distribution lines serving suburban residential areas and distribution lines serving light and heavy industry.

Unusually high voltage- and current-harmonic levels (from frequency-domain measurements) and high impulsive noise that was synchronuous with the power-line frequency (from time-domain measurements) were found on one distribution line serving a few light industrial customers and a large number of residential customers. The source of the harmonics (or impulsive noise) was traced to a small plant that manufacturers envelopes. We did not gain access to the plant, but the temporal and spectral properties of the noise and harmonics on the distribution line feeding the plant were entirely consistent with the use of poorly filtered or unfiltered high-power SCR control devices. The enevlope plant had large transformers on poles adjacent to it to provide secondary power with minimal secondary-line losses. The harmonics (or impulsive noise) passed through the transformers and were imposed on the distribution line. They were detectable along the line, back to a distribution substation and out onto distribution lines that were connected to the same bus in the substation.

The envelop plant is a prime example of the ability of a utility customer of modest size to dominate voltage and current harmonic levels on a distribution line over a large area.

While tracing the source of harmonics from the envelop plant through the distribution substation, the instrumentation van was operated along a fence surrounding a large thermal power plant. Large magnetic-field levels were found near the fence and at other unusual locations. These fields suggested that substantial 60-Hz and harmonic currents were flowing in the fence and along underground pipes and conductors. Measurement sites were selected that avoided fields from the fence and underground conductors.

TES was not testing a DLC system at the time of the measurements; therefore, DLC signals were not examined on the TES system. Measurements indicated that conventional DLC systems would not operate on the distribution line feeding the envelop plant at locations near the plant.

4.6 PUBLIC SERVICE ELECTRIC & GAS COMPANY

The fifth utility selected for measurements was the Public Service Electric & Gas Company (PSE&G) The main office of PSE&G is located at 80 Park Plaza, Newark, New Jersey. Measurements on distribution lines were made from 2 August 1982 through 14 August 1982. Additional measurements were made at the BEST facility operated by PSE&G and at the Deans Transmission Substation immediately following the distribution-line measurements. These additional measurements are included as supplementary tasks in Section 4.12. Mr. Robert Archibald was the PSE&G coordinator.

Ten distribution lines were selected for measurement during an initial meeting with PSE&G personnel. At the request of PSE&G personnel, emphasis was given to the examination of harmonics on distribution lines serving industrial customers.

Severe voltage and harmonic levels were found on two distribution lines serving industrial customers. The lines were heavily loaded, and a wide variety of industrial customers were served. A survey of the two lines did not identify a single source of harmonics, but indicated that many customers contributed to the unusually high harmonic levels. A detailed survey of each customer was not feasible in the time allocated for measurements at PSE&G Of special interest was that some distribution lines had modest levels of 50-Hz current. The source of the 50-Hz was probably an intertie with New York City, which was located a few miles away across the Hudson River.

PSE&G was not testing a DLC system at the time of the measurements.

4.7 SOUTH CENTRAL POWER COMPANY

The sixth utility selected for measurements was the South Central Power Company (SCP).The main office of SCP is located at 2780 Coonpath Road, Lancaster, Ohio. Distribution line measurements were made a SCP from 7 July 1983 through 13 July 1983. Mr. Agit Kadakia was the coordinator for SCP.

SCP is a cooperative power company that serves rural customers in central Ohio. The utility provides electric power to farming areas that are typical of the rural areas in the central part of the country. The distribution lines were often long and served mostly farms and small rural business. The lines ran along rural roads over flat and gently rolling land.

Harmonics and noise at low frequencies were generally lower on the rural lines of SCP than on the lines of utilities located in industralized and urban areas. This would work to the benifit of DLC systems because the remote and substation receivers would have lower noise levels. Nevertheless, an occasional rural customer was found that generated modest harmonic and low-frequency noise levels.

The lower density of customers made it much easier to identify and locate the sources of unusual signals and noise on the distribution lines. Signals and noise associated with the operation of induction motors, series-wound motors, television sets, SCR devices were found on SCP lines just as were found on lines at other utilities. The density of sources was, however, much lower.

The number of sources of gap noise on distribution lines of SCP was about the same as that at other utilities with 12- and 13-kV distribution lines. No significant difference was found that would label rural lines more or less prone to gap noise than lines in urban areas.

Because a DLC system was not installed at SCP during the measurements, the propagation of DLC signals over rural lines was not examined.

4.8 DETROIT EDISON

The seventh utility selected for distribution line measurements was Detroit Edison (DE). The main office of DE is located at 2000 Second Street, Detroit, Michigan. The utility serves a wide variety of residential, small business, and industrial customers. The measurements were made from 24 July 1984 through 4 August 1984. Mr. Donald Hay was the coordinator for the distribution line measurements at DE.

A set of distribution lines in a suburban area north of Detroit was selected for study. A DLC system was being tested on several of the selected lines, which permitted obtaining data on both distribution-line noise and on DLC signals.

Harmonics and noise at low frequencies on DE lines were

generally consistent with those obtained at other utilities. Occasional locations were found with modest to high harmonic levels. These high levels were associated with customer loads that produced harmonics.

The occurrence of gap noise was generally lower at DE than at other utilities, but the weather was not favorable for the operation of gap- noise sources during the DE measurements. Frequent rains kept sources of gap noise wet and prevented them from operating for most of the period of measurement.

Detailed measurements were made of the DLC signals at several remotely located terminals and at other locations that were posible sites for remote terminals. The DLC system under test at DE employed repeaters, and the system design was sufficiently conservative that all remote terminals had sufficient signal to noise for satisfactory operation. One case of signal distortion was noted on a signal from a specific repeater. The repeater, which was mounted on a distribution line pole, had been physically damaged by vandalism. The damaged repeater transmitter caused the signal distortion.

4.9 FLORIDA POWER & LIGHT COMPANY

The eighth utility selected for the measurement of noise and signals on distribution lines was the Florida Power & Light Company (FP&L). The main office of FP&L is located at 9250 West Flagler Street, Miami, Florida. Measurements were made at FP&L from 28 June 1984 through 11 July 1984. Mr. Gary Michel was the corridinator for FP&L.

FP&L serves a wide variety of rural, suburban, urban, and industrial customers. Their service zone is near the ocean, and the measurements were made in the hot, humid month of August.

Prior measurements of radio noise associated with distribution and transmission lines had been completed in southern Florida for the U.S. Navy. These measurements were made to ascertain the extent that power-line noise affected naval communication sites.[2] The measurements provided additional background on radio noise associated with power lines in the humid climate of southern Florida.

Ten distribution lines in and around Miami were selected for examination. Several distribution lines serving the new Miami Metro system were selected to investigate the effects of a modern electrically powered transportation system on power systems. In addition, FP&L had just completed a small solar power generation plant located in a substation adjacent to their headquarters building. Harmonics and noise from the solar plant were briefly examined during initial trials of the system. Radio-noise levels in transmission substations were also measured in an effort to obtain better temporal and spectral data on noise from corona sources.

4.10 CAROLINA POWER & LIGHT COMPANY

The ninth host utility selected for measurement of signals and noise on distribution lines was the Carolina Power & Light Company (CP&L). The main office of CP&L is in Raleigh, North Carolina. The measurements were made from 23 September 1984 through 2 October 1984 and 5 October through 15 October 1984. Mr. Louis Gale was the coordinator for CP&L.

CP&L serves a variety of customers that includes rural areas, small towns, suburban, urban, and industrial customers. 23-kV distribution lines were extensively used in their system compared to the widespread use of 12- and 13-kV lines at other utilities. Although portions of the CP&L system are in coastal areas subjected to salt and corrosion, the measurements were confined to inland areas in and around Raleigh.

A test DLC system was in use at CP&L during the measurement periods. This system was installed on rural distribution lines, and covered large areas. Measurements of DLC signals and noise were made at a number of remotely located terminals and at substations.

CP&L had designed and installed an extensive experimental distribution line. The line was constructed to investigate and study distribution-line problems. Extensive switching was incorporated into the experimental line to permit testing with a variety of line lengths and configurations. Harmonics and noise were measured on this line for several different lengths and configurations. The test line provided a very convenient means of quickly examining and studying a variety of distribution-line phenomena without inconveniencing customers. However, noise levels on the experimental line were considerably different from those found on actual lines with customers. Customer-induced harmonics and noise were not present on the experimental distribution line (except for minor harmonic and noise levels entering the line through the substation supplying power to the line). Thus, testing of DLC systems on the experimental line in its present form would not provide realistic results. The addition of a few nonlinear and switching loads on the experimental line to induce harmonic and noise levels consistent with conditions on actual lines was recommended. As a result of these observations, we understand that CP&L is investigating methods to incorporate realistic noise sources onto the experimental DLC test line. With this addition the CP&L experimental test line will become a valuable test bed in which to test DLC systems under a wide variety of operating conditions.

4.11 VIRGINIA ELECTRIC POWER COMPANY

The tenth host utility selected for measurements was the Virginia Electric Power Company (VEPCO). The main office of VEPCO is located at 700 East Franklin Street, Richmond, Virginia. Measurements were made from 26 November 1984 through 30 November 1984. Mr. Lee Worrel was the coordinator for VEPCO.

The VEPCO distribution system included a large number of 35-kV lines. Measurements at other utilities did not include the use of 35-kV lines. Because harmonic and noise conditions might be different on the higher-voltage distribution lines, a one-week period was established to examine effects found at the higher voltage.

