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Instrumentation for Motor-Current Signature Analysis Using Synchronous Sampling

K. N. Castleberry

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Instrumentation and Controls Division

INSTRUMENTATION FOR MOTOR-CURRENT SIGNATURE ANALYSIS USING SYNCHRONOUS SAMPLING

K. N. Castleberry

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
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ABSTRACT

Personnel in the Instrumentation and Controls Division at Oak Ridge National Laboratory, in association with the United States Enrichment Corporation, the U. S. Navy, and various Department of Energy sponsors, have been involved in the development and application of motor-current signature analysis for several years. In that time, innovation in the field has resulted in major improvements in signal processing, analysis, and system performance and capabilities. Recent work has concentrated on industrial implementation of one of the most promising new techniques. This report describes the developed method and the instrumentation package that is being used to investigate and develop potential applications.

1. INTRODUCTION

The field of motor-current signature analysis (CSA) encompasses a number of techniques that use the presence and amplitude of various frequency components in a motor current to derive condition information about the motor and the driven load. These frequency components result from drive-train vibrations and small variations in the motor load, which cause corresponding changes in the motor current. Since the signals of interest are usually very low in amplitude, often 60 to 80 dB below the amplitude of the 60-Hz line component, special processing is normally required to extract them. Most of the published work in CSA has depended heavily on analog signal processing schemes such as assorted filter configurations and demodulation techniques, which act to separate load-related signals from the large 60 Hz. After recovery by either technique, the composite of the extracted signals is typically amplified by a factor of 100 or more before being fed to either a spectrum analyzer or to a computer, where the composite is digitally sampled and subsequently broken down into its constituent frequency components.

Personnel in the Instrumentation and Controls Division of the Oak Ridge National Laboratory (ORNL) have been investigating the application of various signal processing techniques in the field of CSA for several years.[1] Those studies and ever advancing electronic technology have led to the development of a digital signal processing (DSP) scheme that does not require complex preprocessing of a motor-current signal.[2] Instead, it employs direct-digital sampling of the raw motor-current with a high-resolution analog-to-digital converter (ADC) driven by a precisely controlled sample clock. Subsequent application of DSP allows the analysis process to be easily adapted for monitoring a variety of industrial systems without changing the hardware. By avoiding elaborate analog preprocessing, the DSP approach also avoids most of the inherent weakness of analog preprocessing schemes.

The Electrically Driven Equipment Analyzer (EDEA) developed by ORNL researchers provides the means to both sample and analyze motor-current signals in either laboratory or industrial settings. It also allows both sample and digitally processed data to be archived and later recalled for additional analysis. This report describes that instrumentation.

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[1] S. F. Smith and K. N. Castleberry, "Advanced Techniques in Current Signature Analysis," pp. 63-75 in *Proceedings of the 46th Meeting of the Mechanical Failures Prevention Group, Virginia Beach, VA, April 7-9, 1992.*

[2] K. N. Castleberry, *Distributed Monitoring System for Electric-Motor-Driven Compressors*, ORNL/TM-13127, Oak Ridge National Laboratory, January 1996.

2. SAMPLING CONSTRAINTS

When computer-based analysis of a signal is an objective, a few conditions must be considered before converting an analog signal into digital data. Most of these conditions relate to the analysis method that will be applied to the resulting sample data. The fast Fourier transform (FFT), which provides a means for transforming a finite record of data samples into a finite group of frequency domain components, is the most commonly applied mathematical tool for CSA work, and this presentation is no exception. One of the sampling conditions related to the FFT is selection of the number of data samples to be acquired and analyzed. The FFT can only operate on a sample record of N samples where $N = 2^r$ and r is a positive integer typically in the range of 5 to 12, yielding N's of 32 to 4096 in binary steps.

The sample rate is generally determined based almost entirely on the desired bandwidth of the final transform. According to the Nyquist criterion, if the samples of a band-limited signal are to carry complete information about the signal, the sample rate, f_s, must be at least twice the maximum frequency of interest. A signal bandwidth of 500 Hz would, therefore, require a minimum sample rate of 1000 Hz. The frequency resolution, f_{res}, or bin width in Hertz of an FFT is a function of both f_s and N, where $f_{res} = f_s / N$. Applying this to the 500-Hz bandwidth signal, an FFT bin resolution of 1 Hz or less would also require a minimum N of 1024.

A further constraint relates to the time span covered by the sample window. If the actual signal from which the sample frame is taken is periodic and if the duration of the frame period is an integral multiple of the primary signal period, spectral interbin leakage is reduced in the FFT. In other words, if the data record contains exactly an integer number of cycles of the original signal and if there is exactly an integer number of samples per cycle, transformation errors are minimized. Acquisition of 2^a samples per cycle for 2^b cycles, where both a and b are positive integers, will meet this criterion and also ensure that the data record is some power of 2 in length. A suitable sample rate for a 60-Hz current signal would therefore be 60×2^a, yielding sample frequencies of 120, 240, 480, 960, etc.

Figure 2.1 shows a spectral plot from a typical motor current sampled at 480 Hz. Here, only the 60-Hz component is visible, but when the vertical-axis gain is increased by a factor of 100 (Fig. 2.2), one finds that the 60-Hz energy has spread into a large skirt around the main peak. It is not obvious from the plot whether or not this spreading is real, but it effectively masks any low-level components that might exist there. The spreading is actually interbin leakage, which is still an artifact of the transform process, resulting from inconsistent sample placement in successive cycles of the incoming signal even though a suitable sample rate was used. To overcome this problem, one must ensure that sampling occurs at consistent positions in each successive cycle of the incoming signal. In order to do this, it becomes necessary to not only select a suitable sample frequency but also to precisely control that frequency in relation to the incoming signal. This is accomplished with a sample clock based on a phase-locked-loop (PLL) circuit that uses the fundamental signal frequency as an input reference. An appropriately configured PLL circuit can generate an exact number of sample-trigger pulses during each input-signal cycle. When sampling is done in this way, the resulting FFT exhibits little or no energy spreading around the main spectral components (Fig. 2.3). Note that both Figs. 2.2 and 2.3 represent the same 60-Hz signal sampled at 480 Hz, but for Fig. 2.3, the sample clock was phase locked to the 60-Hz signal. This sampling method employing the discussed constraints was developed by ORNL researchers and is referred to as synchronous sampling.

