ADVANCED SIGNAL PROCESSING AND FILE MANAGEMENT SOFTWARE FOR RELAY TESTING USING DIGITAL SIMULATORS

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Abstract – Commercial equipment for relay testing is primarily used today to perform steady–state and dynamic phasor testing of protection relays. Most of the advanced versions of the commercial equipment can also be used to perform transient testing since their signal replaying subsystem is capable of outputting fault waveforms. However user interface software that supports preparation of the appropriate test waveforms is rather limited.

This paper describes development of signal processing and file management software aimed at facilitating preparation of fault waveforms to be used for transient testing. This software is used on a new digital simulator developed for transient testing of protection relays.

Keywords: Protection, Relay Testing, Digital Simulators

INTRODUCTION

Developments of protection relays in the last twenty years have been quite diverse and advanced. The use of microprocessors in the relay design enabled implementation of a variety of relaying algorithms and protective relaying schemes. The new technology provided for new approaches to implementation of existing relay designs and development of new relays and relaying principles [1].

Developments of new relays and relaying systems introduced a need for new developments in relay testing. Microprocessor based technology introduced the use of various digital signal processing algorithms for measurement of relaying quantities. These algorithms came from different theoretical backgrounds and were based on different assumptions and constraints. Their testing was a challenging problem that required development of new testing methodologies and tools [2].

The final outcome of the developments of relay testing tools were new hardware and software solutions that allowed both phasor and transient testing of protection relay designs [3]. These solutions became known as digital simulators for relay testing and are ranging from low cost PC–based designs [4] to rather costly multiprocessor implementations [5].

This paper describes some software features of the digital simulator development sponsored by the Electric Power Research Institute and several utility companies in the U. S. A. [6–8]. The simulator has been developed and commissioned during the Summer 1992 and is now being evaluated through various relay testing applications. This simulator is capable of using both digital fault recorder (DFR) and electromagnetic transient program (EMTP) files and utilizing them for relay testing [9–11]. An elaborate software has been developed to support DFR and EMTP file processing and management needed for relay testing. Capabilities and performance characteristics of the software are described in this paper.

The first section discusses requirements for relay testing. Digital simulator architecture is outlined in the following section. Next, digital signal processing and file management software developments are described. Examples of the software use are also given. Concluding remarks and references are provided at the end.

REQUIREMENTS FOR RELAY TESTING

Requirements for relay testing depend on the relay types and the purposes of testing. A study of this problem reveals a variety of possible testing approaches and specifications [12]. Recent activities of various working groups within the IEEE Power System Relaying Committee have enhanced understanding of different testing tools and methodologies [13,14]. A summary of test equipment designs and uses is given in Table I to illustrate a variety of means to meet various relay testing requirements.

This paper deals with software developments undertaken to meet requirements for transient testing of protection relays. Digital simulators appear to be an appropriate approach for implementation of the hardware and software tools needed for transient testing.

Table II gives a breakdown of the requirements imposed on the simulator software tools. Each of the groups of requirements given in Table II is further divided and described.

Generation of transients for relay testing is a demanding requirement since DFR and EMTP are not originally designed to support relay testing. DFR design, recording practice and file organization are not developed for direct use in relay testing and significant action from the operator is needed to make this application possible [9]. The same comment is valid for EMTP. The simulation files cannot be directly used for relay testing and instrument transformer models have to be added [10,11].

Conversion is needed for both DFR and EMTP files. DFR files are usually recorded in a packed binary format which is unique to a given recorder. A similar situation is present with the EMTP output files where they may be either binary or ASCII and have a unique format. Digital simulators use their own internal format for data files which is, again, unique to

Table I. Summary of Relay Test Equipment Designs and Uses

Test Equipment	Uses
Programmable Test Signal Generators (conventional test equipment)	• portable testing for substation applications • phasor testing for scheduled maintainance • synthesized waveform testing for limited trouble shooting maintenance
Digital File Replaying Systems (new extension of the conventional test equipment)	• portable testing for substation applications • testing systems for laboratory applications • transient testing for application evaluation • transient testing for trouble shooting maintenance
Digital Simulators for Relay Testing	• testing systems for laboratory applications • transient testing using DFR files • transient testing using EMTP files