The coverage area of VEPCO includes a wide variety of rural, suburban, urban, and industrial customers. A small test DLC system was in operation at VEPCO in a small town a few miles from Richmond. Most of the measurements at VEPCO were concentrated in the area of the DLC system.

The effects of customer-induced harmonics and low-frequency noise were similar to those found at all other utilities. The number of poles per mile containing sources of gap-noise, however, was higher for the 35-kV lines than for lines operating at lower voltages. The characteristics of gap noise were similar to those found on lower-voltage distribution lines and on higher-voltage transmission lines.

4.12 SUPPLEMENTAL TASKS

4.12.1 General Comments

Several supplemental tasks were added to the field-measurement portion of the effort. Measurements for these tasks were scheduled between measurements at the utlities selected for investigating noise and signals on distribution lines. The supplementary tasks varied from minor efforts such as measuring harmonics or noise at a specific location to major tasks such as defining noise and harmonics from alternate sources of electrical power.

Because the purpose of this report is to provide results of the primary measurements made for Project 2017-1, only a brief description of each supplemental tasks is provided. The supplemental tasks are listed below along with the titles of technical memorada that have been published for most of the tasks. A more complete summary of each supplemental task is provided in Appendix A.

Readers interested in further information about any of the supplemental tasks can obtain additional details from the memoranda listed below.

4.12.2 Supplemental Task 1--Characteristics of Rectifying Device

Task Description: The technical properties of rectifying devices marketed for the increased life and reduced cost of incandescent lighting were briefly examined.

Publication: John D. Meloy, "Some Effects Of A Rectifying Device On House- And Distribution-Line Currents," Technical Memorandum 3564-072882, EPRI Project RP2017-1, SRI Project 3564, SRI International, Menlo Park, California (July 1982)

4.12.3 Supplemental Task 2--Harmonics And Noise From Fuel-Cell Inverter

Task Description: Harmonics and radio noise generated by an inverter associated with a fuel-cell power plant were examined.

Publication: Billy P. Ficklin, Jane M. Clemmensen, and W. Ray Vincent, "Harmonics And Noise From A Fuel Cell Inverter," Technical Memoranda 3564-092482, EPRI Project RP2017-1, SRI Project 3564, SRI International, Menlo Park, California (February 1983)

4.12.4 Supplemental Task 3--Harmonics And Noise From A Magnetohydrodynamic Power Generator Inverter

Task Description: Harmonics and radio noise from an inverter associated with a magnetohydrodynamic power generation facility were investigated.

Publication: Jane M. Clemmensen, Robert L. Bollen, Billy P. Ficklin, and W. Ray Vincent, "Harmonics And Noise From A Magnetohydrodynamic (MHD) Facility Inverter," Technical Memorandum, EPRI Project RP2017-1, SRI Project 3564, SRI International, Menlo Park, California (13 April 1983)

4.12.5 Supplemental Task 4--RF Attenuation of Building

Task Description: The RF attenuation of a building located in a substation was measured. It was measured to obtain data on the isolation of equipment inside buildings from external electromagnetic fields.

Publication: W. Ray Vincent, Jane M. Clemmensen, and Billy P. Ficklin, "Building Attenuation At The Deans Transmission Substation," Technical Memorandum, EPRI Project RP2017-1, SRI Project 3564, SRI International, Menlo Park, California (20 April 1983)

4.12.6 Supplemental Task 5--Investigation Of Capacitor Failures

Task Description: Harmonics and noise on a distribution line at the locations where capacitor failures had been experienced were measured.

Publication: W. Ray Vincent and Robert L. Bollen, "Distribution-Line Harmonics And Noise at Export, Pennsylvania," Technical Memorandum 3564-051783 EPRI Project 2017-1, SRI Project 3564, SRI International, Menlo Park, California (17 May 1983)

4.12.7 Supplemental Task 6--Electrical Environment Of Homes

Task Description: The electrical environment in homes was investigated. The investigation included measuring electrical noise generated by appliances and loads in homes and conducted over home wiring, examining conducted signals from home-control-communication systems, and measuring electromagnetic fields in homes.

Publications: W. Ray Vincent, Jane M. Clemmensen, And Robert L. Bollen, "Residential Electrical Noise Measurements" Progress Report, EPRI Project RP2017-1, SRI Project 3564, SRI International, Menlo Park, California (9 May 1983)

A comprehensive final report is being prepared for this effort.

4.12.8 Supplemental Task 7--Transmission-Line Faults

Task Description: Electromagnetic radiation and conducted harmonics generated by transmission-line faults were measured to ascertain if these signals were useful for locating faults. Radiation and signals from line- to-ground, line-to-line, and line-to-shield-wire faults were examined at three test locations.

Publication: W.R. Vincent, R.L. Bollen, and R.R. Evans, "Transmission Line Fault Measurements," Technical Memorandum 3564-061284, EPRI Project RP2017-1, SRI Project 3564, SRI International, Menlo Park, California (June 1984)

4.12.9 Supplemental Task 8--Harmonics And Noise From Electric Automobile Battery Chargers

Task Description: Harmonics and radio noise from battery chargers for electrically powered automobiles were examined at suburban locations under conditions that simulated widespread use of electric automobiles.

Publication: Data obtained during the measurements were more complex than anticipated and data analysis is still underway. A publication is not available at this time.

4.12.10 Supplemental Task 9--Harmonics And Noise From The BEST Converter

Task Description: Harmonics and noise from the inverter associated with the large scale battery storage of energy were measured. The BEST facility was operated by the Public Service Electric & Gas Company of Newark, New Jersey.

Publication: R. L. Bollen and B. P. Ficklin, "Harmonics And Noise From The Best Converter" Technical Memorandum, EPRI Project 2017-1, SRI Project 3564, SRI International, Menlo Park, CA, December 1983

4.13 DISTRIBUTION SUBSTATION NOISE

Information about conducted noise and harmonics (at frequencies below about 1 MHz) on substation secondary power circuits and on distribution lines leaving substations is included in sections of this report that present similar data from distribution lines and secondary circuits associated with customers. Radio noise at higher frequencies that might affect the performance of VHF and UHF receivers that are located in or near distribution substations (for purposes of load managment) was investigated whenever time and measurement schedules permitted. Data from these higher frequency measurements are included in the report as a separate topic.

Distribution substation noise was measured with a 1-m rod antenna. Because the measurements were made in the distant zone of the noise sources, magnetic-field measurements were not considered necessary. The temporal and spectral features of the noise are presented in formats identical to data obtained at lower frequencies. Spectral and temporal features were associated with the common sources of radion noise found in substations. This association permitted the rapid identification of noise sources.

Section 5

ANALYSIS OF RESULTS

5.1 GENERAL APPROACH

The results of the measurements from all selected utilities have been integrated into a comprehensive presentation of information and data on conducted and radio noise associated with distribution lines. Examples of data from all utilities are used to illustrate typical results. The source of each example, and the pertinent parameters for each example are given in Appendix B. The remarkable similarity of most data from utility to utility permited integrating the data into a single presentation. Special results that were obtained at a single utility or at only a few utilities are clearly identified in the discussion of those examples.

The configuration of the instrumentation was essentially constant throughout the entire project. All instruments in the basic system remained in the system for the duration of the project. Substitute or replacement instruments were not used. No significant instrument repair was required during the project. Although some improvements in and additions to the auxilary instrumention components the course of the work were made; no improvement affected the ability to compare data obtained from one utility with that obtained from another utility.

Examples of improvement in the instrumentation during the project include replacing the 1-m rod antenna with a flat-plate electric field sensor for low-frequency measurements during the first year's work, constructing improved sensor-calibration devices as their need became evident, adding a time-expansion control to the UA500A chann-elized analyzer, and the use of a Sony digitial recorder during the later stages of the work.

Although the configuration of the instrumentation remained nearly fixed, a fixed procedure for taking the measurements was not feasible for measurements at all utilities. Measurement procedures were similar for each utility, but local conditions, differences in distribution-line configurations, the investigation of special problems at some utilities, the existence of DLC systems at some utilities but not other utilities, and other similar reasons required that a flexible approach be used in taking the measurements. In all cases, the instrumentation parameters for each specific measurement are provided in Appendix B.

During the conduct of the project, the published literature about man-made radio noise was reviewed each month. The work of other groups, laboratories, and utilities was used extensively in planning and implementing the work described in this report. Measured data were compared with data from other organizations

whenever possible to ascertain the reasons for any difference or agreement. In general, the measurements were made in accordance with the basic principles of existing standards such as IEEE 430-1976 and other standards listed in Appendix C. However, a broad view of the intent and purposes of the standards was taken rather than strictly adhering to portions of the standards that might prevent making meaningful measurements. Emphasis was placed on making measurements that were consistent with basic electromagnetic principles. For example, both the electric and the magnetic fields were measured when sensors were within the near region of a source; a practice not always followed in investigations of man-made radio noise.