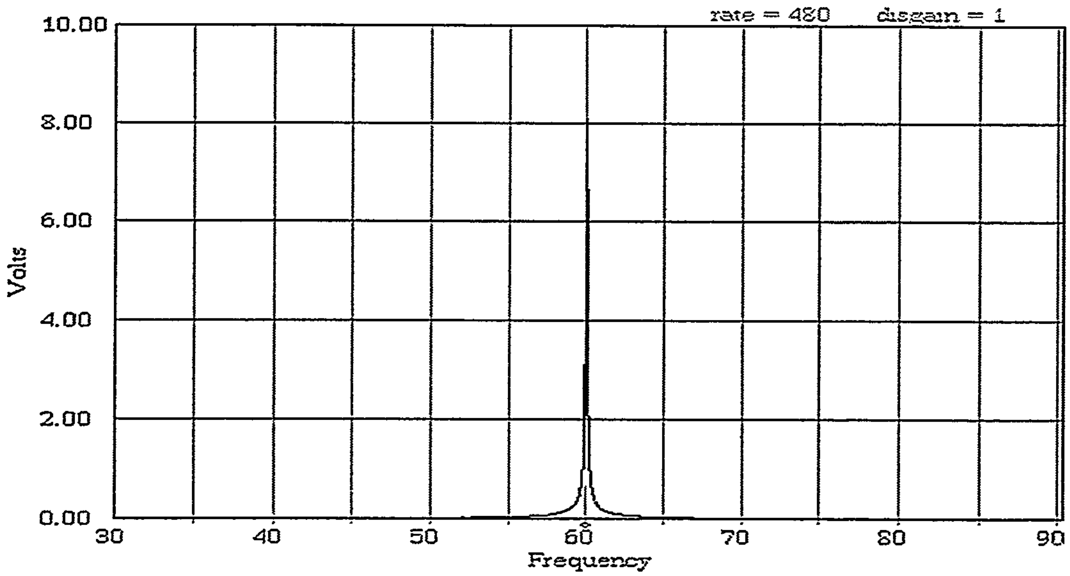

Fig. 2-1. Nonsynchronous spectrum with display gain equal to one.

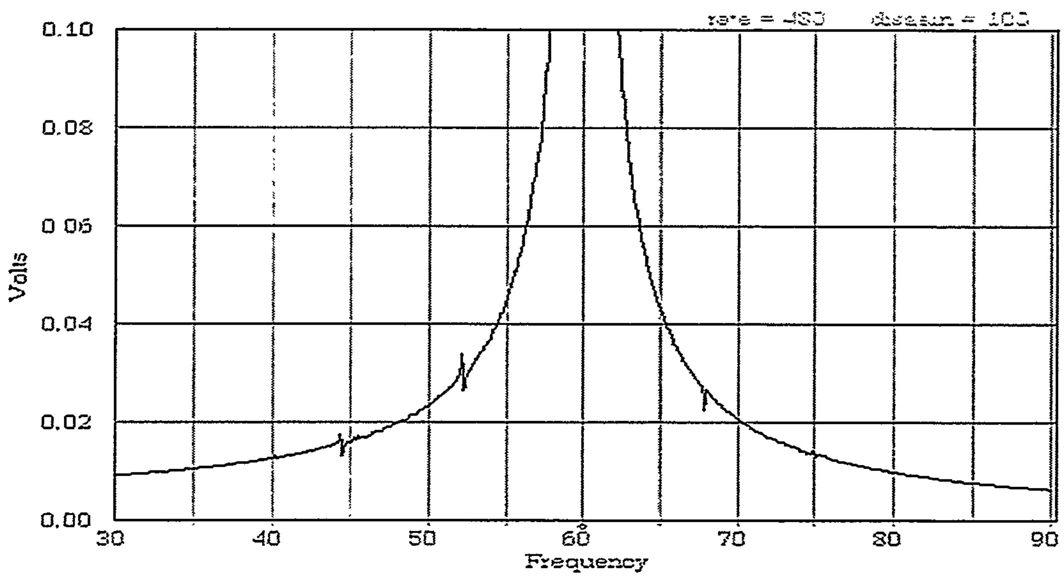

Fig. 2-2. Nonsynchronous spectrum with display gain equal to 100.

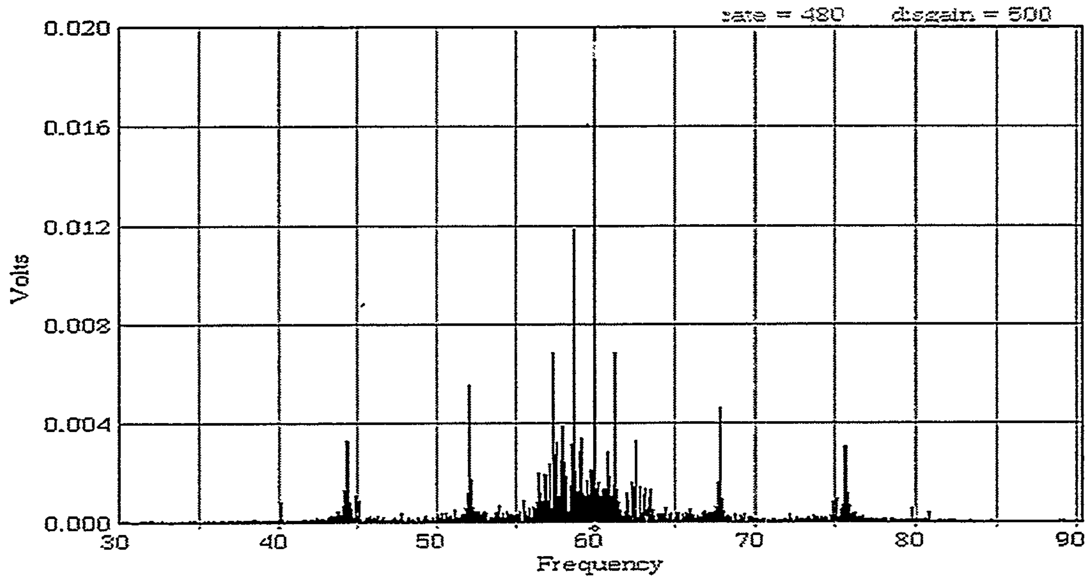

Fig. 2.3. Synchronous spectrum with display gain equal to 500.

3. SYSTEM HARDWARE

As currently configured, the EDEA consists of a signal-conditioning unit and a personal computer (PC) with a high-resolution ADC card. Although the instrument (Fig 3.1) was originally based in a standard 386-type PC, it was downsized into a 486-type notebook to improve portability. The notebook has a 200-MB hard drive and an active-matrix, VGA-color display and uses an accompanying docking station as a convenient interface for a 16-bit ADC card. The electronics unit conditions an input-current signal and outputs the signal and an internally generated clock that is used as the sample trigger. For acquiring data in remote locations without the need for on-the-spot analysis, the portable digital audio tape recorder (DAT) and attached current probe in Fig. 3.1 are often used.