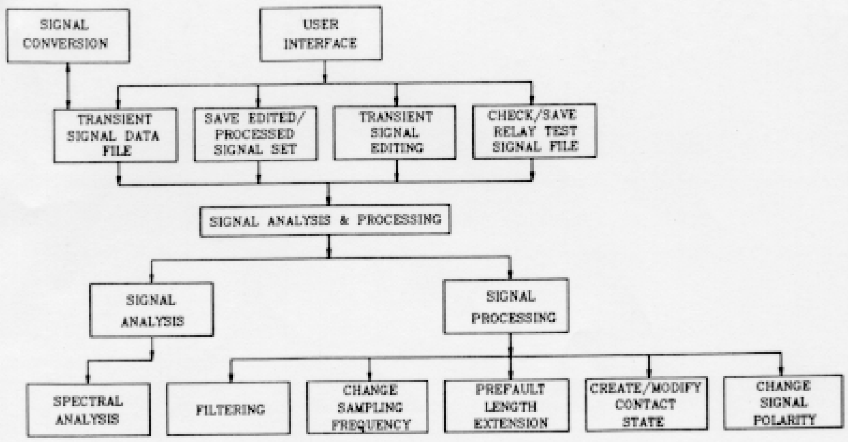

Fig. 3. Software Modules for Transient Testing

SOFTWARE FOR TRANSIENT TESTING

The software has been organized into four main modules: User Interface, Signal Conversion, Signal Analysis and Signal Processing. Each module contains routines to perform specific tasks. The block diagram in Figure 3 shows the various functions available in the software. The software has been developed in MATLAB [16].

The following sections describe the various functions with some examples for illustration.

User Interface Module

The functions for input/output of data files and user interface functions for signal presentation and editing form an integral part of this module. It exploits the capabilities of MATLAB completely to provide required interface with external programs and with the user.

Transient Signal Data File

Signal data files are presented as input to the software using this function. The data files can be of the following formats:

- IEEE COMTRADE (ASCII) Files [17]: This is a common file format for transient data representation recently defined as an IEEE/ANSI Standard. Two separate files are defined by the standard. One file contains the raw sampled values, while the other is a text file describing the data file.
- ASCII data file: Transient signal sampled data is represented using ASCII characters. The text file describing the data file is not defined. The data file description is generated internally by the software after obtaining information from the user like calibration factors, units, etc.
- MATLAB (Binary) files: Transient signal sampled data is represented using binary format. The data files follow the MATLAB binary format while the text file describing the data file as specified by COMTRADE and is given in ASCII.
- Digital Fault Recorder (DFR) files: These files are actual recordings of power system faults/disturbances. They contain both sampled signal data and some descriptive information related to the DFR recording set-up. These files are represented using a binary format.
- Electromagnetic Transient Program (EMTP) files: Transient signals can also be obtained by simulating the power system faults using the Electromagnetic Transient Program. These files are represented in either binary or ASCII format. The ASCII format is used in this application.

Files following the last two formats are first converted to IEEE COMTRADE standard format before being read by the software.

Save Edited/Processed Data File

The edited/processed data files can be saved in either one of the following formats.

- IEEE COMTRADE (ASCII)
- MATLAB (Binary)

The binary files occupy less disk space. Less time is taken to read the file as compared to that of the COMTRADE/ASCII data files. The IEEE COMTRADE standard format is used for transporting data files.

Transient Signal Editing

The data files obtained from DFRs may not be in the form appropriate for relay testing. In such cases, the files may be edited to obtain the desired set of test signals. Functions to edit different aspects of the file have been implemented. User interface needed for this purpose has been provided by menus. The following waveform signal editing functions are provided:

- Selection of channels of interest.
- Set signal length.
- Modify calibration factors and units.

Table II. Requirements for Software Tools for Transient Testing of Protection Relays

Requirement Category	Requirement Description
Generation of Transients	• DFR files of a fault captured in a substation • EMTP simulation of a fault using power system model
Conversion of Files Containing Transients	• Conversion of files recovered in different DFR formats into a common format used for waveform replay • Conversion of EMTP output files into a common format used for waveform replay
Signal Analysis	• Waveform representation in time domain • Waveform representation in frequency domain
Signal Processing	• Filtering • Waveform parameter identification and reconstruction • Change of waveform characteristics
Operator Interface	• Waveform Editing • Waveform Viewing • Test file processing and management • Test Initiation • Test Result Viewing

a given I/O driver. Obviously, conversion of both DFR and EMTP files is required to accomodate the need to have files compatible with the simulator I/O driver.

Signal analysis in both time and frequency domain is essential since fault transients have significant frequency constants across the spectrum. Since relay designs may be sensitive to a given signal component, it is important to have means of analyzing the signal in order to determine its properties.

Signal processing is needed if test signal properties have to be altered or various parameters have to be determined. A typical need for signal processing appears when sensitivity of relays to various signal characteristics is to be tested. Signal filtering, change of signal length, variation of number of samples points in signal representation, and various scaling operations are examples of the useful signal processing operations.

Operator interface is one of the most important requirements since transient testing assumes intensive operator interaction. Most of the operator involvement is in preparing test files containing transient waveforms. Once the files are prepared, operators have to initiate testing. Viewing of the results is a final stage of the operator involvement.

DIGITAL SIMULATOR ARCHITECTURE

A detailed discussion of the characteristics of the digital simulator developed under the EPRI sponsorship is given in a number of previously published references [6-11]. The following is a brief description of the simulator hardware and software architecture.

Simulator hardware architecture is shown in Figure 1.

A simulation computer is used to generate transient waveforms, either through EMTP simulation or from DFR files. This computer has an elaborate graphical interface for the operator. It also communicates with a waveform replay subsystem.