To achieve the purposes of the project, measurements were made over a very wide range of frequencies. Frequencies of interest ranged from as low as 10 Hz to above 1000 MHz. The spectral and temporal properties of noise and the sources of noise changed considerably over this range of frequencies. Figure 5-1 illustrates how some of the types of noise change with frequency. Termonology commonly used to describe noise associated with power lines is used in the figure. At frequencies below the fundamental line frequency, subfundamental discrete frequency signals, broad band noise, and impluses were found. At frequencies immediately above the fundamental line frequency, the well-known voltage and current harmonics dominated most other effects. Transients were also frequently observed on distribution lines with considerable signal power along with harmonics. At frequencies from 1 or 2 kHz to about 1 MHz, the dominant noise was synchronous impulsive noise. This noise could be described as synchronous impulsive noise in the time domain or as harmonics in the frequency domain. The instrumentation could measure the noise in either domain with consistent results. The source of the synchronous impulsive noise was usually utility customers operating various switching devices. At frequencies from about 500 kHz to more than 500 MHz, gap noise from loose and sometimes faulty pole hardware was the dominant noise. Gap noise was sometimes found at lower frequencies (down to about 40 kHz) but was never found below 30 kHz.

Different kinds and sources of noise were found in addition to the types given in the general summary. Other kinds and sources of noise, however, were either more intermittent in occurance, lower in amplitude, or existed at only a few locations. Several other types and sources of noise are presented later in this section to provide a complete summary of all types encountered. The types of noise in Figure 5-1 were the dominant types of noise found associated with distribution lines throughout the country.

5.2 TYPES OF DISTRIBUTION LINE NOISE

For convenience in organizating the complex array of data obtained during the project, the types of noise associated with distribution lines will be presented in general accord with the summary of noise types given in Figure 5-1. Types and sources of noise encountered at low frequencies will be presented first, followed by types found at progressively higher frequencies. Less

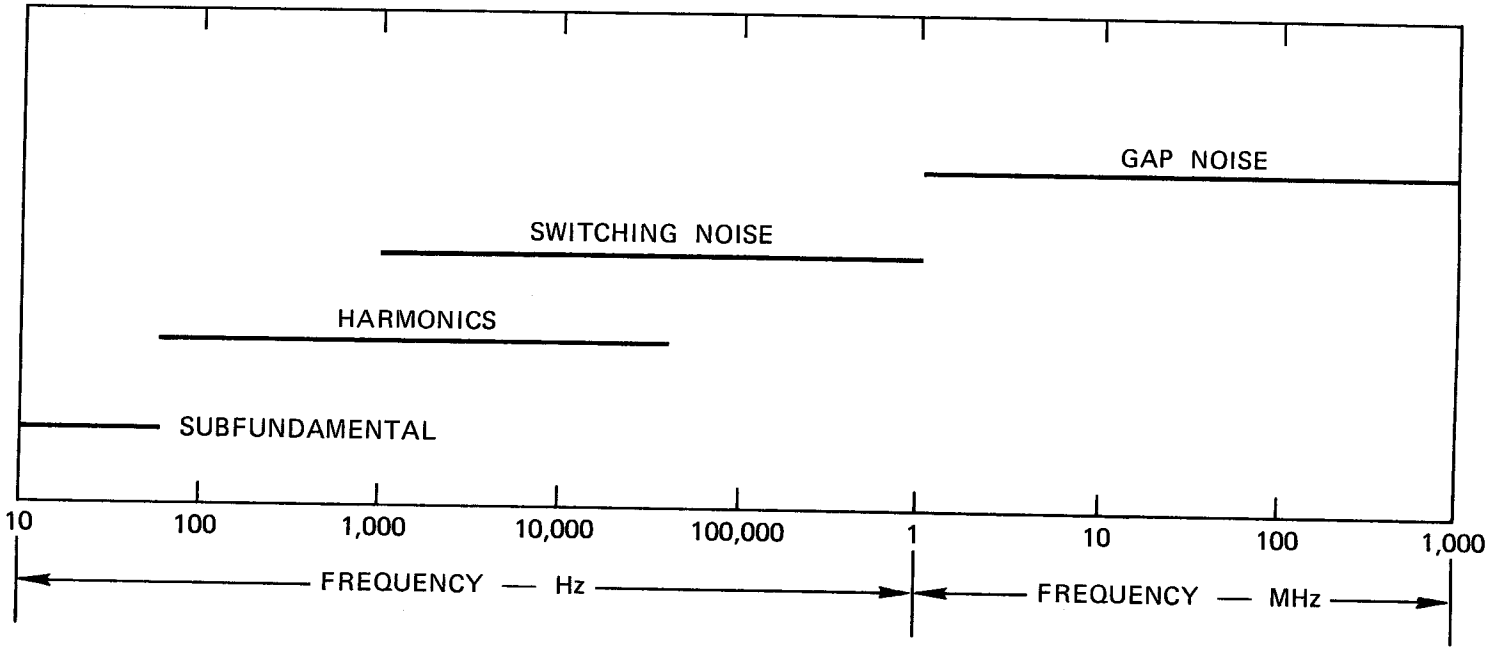


Figure 5-1. Frequencies Affected by Distribution Line Noise

dominant but still important types of noise are also described.

5.2.1 Subfundamental Signals And Noise

Subfundamental signals and noise at frequencies from 5 Hz up to 60 Hz were found on a number of distribution lines located throughout the country. Many discrete frequency subfundamental signals were found that were phase locked to the primary frequency of the power line; they were not always subharmonic frequencies. Hence, the more general term "subfundamental signals" was chosen to describe all discrete frequency signals found below 60 Hz including signals at subharmonic frequencies.

Figure 5-2 shows an example of subfundamental voltage signals found on a 13.8-kV distibution line operated by the Nevada Power Company. Signals can be found in both the 3-axis view and the amplitude-versus-frequency view at 10, 20, 30, 40, and 50 Hz. Related signals above the fundamental frequency at 70 and 80 Hz are also shown as well as a weak second harmonic of 60 Hz and a stronger third harmonic. The current flowing in the distribution line at the subfundamental frequencies shown was below the threshold level of the measurement system. The source of the subfundamental signals was traced to a nearby laboratory containing an SCR-controlled load. The SCRs were triggered by a divide-by-six counter that was synchronized to the 60-Hz voltage waveform of the distribution line. The SCR controller placed voltage spikes on the wiring leading to the distribution-line transformer and on the distribution line. The spectral components of the impulses at the frequencies noted were coupled to the distribution line where the measurement was made.

Subfundamental voltage and current signals have been found on many distribution lines at a number of locations throughout the country. Base frequencies of 10, 15, and 30 Hz that originated from switching devices operated at subfundamantal frequencies have been observed as well as signals at 25 and 50 Hz that were related to nearby power systems operating at these frequencies.

Broadband subfundamental voltage noise was found on a few distribution lines located near substations. Figure 5-3 shows an example of noise voltage on a 13.4-kV distribution line located in southern Ohio. The source of the noise was not identified, and this type of noise is still under investigation.

An unusual subfundamental signal associated with a transmission line is shown in Figure 5-4. A signal at 30 Hz is shown along with a third harmonic at 90 Hz. The signal at 60 Hz may be a second harmonic of 30 Hz or a fundamental signal of the power system. The example was obtained while investigating radiation from an underground cable. Power was not applied to the underground cable at the time of the measurement, and signals from that source were not present. The signals were from a 138-kV transmission line located about 300 m from the measurement site. The measurements were made at about 1430 on 29 February 1984. At this time, a power blackout existed over a significant portion of central California caused by a failure of a transmission line switch at the Moss Landing power plant of the