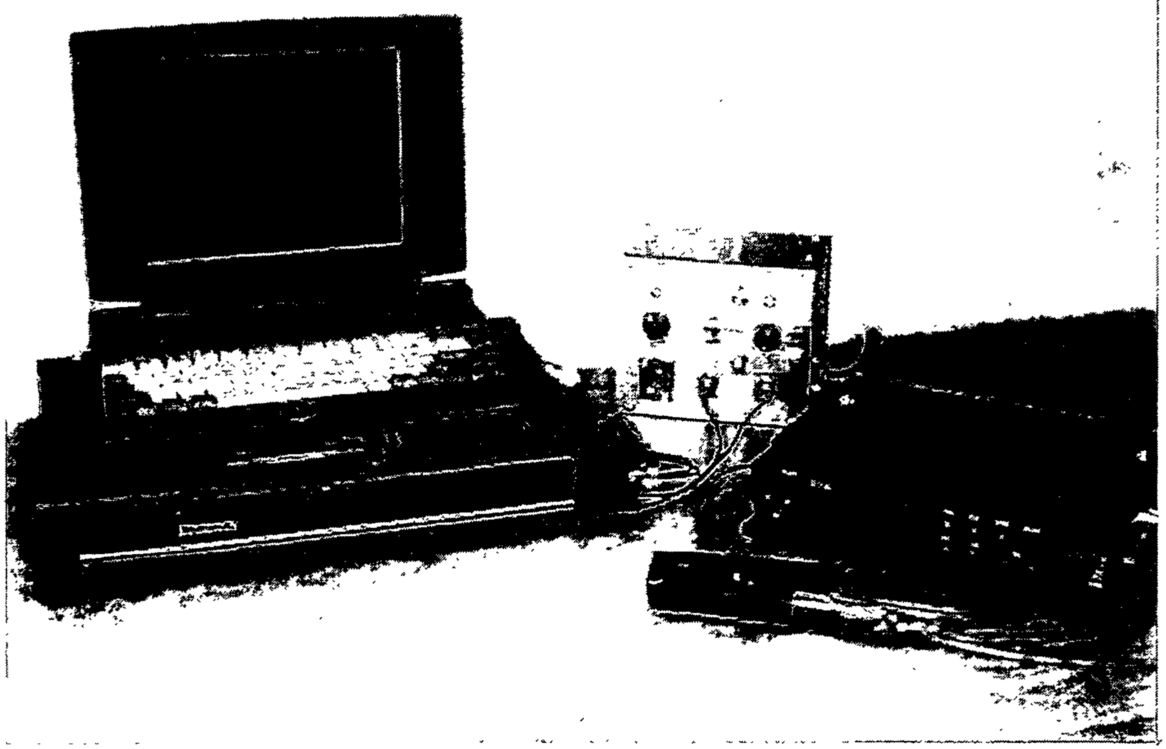

Fig. 3.1. EDEA hardware.

3.1 SPECIAL ELECTRONICS

The signal-conditioning unit provides gain adjustment for an incoming signal and generates a sample clock that can be synchronized with either the ac power line or the signal being sampled. Input current signals are fed to an A3F-type connector, which provides a balanced-input path to a differential-input instrumentation amplifier (Fig 3.2). This input was

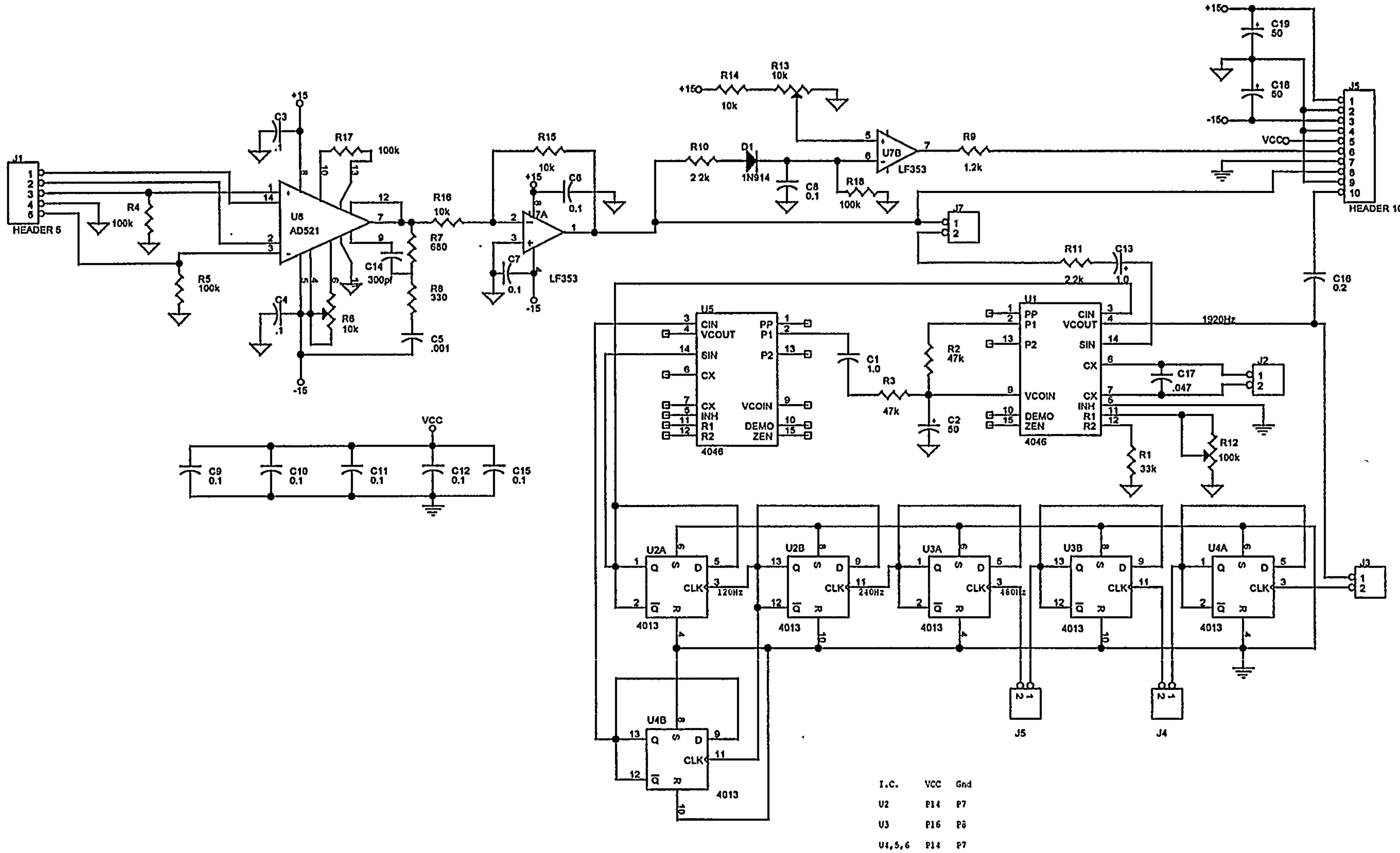

Fig. 3.2. Electronics unit — circuit board schematic

designed to receive the signal from a current probe, although it can also be used to receive preconditioned signals like those from a DAT. Input gain can be adjusted over a range from 1 to 1000, and a light-emitting diode on the front panel illuminates when an adequate gain setting is reached. To provide good signal resolution, the output voltage swing is normally adjusted to use as much of the ADC range (±5 V) as possible. After amplification, the signal is fed out to one channel of the ADC card.

Either the current signal or a voltage signal from a small ac power transformer can be selected to feed the input of the PLL-clock circuit. The circuit uses the phase detectors from two PLL integrated circuits to derive the control signal needed to phase lock one of the voltage-controlled oscillators to the selected signal. This configuration reduces control-voltage ripple and improves the stability of the clock frequency. One of three clock possible frequencies (960, 480, or 240 Hz) is selected and fed to the ADC card. Additional wiring and construction information about the electronics unit is provided in Appendix A.

3.2 ADC CARD

A DirectConnect Model 5508-SHR card provides eight input channels to the ADC, as shown in Table 3.1. The software for acquiring sample data is hardware specific, but it could easily be adapted to use almost any commercially available 16-bit A/D card that is PC compatible. The hexadecimal address for the A/D card is set to 0x110, and the interrupt line is disabled. Samples are triggered by a TTL compatible clock signal that is fed to the External Trigger input on the 5508. The external sample clock runs continuously, so the sampling process is software controlled by enabling or disabling the trigger input.

Table 3.1. 5508 SHR input connections

Pins	Function
1 - 8	Channel inputs 1 to 8 respectively
19	External Trigger
20	Ground

4. SOFTWARE

The EDEA software provides all of the acquisition and analysis capabilities needed for conducting manual investigations of most motor-driven equipment and electrical systems. In that role, the software has evolved significantly over the last 2 or 3 years. As the need for a display or a new analysis capability has arisen, it has typically been developed and added to the software. Since all of the employed DSP is executed in software, the system has also provided a platform on which to develop and test new detection and analysis algorithms for application in dedicated monitoring systems also developed by ORNL personnel. The software operates under DOS 3.2 or a later version and is compiled using Microsoft C, Version 6.0. At the time of this report, there are 16 C-source files that are compiled in large-model mode and linked together to form the executable file, "samp.exe." Only one additional support file, "tms-rmn.fon," is required for proper program execution. This file is a screen font file that comes with the compiler. No other special software or vendor supplied drivers are needed in the compilation or running of the program.

4.1 DATA ACQUISITION

Signal sampling is controlled by a combination of software and the external sample clock. The software controls when sampling occurs and how many samples are acquired, while the sample clock sets the sample rate. Since the system is intended as both a development and an investigative tool, it is configured to provide fairly high-frequency resolution in calculated FFTs. To do this, each data record consists of 4096 data points and yields a 2048-point FFT. At the lowest clock frequency, 480 Hz, the resulting 240-Hz FFT has a resolution of 0.117 Hz per bin. Note that Fig. 2.3 shows only 512 of the 2048 points contained in the actual FFT. The 1920-Hz clock yields a 960-Hz FFT with a bin resolution of 0.47 Hz per bin.

Averaging of consecutive FFT arrays can also be useful in refining the spectral data in some noisy situations. The desired number of averages, n, must be set before the first sampling cycle is begun. A sampling cycle involves the acquisition of 4096 data points and the calculation of the resulting FFT. When an n greater than one is entered, that number of sampling cycles is performed. Each time an FFT is calculated, it is added to a totalizing array, and an new average FFT is displayed. Instead of just averaging the FFT-component magnitudes that are displayed, averaging is conducted on both real and imaginary parts of the FFT. In this way the integrity of contained phase data is maintained. When n cycles have been completed, the acquisition process is halted, and the average of the n FFTs is displayed.

4.2 DATA DISPLAY

When a 60-Hz signal is sampled, the software automatically determines what sample rate was used and sets the display parameters accordingly. To maintain compatibility with most PCs and notebooks, the software only requires a VGA (640×480) display. Because of the limited screen resolution, only 512 members or one page of the 4096 time-data points or 2048 FFT bins can be displayed at once. When displaying FFT data, the default page always contains the 60-Hz component. Screen controls allow the view of either data type to be panned in several steps over the entire range of the data.

4.3 COMPONENT MEASUREMENTS

The basic premise of CSA is that any change in the mechanical load presented to a drive motor results in a comparable change in the amplitude and phase of the motor current. When changes occur at a particular frequency, that frequency usually appears in the resulting FFT as a modulation on each side of the 60-Hz carrier. The size of a modulation is affected not only by the load change that caused it but also by the total amplitude of the motor current. If the current amplitude is then different from motor to motor, direct comparison of their modulation components is difficult. To overcome this difficulty, the EDEA software normalizes the measurement of any component's energy against the amplitude of the total current. The result is a measurement in the form of a modulation percentage, which can be compared with modulations from other signals without concern for their average amplitudes.

A simplification that limits the usefulness of spectral information obtained from most spectrum analyzers is that only the magnitudes of spectral components are presented. This totally ignores the phase data that are also associated with each component. Special algorithms have been developed for the EDEA software that interpret the phase information included in the FFT data and treat every frequency component as a vector. By doing this, modulation energy that is spread into multiple FFT bins can be combined into an accurate measure of a side-band component. As vectors, the upper and lower side-band components can then be combined to determine the original amplitude of the modulating frequency. The combined vector phase can be used to characterize the original modulation mechanism.

4.4 DATA FILES

Early in the development of the EDEA software, the need for data archival and retrieval was realized. As a result, functions were included that allow the storage of sample, FFT-magnitude, and FFT-phase data. Data files can be named as desired and directed to the PC hard drive or to floppy disk. The 4096, 16-bit, time-data samples are stored in binary format with no header information, so the file size is consistently 8192 B. The FFT-data files are stored in ASCII format so they can be imported into a spreadsheet program like Microsoft Excel. Spreadsheets allow the imported data to be arranged and plotted in different formats and ranges. All 2048 FFT bins could, for example, be printed in a single graph.

When a sample-data file is retrieved by the EDEA software, the sample clock frequency is determined just as it is for newly sampled data. The FFT of the retrieved data is also calculated and made available for further manipulation.

5. USER INTERFACE

The EDEA software provides several display and data manipulation functions that aid in the examination and analysis of a data set. Screens and related controls are provided for viewing either the sample data or the FFT data and for data archival. The keyboard acts as the user input device for changing display modes or controlling software operations. Since the operation of most function keys is screen dependent, the purpose of each active key is displayed at the bottom of the selected screen.

5.1 TITLE SCREEN

When the software is started, the first screen to appear is the title screen (Fig. 5.1). This screen provides access to the data viewing and manipulation screens via four function keys (Table 5.1) that are displayed at the bottom of the screen. One of the four keys provides the only orderly exit from the program to DOS.