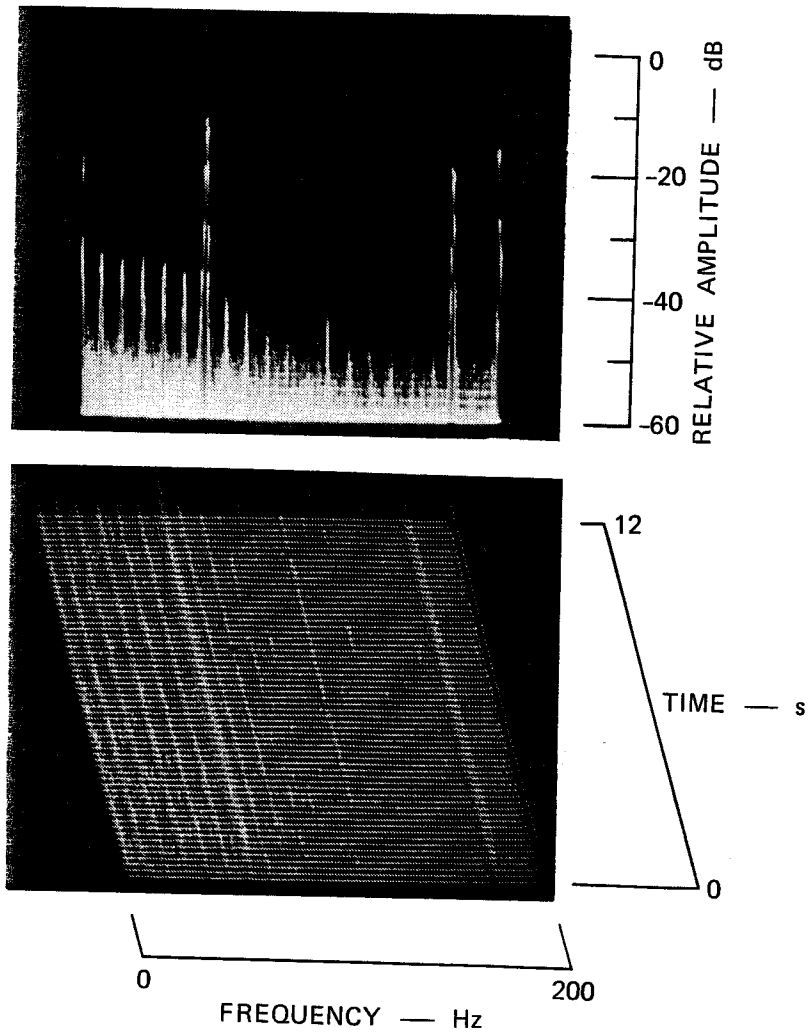


Figure 5-2. Subfundamental Signals on Distribution Line

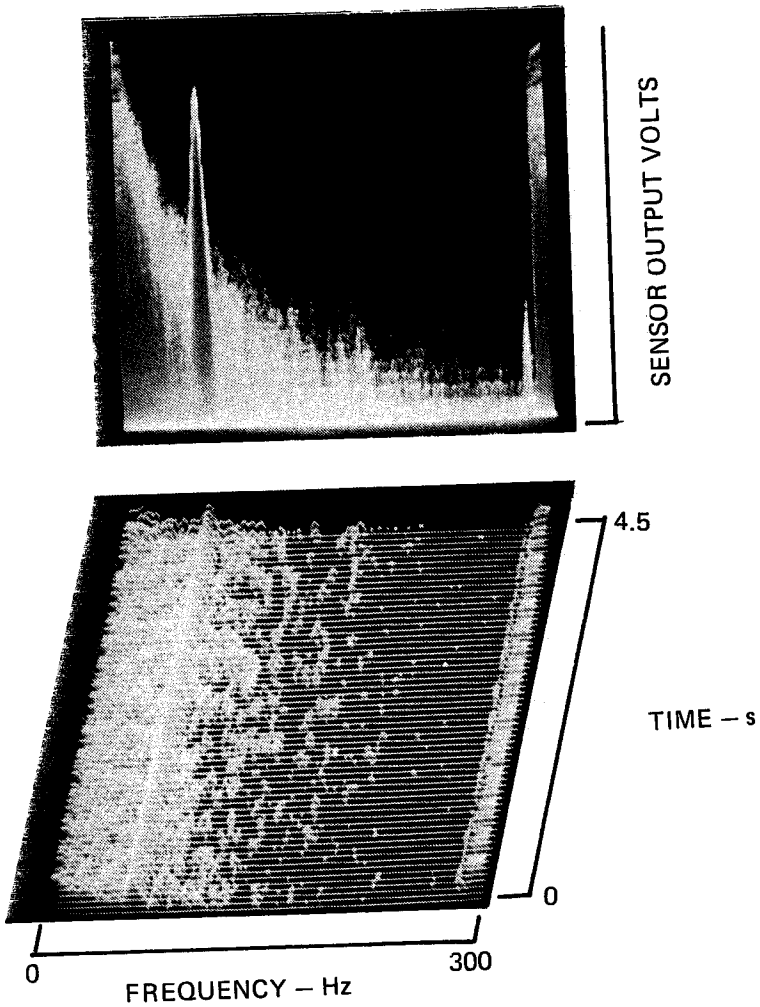


Figure 5-3. Subfundamental Noise on Distribution Line

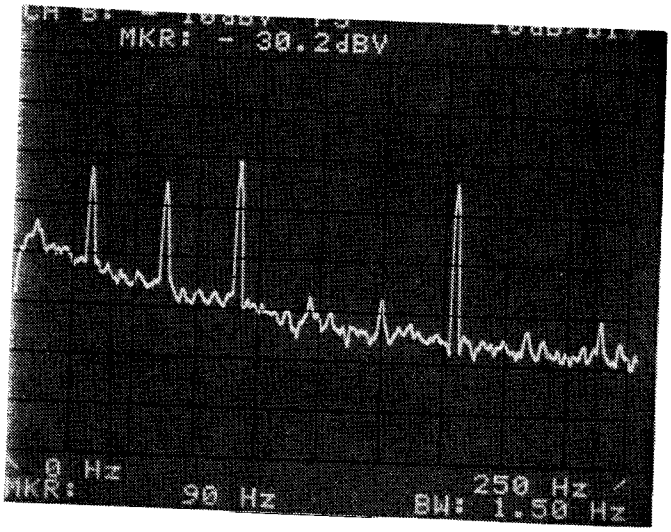


Figure 5-4. Subharmonics Associated with a Transmission Line

Pacific Gas And Electric Company. The 30-signals were associated with the transmission during the time the transmission-line network was being reconfigured.

The examples of subfundamental signals and noise are shown to illustrate that such signals and noise exist. They can occur at almost any location, and they can be caused by simple and inexpensive sources. Subfundamental signals have been found in remote rural locations, in suburban locations, and in areas containing heavy industry.

5.2.2 Harmonics And Line-Synchronuous Impulses

The electric utilities have been active in developing techniques to suppress harmonics since the beginning of the transmission of alternating electric power from generating plants to customers. They have successfully reduced harmonics from generation and transmission equipment to acceptably low and levels. Harmonics on distribution lines, however, can be quite high, and the frequency range of distribution-line harmonics can extend upward considerably beyond the commonly accepted limits for harmonics. Significant harmonic levels at DLC frequencies, for example, were found.

Most utilities consider 1 or 2 kHz the upper frequency limit for the measurement of harmonics. Although there is no commonly accepted upper frequency limit for harmonics, equipment limitations frequently limit measurements to about the 20th harmonic (about 1200 Hz). This limit usually includes the primary harmonics and those of significance for the design of distribution line components. Very little data were found in the published literature about harmonic levels on distribution lines at higher frequencies. Therefore, measuring voltage and current harmonic levels at DLC frequencies and at other frequencies that might be used for controlling electrical power in distribution systems was emphasized. Individual voltage and current harmonics could be resolved and measured by the instrumentation system up to Harmonic Number 500,000 (30 MHz).

During on-site measurements, harmonics usually were first examined by making a general survey of each distribution line with electric- and magnetic-field sensors mounted on the roof of the instrumentation van. The van was driven along the distribution line while the general level of harmonics was observed. This procedure did not produce precise voltage and current values for a number of reasons. The roof-mounted sensors were too far from the distribution line for precise measurements; the total electric and magnetic field from all conductors was examined rather than the field from a single conductor; common-mode harmonics sometimes dominated; and the distance between the overhead conductors and the sensors varied as the van was driven along the line. The measurements did provide a means of examining the gross amplitude of harmonics along distribution lines, locating regions of unusual harmonic amplitude, and obtaining spectral and temporal information on harmonics and noise along each line. The procedure was very useful in identifying the general location of harmonic and noise sources.

The general survey was then followed by more detailed measurements of harmonics at specific locations. These included the measurement of voltage and current harmonics with directly coupled probes, the identification of specific sources, and the investigation of the amplitude of harmonics at DLC terminals.

High current harmonic levels were often found at multiple locations along distribution lines. High current harmonics were usually accompanied by modest increases in voltage harmonics at frequencies below about 2 kHz. Above about 2 kHz, the assumption that the line was a low-impedance conductor did not apply, and voltage and current harmonics were not directly associated with the amplitude of voltage and current at the fundamental line frequency. The current and voltage harmonic levels at frequencies above about 1 or 2 kHz varied widely from one location to another along a distribution line, from one distribution line to another, and sometimes with time of day. These variations in harmonic amplitude were similar at all utilities. Measureable discrete frequency harmonics often extended to frequencies above 1 MHz.

The primary reason for variations in harmonic amplitude along a distribution line was the spatial distribution of customers operating nonlinear loads. A few cases of line resonance, caused by the improper location of capacitors, were found. Line resonance caused high current and voltage harmonic levels in sections of a line at specific harmonic frequencies. The major cause of high current and voltage harmonics on distribution lines, however, was customer loads. Harmonics were generally higher along distribution lines than at the substation origin of the lines.

Specific sources of harmonics were identified at a large number of locations. Customer-operated switching devices that operated synchronously with the line frequency were the primary source of harmonics. These included solid-state load controls of many varieties, television sets with switching circuits that control picture scanning processes, computer displays, and many similar devices. Other nonlinear loads such as battery chargers, rectifier loads, fluorescent lights, and saturated magnetic devices also severely distorted the current waveform that was synchronuous with the line frequency. The low cost and effectiviness of modest size SCR devices and other solid-state switches used for controling loads in manufacturing plants of all sizes, office buildings, service busineses, retail stores, and homes has created a vast number of switching-type loads. The great variety and diversity of utility customers makes it impossible to provide a complete description of customer loads and their generation of harmonics.

The effects of synchronuous impulses can be described in the frequency domain as harmonics of the fundamental impulse switching rate or in the time domain as impulses with a defined shape and period. The instrumentation van had the capability of measuring signals in either one or both domains. Subsequent discussion and examples will use data from both the frequency domain and the time domain to illustrate the relationship between the two types of data.