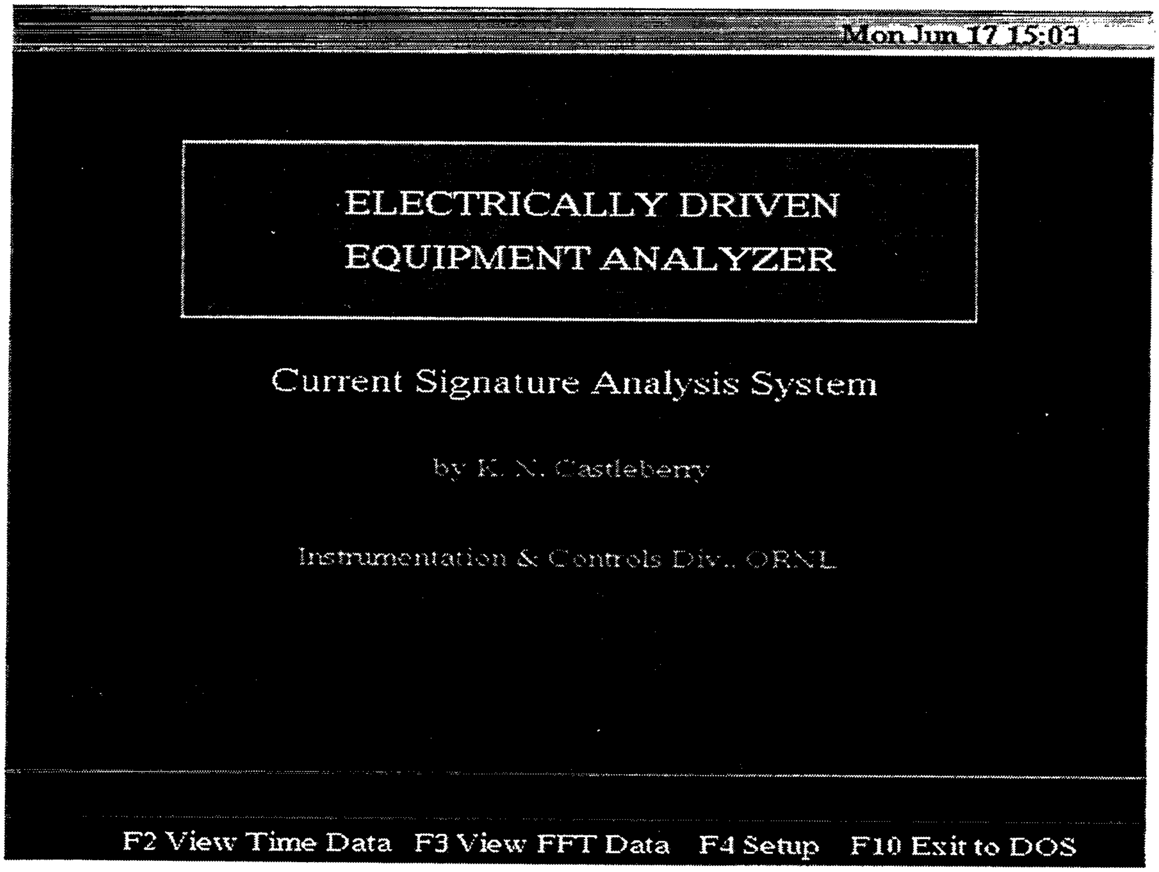

Fig. 5.1. Title screen.

Table 5.1. Title screen function keys

Key	Label	Function
F2	Time Data	Shows the Time Data screen
F3	FFT Screen	Shows the FFT Data screen
F4	Setup	Allows manual adjustment of the sample rate used to set up the FFT plot
F10	Exit to DOS	Terminates the EDEA software

5.2 TIME-DATA SCREEN

A Time Data screen (Fig. 5.2) can be accessed from the either the Title screen or the FFT screen. It provides an oscilloscope-type plot of the recorded time data on a bipolar 5-V scale. Like the FFT plot, only 512 points of the time data array can be displayed at once, so function buttons are provided to pan over the entire 4096 data points. Table 5.2 provides an explanation of the screen function buttons.

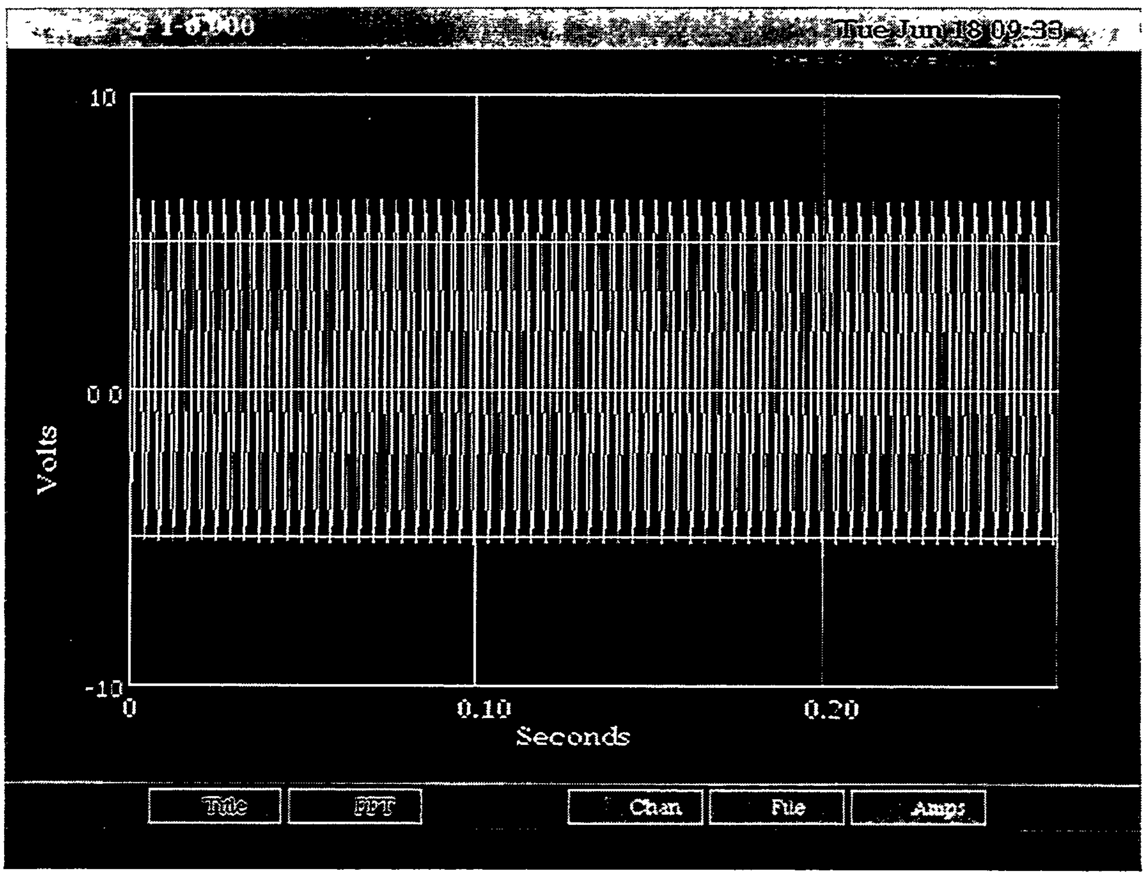

Fig. 5.2. Time Data screen.

Table 5.2. Time Data screen function keys

Key	Label	Function
F1	Title	Shows the Title screen
F3	FFT	Shows the FFT Data screen
F4	Channel	Allows any one of the eight input channels to be selected for input
F5	Files	Shows the Files screen
F6	Amps	Displays a calculation of the magnitude of the sampled motor current from the ammeter loop of a 3300-hp motor
PgUp		Pans the time data plot forward in time
PgDn		Pans the time data plot backward in time

5.3 FFT SCREEN

The FFT screen (Fig. 5.3) displays a plot of the FFT calculated from the time data samples. Since only 512 points at a time can be displayed on the screen, provisions are made for panning over the entire 2048 points. The function buttons (Table 5.3) at the bottom of the screen provide control functions for modifying several display parameters for the FFT data. Two of the buttons are used to toggle between different plot modes, and their labels change to indicate the next change.

A difficulty associated with displaying FFT data is its dynamic range. Even if the 60-Hz component uses all of the vertical display range, on a linear scale most of the important load-related components will not be visible. To overcome this when using a linear vertical scale, the EDEA software provides multiple display ranges down to a few millivolts full scale. When the vertical range is decreased, larger components like 60 Hz are truncated at the scale limits so they do not adversely affect the display of smaller components. A logarithmic vertical amplitude scale can also be selected.

When displaying FFT data in Cursor mode (Fig. 5.4), the frequency marked by the cursor is displayed at the upper-left corner of the plot area. If the logarithmic scale is in use, the decibel reading of the marked component is displayed with the frequency. In either case, a new list of function key operations is shown at the screen bottom. These keys provide vertical scale adjustment, component labeling, demodulation, and component attenuation functions. Table 5.4 provides an explanation of these keys along with several others not shown by the display.

Two of the Cursor-mode function keys cause the modulation index of the marked component to be calculated. This calculation is perhaps the most unique and useful function provided by the EDEA software. It combines the vector of the selected component with the vector from two bins on each side of it. This combination accounts for some of the energy that results from spreading similar to that discussed in Sect. 2 of this report. The spreading of side-band energy is present because the discussed sampling constraints only dealt with minimization of spreading of the 60-Hz carrier energy. As a result, any component that is not some power of 2 above or below 60 Hz is still subject to spreading. Any modulation is displayed as both an upper and a lower side band of 60 Hz, so the related and unmarked component is analyzed as well. The result of the operation is displayed as the actual frequency of the original modulation along with the modulation percentage and vector phase angle for both of the upper and lower side-band components. In addition, the side-band components are combined into a composite magnitude and phase. This composite is then separated based on the phase angle into pseudo amplitude and phase modulations. Just how these calculations are performed is the subject of a forthcoming invention disclosure and will not be presented here.

5.4 FILES SCREEN

All operations related to saving data to disk files or recalling time data are performed via the Files screen (Fig. 5.5). When accessed from the Time Data screen, it handles sample data, and Table 5.5 explains the operations of the active function keys. When accessed from the FFT screen, it handles FFT data and only has two function keys, Save and Escape. If Save is selected, the user must answer several questions concerning what data to save and desired filenames.

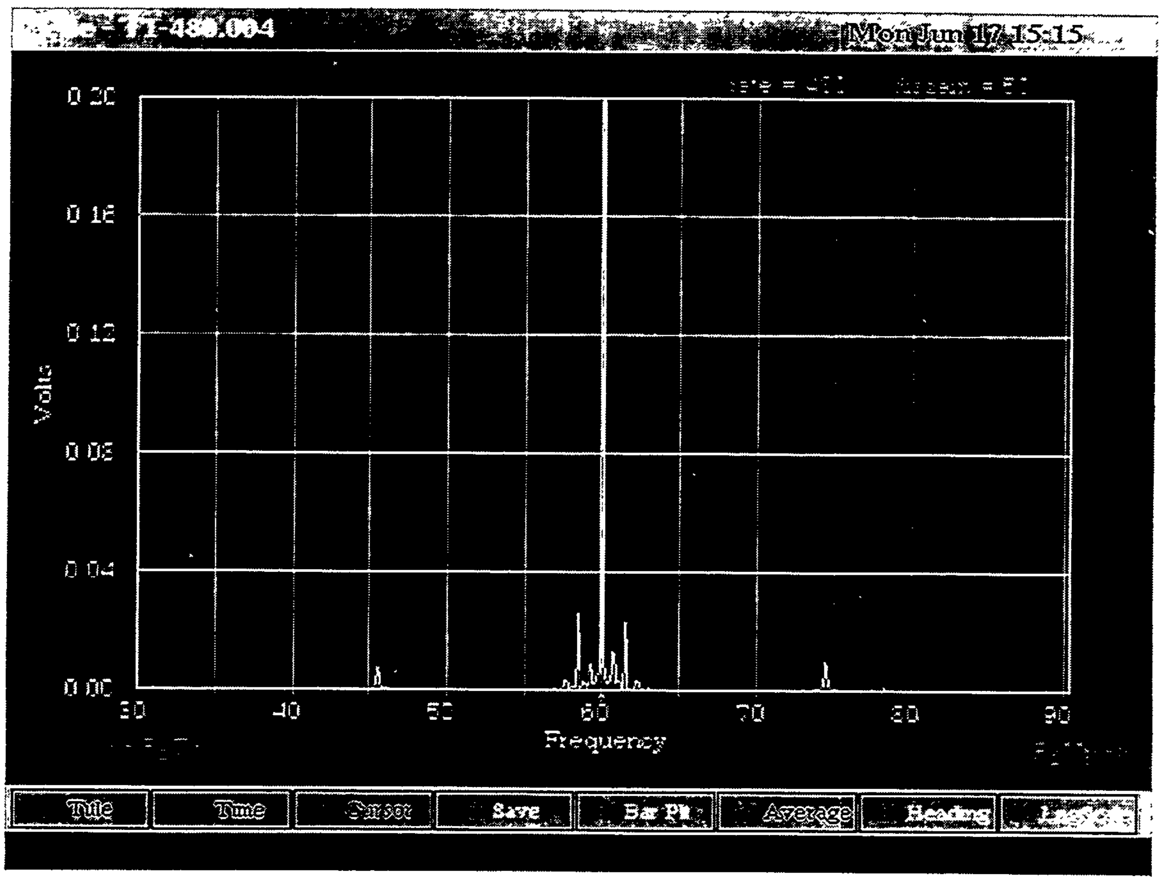

Fig. 5.3. FFT screen.