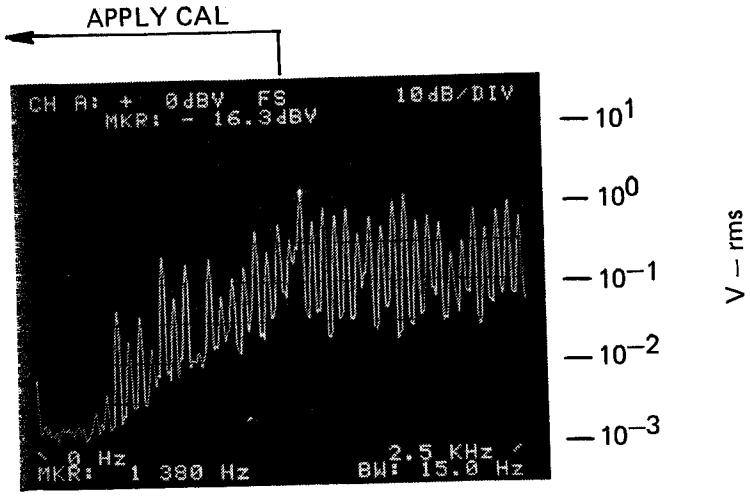
The background voltage harmonic levels from a 23-kV distribution

line at a substation are shown in Figure 5-5 for frequency ranges of 0 to 2.5 kHz and 0 to 5 kHz. The data were taken from a coupling capacitor connected to the 23-V line and used by a DLC substation communication terminal. The data show voltage harmonic levels imposed on a DLC receiver terminal, and they show the approximate harmonic levels on the 23-kV line. Harmonic levels below 1 kHz must be corrected in amplitude because the voltage probe used for the measurements deemphasized low-frequency signals. Above 1 kHz, voltage harmonic amplitude can be scaled directly from the two frequency domain views. The low-frequency deemphasis reduces the dynamic-range requirements of the instrumentation system and allows harmonics to be measured over a very wide bands of frequencies. The probe design works well with the frequency-domain instrumentation used in the measurements, but it cannot be used with simple voltmeter indicators of amplitude. Table 5-1 provides the amplitude of harmonics below 1 kHz.

Voltage harmonics and noise at higher frequencies (0 to 20 kHz) at the same location are shown in Figure 5-6. Peaks and nulls in the amplitude of the voltage signals are shown with strong peaks at about 10 and 12 kHz. These peaks and nulls result from source and line resonance conditions that were found on all distribution lines at DLC frequencies. Data were also taken at a DLC frequency used by the utility of 12.5 kHz to investigate harmonic and noise levels at and near the DLC frequency. Figure 5-7 shows the amplitude of individual voltage harmonics and noise level near the operating frequency of a DLC system from the coupling capacitor. The frequency scale was centered at the DLC frequency, and harmonics and noise at frequencies 250 Hz above and below the DLC frequency are shown. The maximum harmonic amplitude in the immediate vicinity of the DLC frequency was about 10-mV rms. The noise level between the harmonics was about 20 dB below the harmonic level at about 1-mV rms.

The substation also contained a transformer to couple DLC signals onto the 23-kV distribution line. Harmonic levels at the transformer terminals were also measured. Figure 5-8 shows the voltage harmonic levels at the transformer terminals over the frequency range of 0 to 2 kHz. The amplitude of harmonics below 1 kHz must be corrected for the low-frequency deemphasis of the measurement probe. Harmonic amplitudes above 2 kHz can be read directly from the figure. Figure 5-9 show harmonic and noise amplitudes at frequencies from 0 to 20 kHz. Individual harmonics cannot be resolved in the view because of the wide frequency range shown. A peak in voltage harmonic amplitude was found at about 10 kHz. Harmonic levels remained constant for the time of the 3-axis view.

Measurements similar to those shown in Figures 5-5 through 5-9 were made at a number of locations at each utility that were testing a DLC system. Although some details of the results were different, the general harmonic and noise levels were similar at all locations. Additional examples will illustrate some of the differences found from one site to another, but a complete accounting of all small differences is beyond the scope of the report. Figure 5-10 shows voltage harmonic amplitudes on the secondary side of a coupling transformer (at another substation of the same utility for the previous examples) for a frequency range of 0 to 2 kHz. These data can



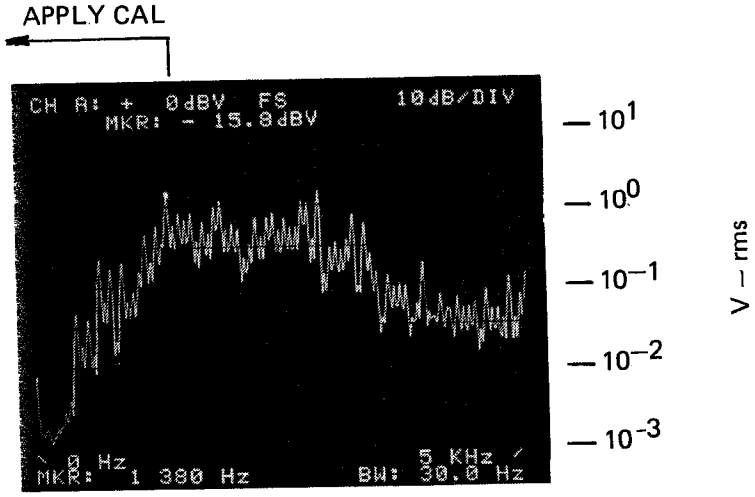


Figure 5-5. Voltage Harmonics, 0 to 2.5 and 0 to 5 kHz, Coupling Capacitor, Substation A

Table 5-1

VOLTAGE HARMONIC VALUES

Harmonic No.	Measured dBv	Cal. Factor dB	Amplitude V
5	-51	30.1	0.09
6	-46	23.8	0.08
7	-26	17.5	0.38
8	-34	9.5	0.06
9	-26	8.4	0.13
10	-33	5.3	0.04
11	-11	2.4	0.37
12	-22	1.9	0.10
13	-13	1.1	0.25
14	-39	0.7	0.01
15	-12	0.4	0.26
16	-21	0.2	0.09
17	-19	0.0	0.11
18	-15	0.0	0.18
19	-8	0.0	0.40
20	-11	0.0	0.28
21	-5	0.0	0.56
22	-10	0.0	0.32
23	+2	0.0	1.25
24	-5	0.0	0.56
25	-1	0.0	0.89
26	-2	0.0	0.79
27	-1	0.0	0.89
28	-8	0.0	0.40
29	-4	0.0	0.63
30	-6	0.0	0.50

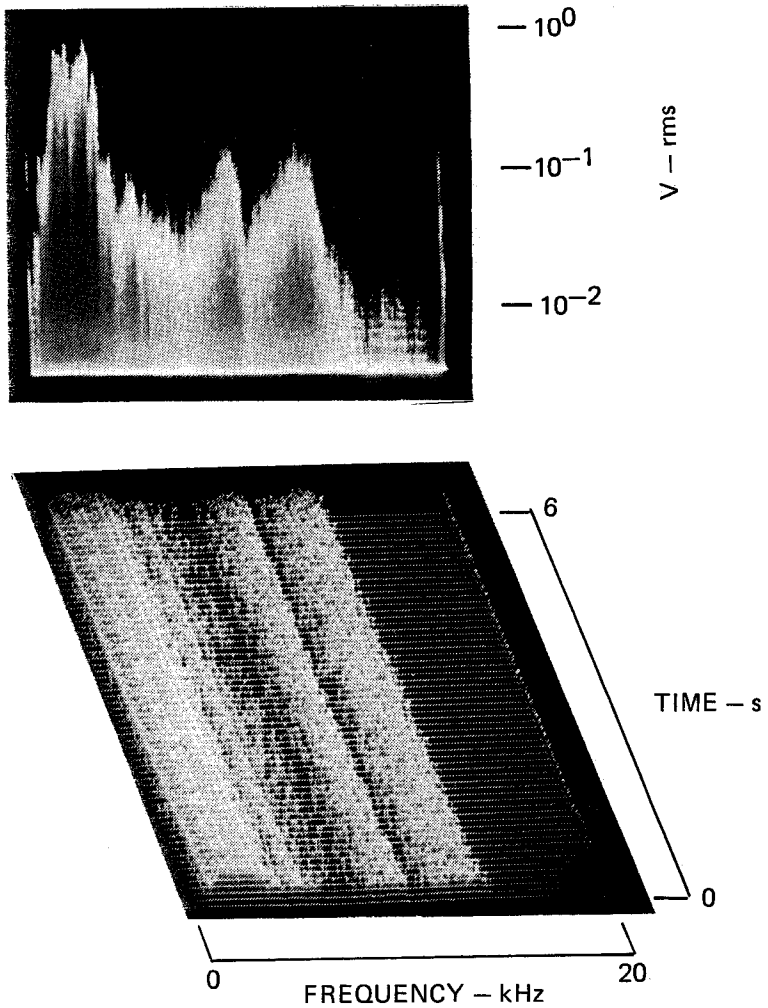
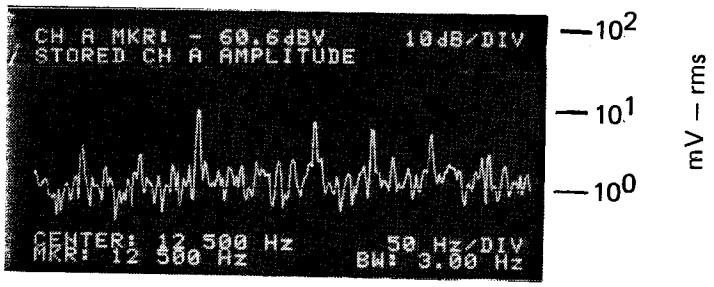