Table 5.3. FFT screen function keys

Key	Label	Function
F1	Title	Shows the Title screen
F2	Time	Shows the Time Data screen
F4	Cursor	Toggles between Normal and Cursor modes for the FFT plot
F5	Save	Shows a screen where FFT phase and magnitude data can be saved to a disk file
F6	Bar Plot	Toggles the plot style from line to bar
F6	Linear	Toggles the plot style from bar to linear
F7	Average	Asks for the number of sampling cycles desired
F8	Heading	Allows a title to be input for display above the FFT plot
F9	LogScale	Toggles the vertical scale from linear to logarithmic
F9	Linear	Toggles the vertical scale from logarithmic to linear
F10	Exit to DOS	Terminates the EDEA software
PgUp		Pans the FFT plot up in frequency
PgDn		Pans the FFT plot down in frequency

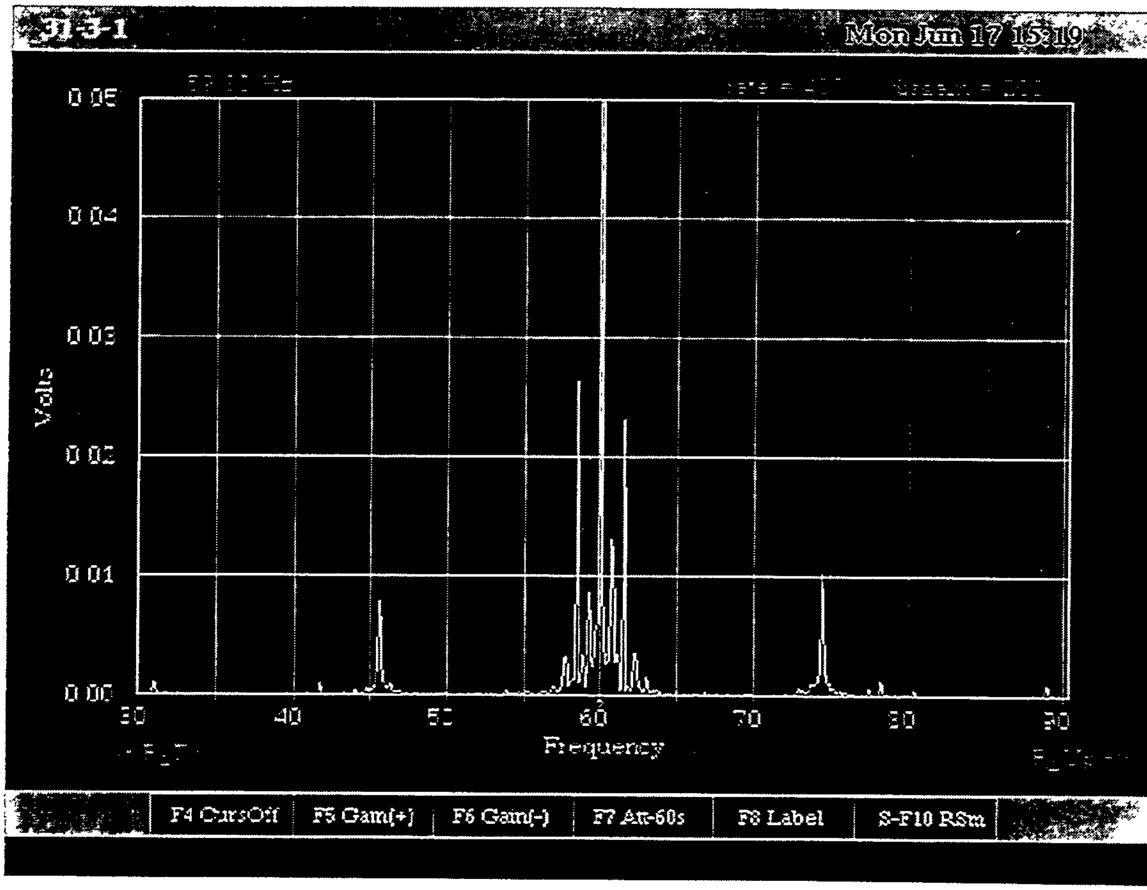

Fig. 5.4. FFT screen with active cursor.

Table 5.4. FFT screen — cursor functions

Key	Label	Function
F4	CursOff	Toggles Cursor mode off
F5	Gain(+)	Increments the vertical display gain in preset steps
F6	Gain(-)	Decrements the display gain
F7	Att-60s	Attenuates 60 Hz and its harmonics by 20 dB
F8	Label	Places a frequency label on the peak marked by the cursor
F10	Demod	Calculates the modulation percentage for the frequency marked by the cursor
S-F10	RSmod	Finds the running speed for a 1200-rpm motor and calculates the modulation percentage
⇐		Moves the cursor one bin to the left
⇒		Moves the cursor one bin to the right
Cntl ⇐		Moves the cursor 16 bins to the left
Cntl ⇒		Moves the cursor 16 bins to the right
PgUp		Pans the FFT plot up in frequency
PgDn		Pans the FFT plot down in frequency

Active file directory is - a:\x333-4

. <DIR>	19. 4-3.020	39. 8-7.042
.. <DIR>	20. 4-4.021	40. 8-8.043
1. 2-1.000	21. 4-5.022	41. 9-1.045
2. 2-2.001	22. 4-6.023	42. 9-2.046
3. 2-3.002	23. 4-7.024	43. 9-3.047
4. 2-4.003	24. 4-8.025	44. 9-4.048
5. 2-5.004	25. 7-1.027	45. 9-5.049
6. 2-6.005	26. 7-2.028	46. 9-6.050
7. 2-7.006	27. 7-3.029	47. 9-7.051
8. 2-8.007	28. 7-4.030	48. 9-8.052
9. 3-1.009	29. 7-5.031	
10. 3-2.010	30. 7-6.032	
11. 3-3.011	31. 7-7.033	
12. 3-4.012	32. 7-8.034	
13. 3-5.013	33. 8-1.036	
14. 3-6.014	34. 8-2.037	
15. 3-7.015	35. 8-3.038	
16. 3-8.016	36. 8-4.039	
17. 4-1.018	37. 8-5.040	
18. 4-2.019	38. 8-6.041	

Save **Escape** **Load** **Dir-list** **Chng-dir**

Fig. 5.5. Files screen.

Table 5.5. File screen function keys

Key	Label	Function
S	Save	Saves the current sample data to a file
Esc	Escape	Returns to the Time Data screen
L	Load	Prompts for a file number from the directory list and loads the file
D	Dir-List	Displays the file list in the current directory
C	Chng-Dir	Prompts for a new active directory and changes to that directory

6. FINAL COMMENTS

The EDEA has been used extensively in the acquisition and analysis of motor-current signals from literally hundreds of motors used in the United States Enrichment Corporation facilities at Portsmouth, Ohio, and Paducah, Kentucky. These plants use motors that range from 100 to 3300 hp to drive large gas compressors in a process that enriches uranium. A distributed and automated version of the EDEA was subsequently developed and installed as a dedicated monitoring system for detecting problems in the largest of this plant equipment. One of these prototype systems is installed at each plant providing equipment status information to the process operators and archiving data for future reference. Since these systems execute detection algorithms that are specifically designed for the monitored equipment, they do not need many of the general data-manipulation capabilities of the EDEA. They do, however, save sample-data files that can the examined by EDEA software running on almost any office PC. This allows additional equipment phenomena to be investigated and new detection software to be developed as deemed necessary. As an analysis tool, the EDEA continues to play a significant system-support role while also facilitating investigative work on other equipment systems.

Appendix A

EDEA ELECTRONICS UNIT

The EDEA electronics unit is constructed in a small 5 × 6 × 4 in. aluminum box made by Bud Industries, Inc. Figure A.1 shows the layout used for the front-panel controls and connectors. The box contains a circuit board comprised of the circuitry shown in Fig. 3.2 and associated wiring and components shown in Fig. A.2.

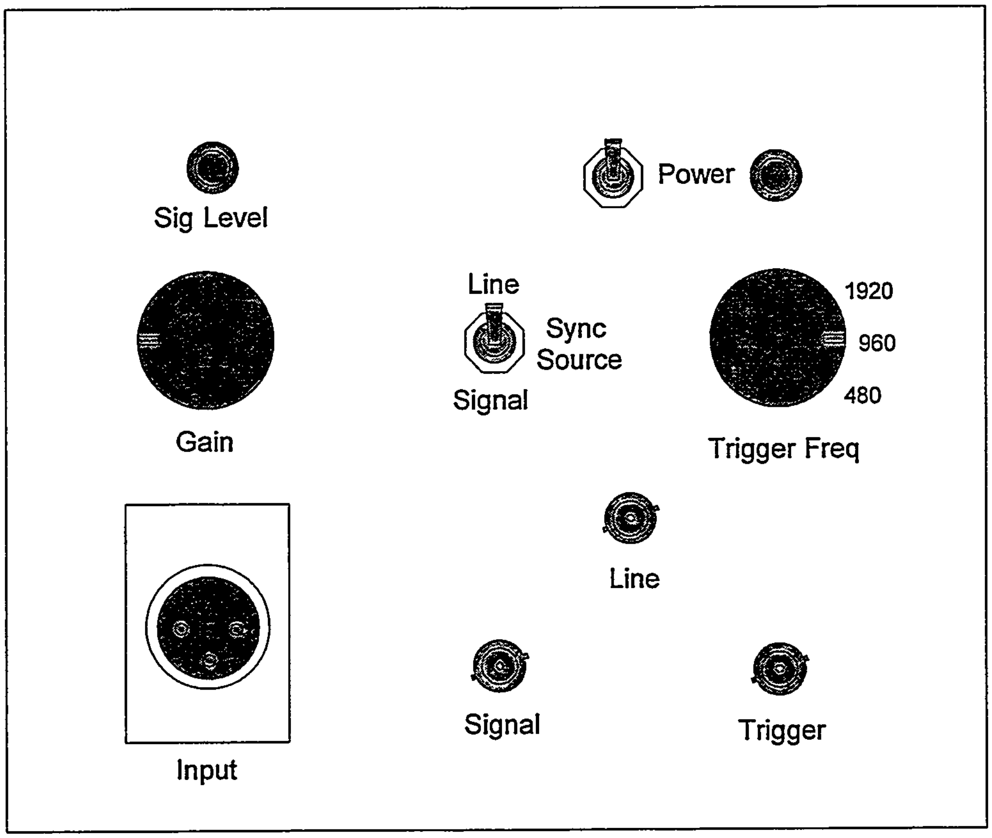

Fig. A.1. Electronics unit front panel.

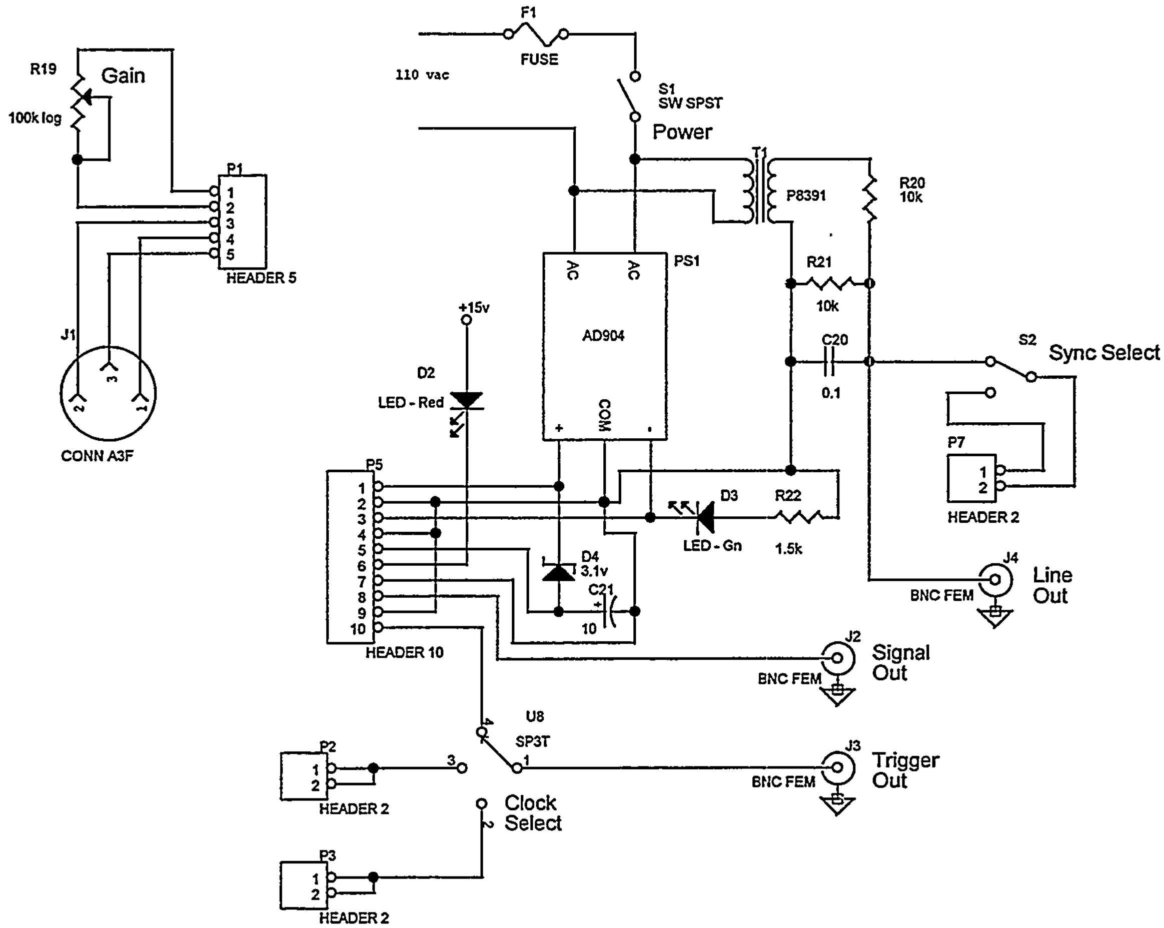

Fig. A.2. Electronics unit wiring.

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