Figure 5-6. Voltage Harmonics, 0 to 10 kHz, Coupling Capacitor, Substation A



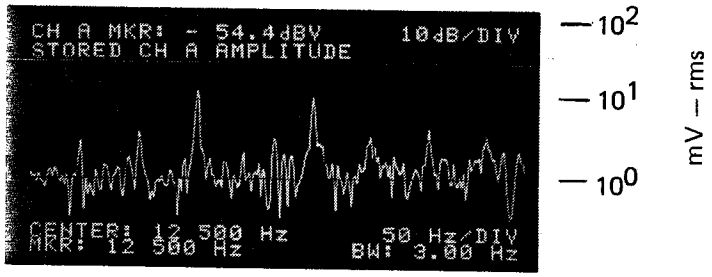


Figure 5-7. Voltage Harmonics Near 12,500 kHz, Coupling Capacitor, Substation A

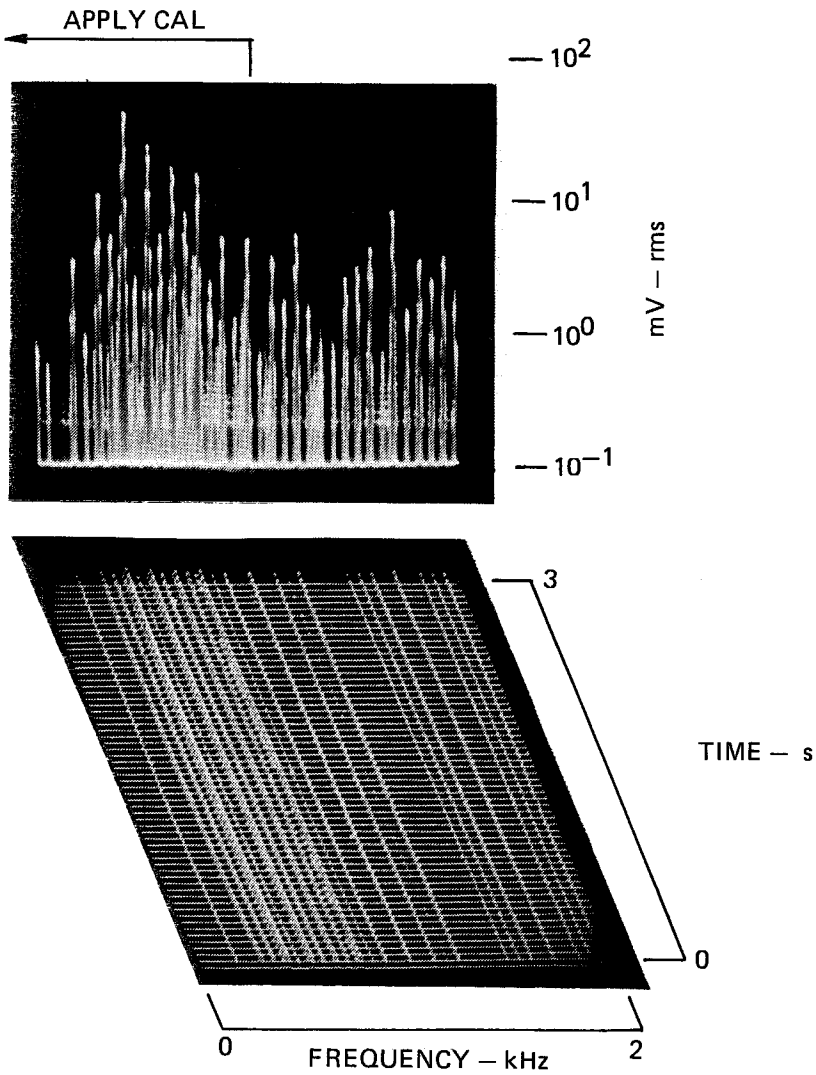


Figure 5-8. Voltage Harmonics, 0 to 2 kHz, Transformer Coupling, Substation A

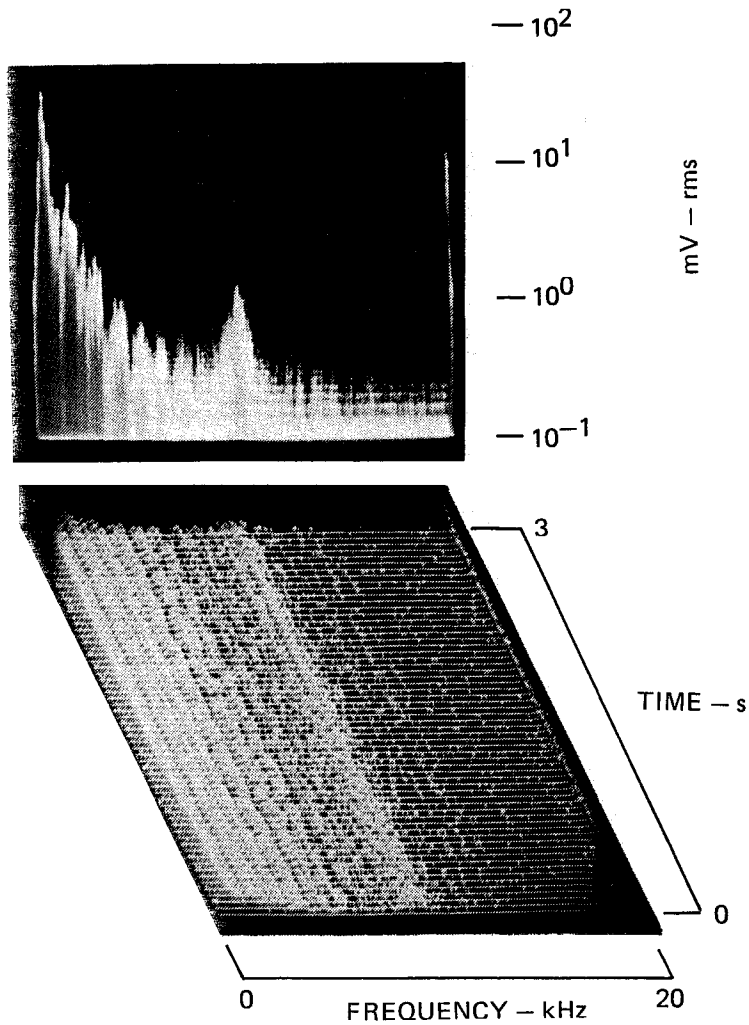


Figure 5-9. Voltage Harmonics, 0 to 20 kHz, Transformer Coupling, Substation A

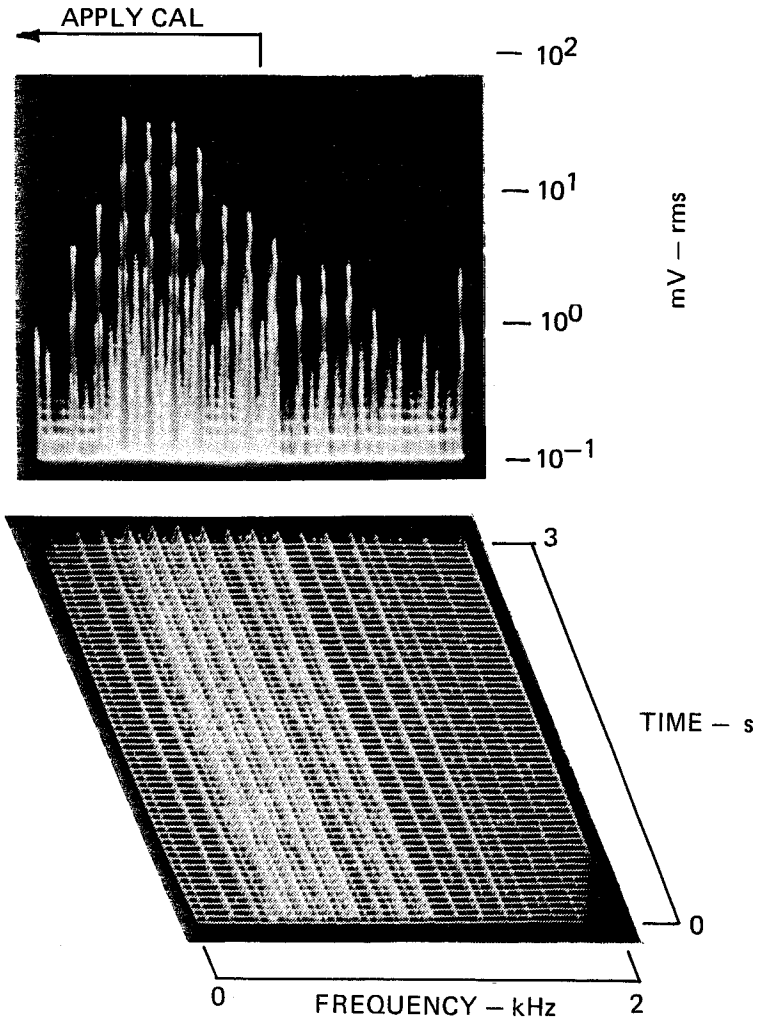


Figure 5-10. Voltage Harmonics, 0 to 2 kHz, Transformer Coupling, Substation B

be compared with those in Figure 5-8 to show the similarity in data from one substation to another. Figure 5-11 shows data taken at the second substation over the frequency range of 0 to 20 kHz. Voltage harmonic levels in Figure 5-11 can be compared with those shown in Figure 5-9. The peak in voltage harmonics of about 10 kHz found in Figure 5-9 moved up in frequency to about 17.5 kHz at the second substation. The harmonics were again stable in amplitude for the duration of the 3-axis view. The high-frequency peak in harmonic amplitude was present in most data taken at substations and along the distribution lines. The frequency of the peak ranged from about 5 kHz to about 18 kHz.

Voltage harmonics at a third substation were somewhat different from those of the previous examples. Figure 5-12 shows voltage harmonic levels over the frequency range of 0 to 5 kHz. Dual peaks in harmonics are shown in the view, which suggest that multiple-pulse power-conversion devices were operating on the distribution line. While observing harmonic conditions on the line, the highest frequency set of harmonics at 4800 Hz disappeared from view leaving the harmonic pairs at 5460 Hz and 2820 Hz. Figure 5-13 shows voltage harmonic levels from 0 to 20 kHz. The large frequency range of the view prevents resolving individual harmonics and the harmonic pairs shown in the previous two figures. Two resonant peaks in general harmonic level are shown at about 5 kHz and 11 kHz. A transient is shown about 9 s along the time axis with a spectral peak near 15 kHz.

The pairs of harmonics shown in Figures 5-12 and 5-13 suggest that switching impulses should be present on the distribution line. Figure 5-14 shows an example of the temporal detail of impulses in the 3-axis view and the amplitude of the impulses with frequency in the upper view. The impulses are the slanting lines across the 3-axis view. The low- amplitude discrete frequency signals are transmission line power carrier signals. Pulse pairs are shown in the 3-axis view, and they are spaced 16.6 ms apart, and they are synchronized to the line voltage waveform. The impulses in each pair are separated by about 4 ms. The amplitude of each pulse in the pairs is shown in the upper view. Small variations in amplitude with frequency are shown. These variations result from small differences in impedance from the two switches responsible for pairs of impulses to the measurement location.

The examples presented in Figures 5-5 through 5-14 were taken at DLC receiver terminals located in substations. Figure 5-15 shows data taken at a remote terminal located near the end of a distribution line about 8 miles from a substation. The amplitude of harmonics are shown over the frequency range from 0 to 20 kHz. Distinct peaks in harmonic amplitude were found near 8 and 15 kHz. A deep null in harmonic amplitude was found at 12 kHz. The measurement was made at the secondary of a distribution-line transformer that was used to connect DLC signals to the distribution line. The example can be compared to data from substation locations given in Figures 5-11 and 5-13.

Data shown in Figures 5-5 through 5-15 repesent periods with little change in amplitude with time. Figure 5-16 was taken at the same location as that for Figure 5-15 but 33 min later. A large increase in noise (a 20-dB increase) was observed at the frequency

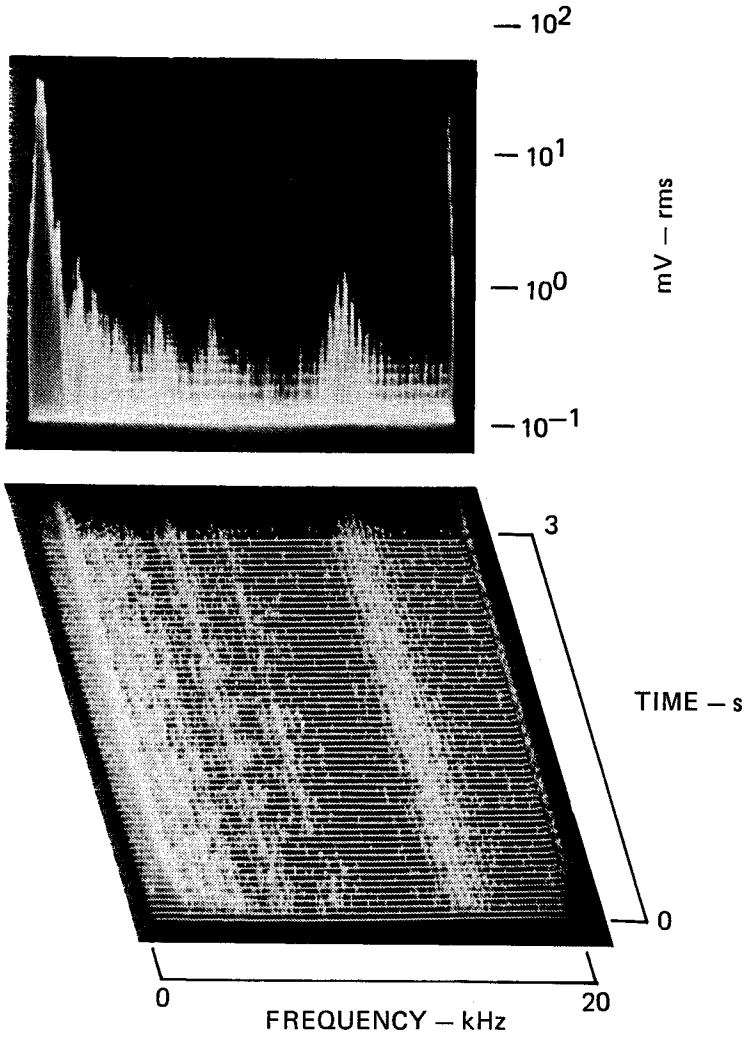


Figure 5-11. Voltage Harmonics, 0 to 20 kHz, Transformer Coupling, Substation B

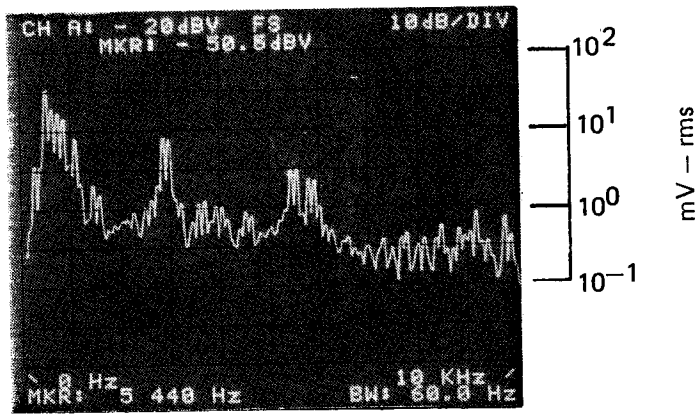


Figure 5-12. Voltage Harmonics, 0 to 5 kHz, Transformer Coupling, Substation C

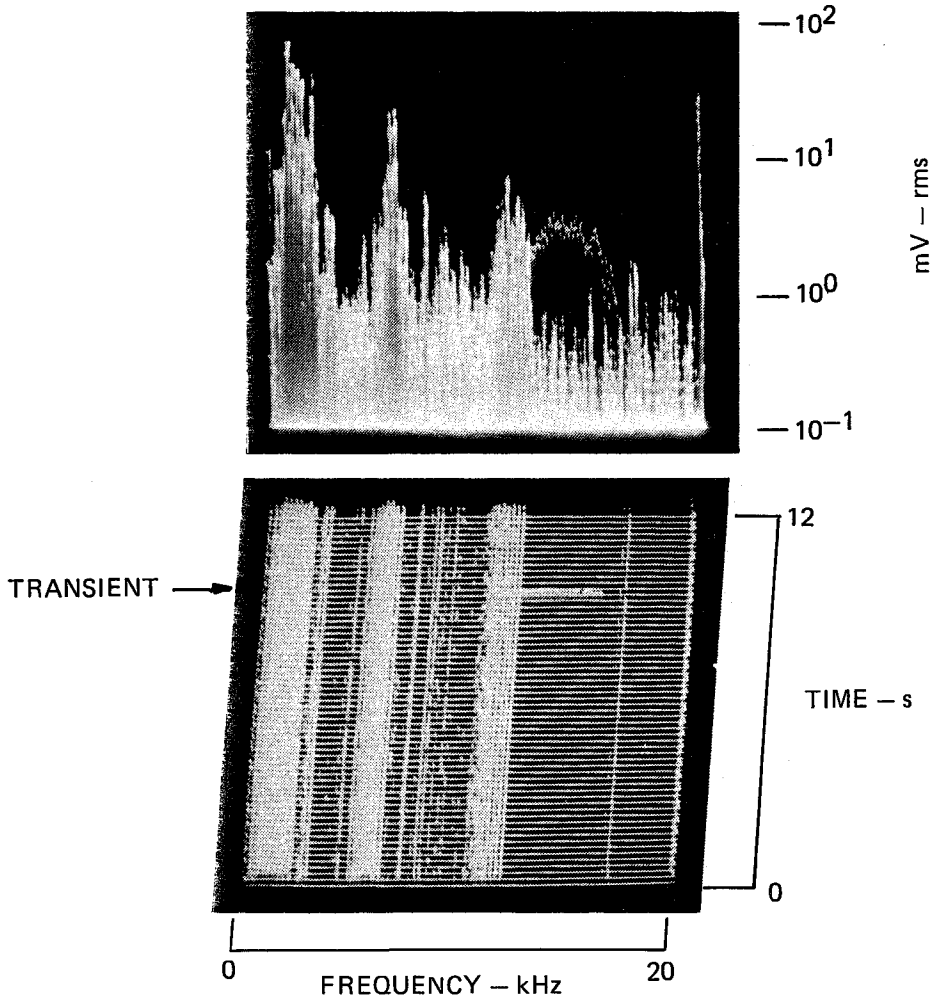


Figure 5-13. Voltage Harmonics, 0 to 20 kHz, Transformer Coupling, Substation C

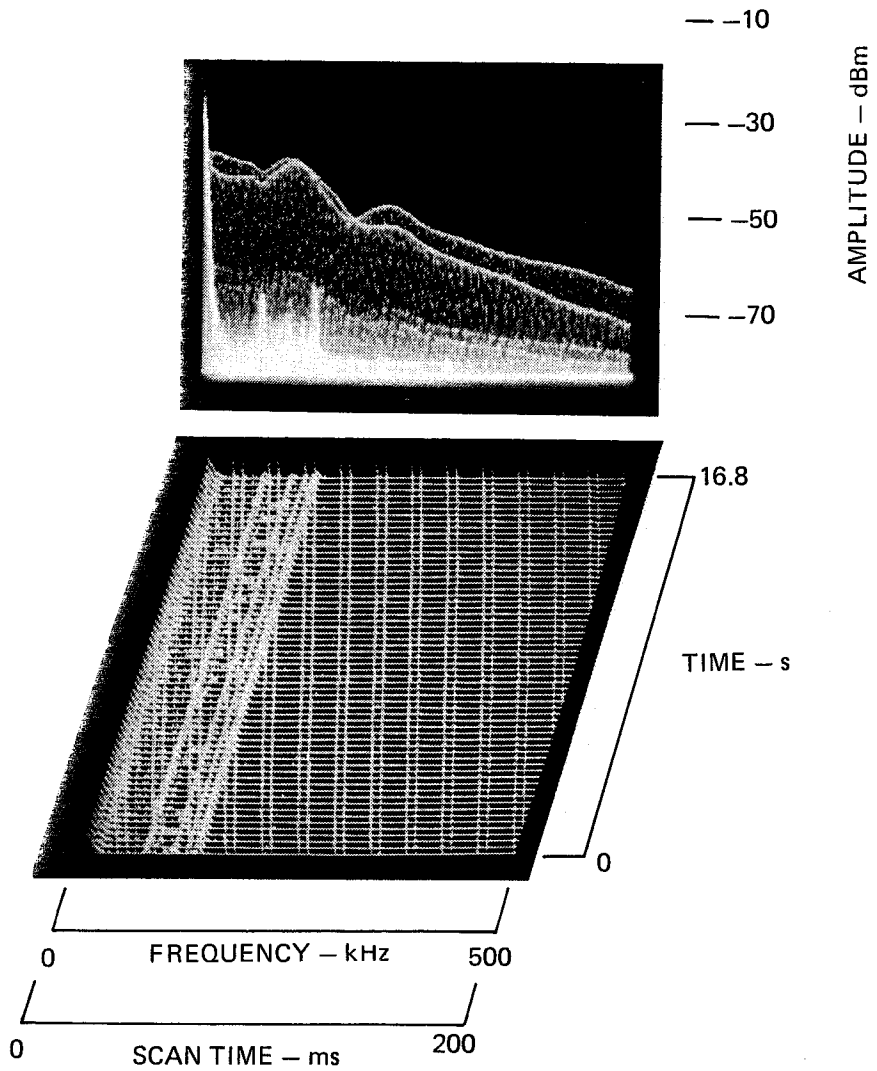


Figure 5-14. Synchronous Impulsive Noise, 0 to 500 kHz, Transformer Coupling, Substation C

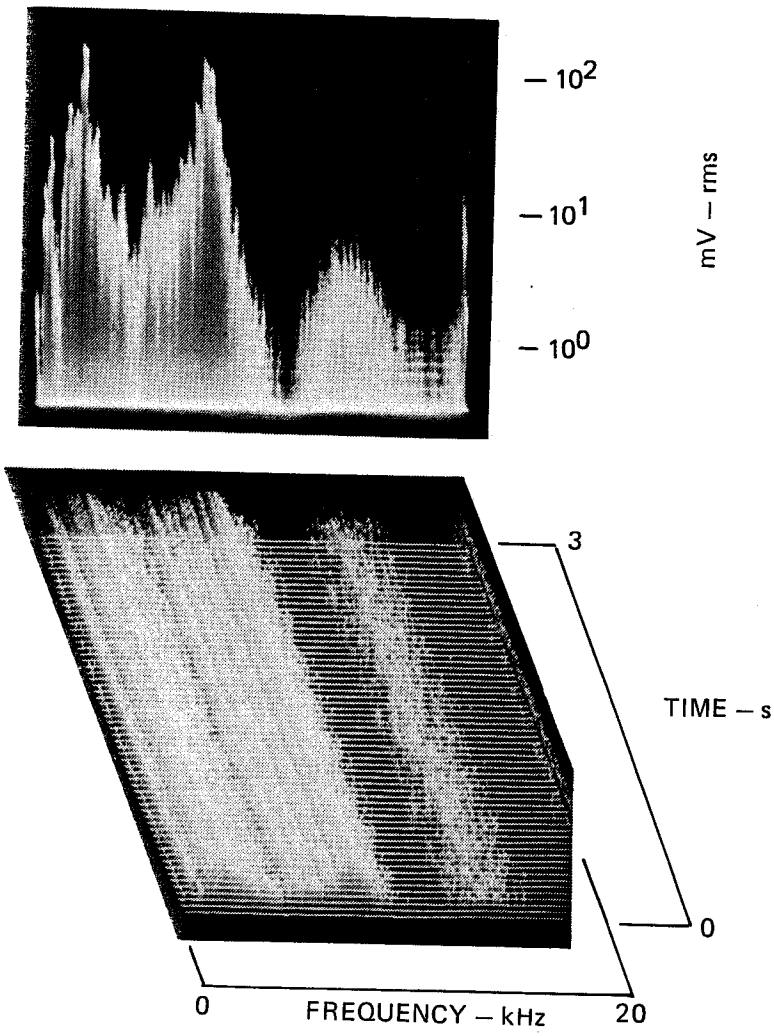


Figure 5-15. Voltage Harmonics, 0 to 20 kHz, Capacitor Coupling, 23-kV Line, Site A

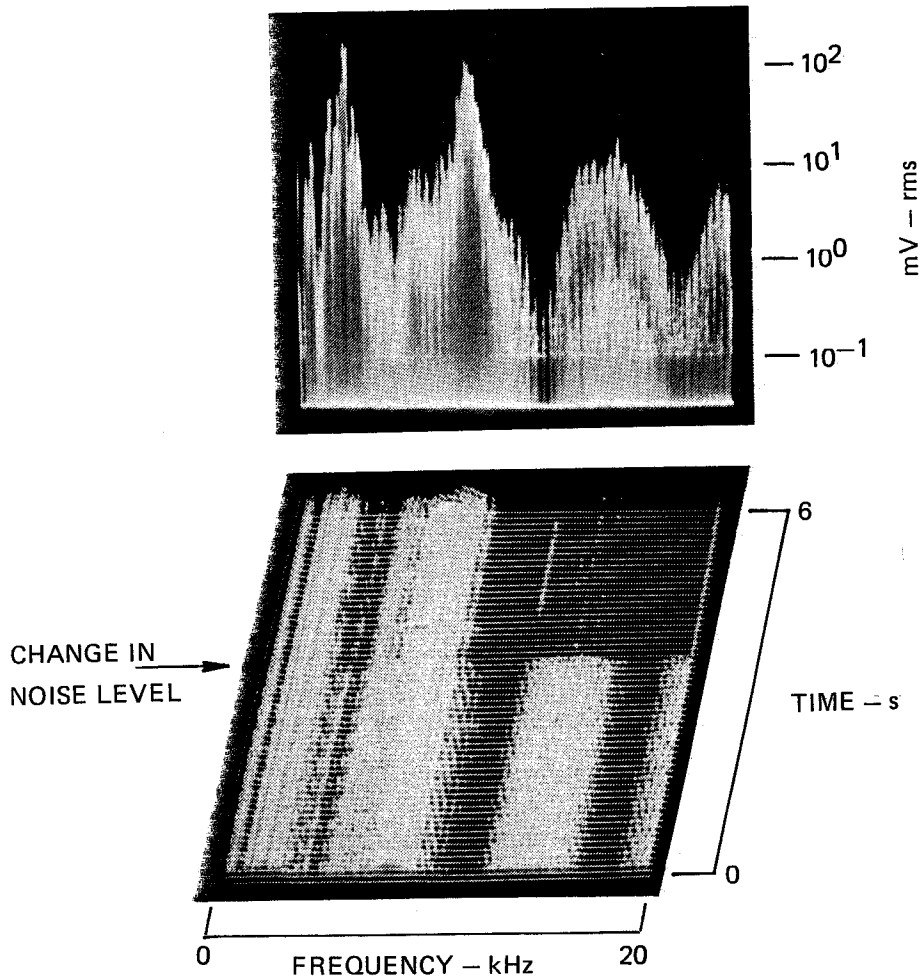


Figure 5-16. Sudden Change in Harmonics, 0 to 20 kHz, Capacitor Coupling, 23-kV Line, Site A