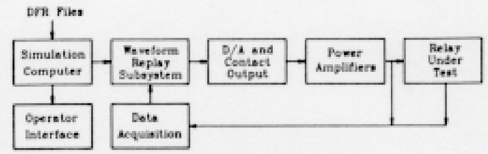

Fig. 1. Simulator Hardware Architecture

Waveform replay subsystem is a separate computer system that is used for real-time waveform reconstruction. It feeds waveform samples into the D/A subsystem. It also generates contact data. At the same time, this subsystem interfaces to the data acquisition equipment which captures relay and simulator outputs.

The D/A and contact output subsystem is used to convert signal samples into analog waveform and contact signals. These signals are eventually used to feed relays for testing purposes.

Power amplifiers are needed to increase power of the analog waveforms to the levels present at the secondaries of the instrument transformers. Using the amplifiers, test signals with the characteristics very close to the ones the relay sees in the field are produced.

Software architecture of the simulator is shown in Figure 2. It shall be noted that some of this software is commercially available, while some of the software had to be developed. The software blocks marked by an asterisk are the developed ones. A brief description of the commercial packages is given below, while the new software developments are described in the following section.

EMTP is a well known program for simulation of transients in power networks [15]. This package is quite complex and requires elaborate input data for modeling of power system faults. Extensions for instrument transformer modeling are needed when EMTP is used for relay testing [10,11].

MATLAB is a general purpose signal processing package which allows extensive signal parameter calculation and analysis [16]. This package provides the user with a high level command language which can be used to develop various applications.

DFR Master software is developed by DFR manufacturers to allow for viewing and editing of DFR files. Characteristics of these packages vary from vendor to vendor.

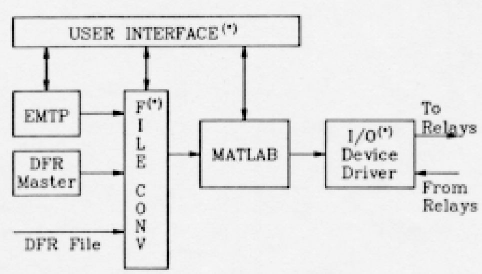

Fig. 2. Simulator Software Architecture

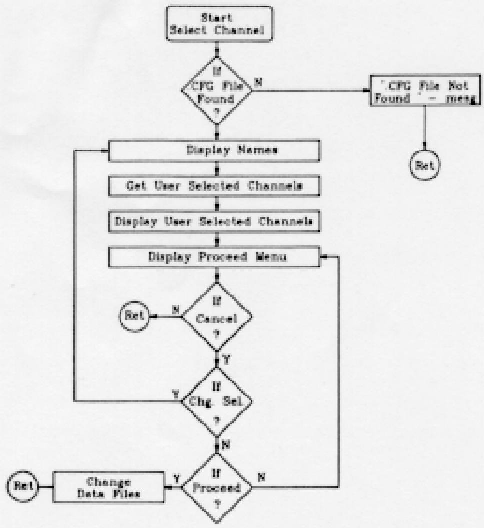

Fig. 4. Select Channels

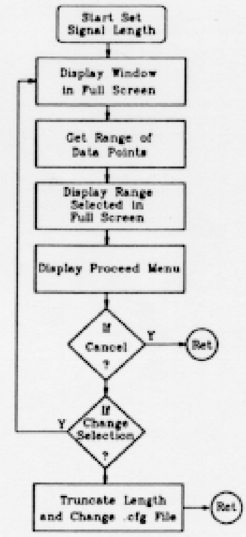

Fig. 5. Set Signal Length

Select Channels function is needed to allow selection of the DFR channels to be used for relay testing. Utility companies use DFRs to record the waveforms in the actual power system. In a case of power system misoperation, power and relay engineers can view these records and analyze the reasons for failure. The DFRs can record multiple channels. During a fault, only a few may be relevant to the failure.

The software is an effective tool to view the waveforms and to make a decision on which channels should be selected. The other channels are discarded only from memory and are not deleted from the disk. Figure 4 shows the organization of this function with emphasis on the user interface.

Set Signal Length function is needed to allow selection of the signal length. DFR waveform records typically contain more than a second of the signal length. Relays operate during this interval. Autorecloseing may have been attempted within the first few cycles of the fault. In many cases, the fault might have cleared during the entire portion of the record. The utility companies tend to set up the DFRs to record all such events following the fault. Records of such length are not necessary for relay testing. The objective is to simulate the conditions for relay operation. Hence, it becomes necessary to limit the length of the record before replaying the signals. But, some conditions of relay testing still require long records.

Figure 5 shows the organization of this function with emphasis on the double checking of the range selected by the user before setting the length to this range.

Modify Calibration Factors and Units is the function needed to change the calibration factors and units read from the text file defined by COMTRADE. The user interface is simple with prompt for the user to enter the new factors and units.

Check/Save Relay Test Signal File

This function is needed to check if the signal file being viewed/edited conforms to the hardware capabilities of the digital simulation. The signal file must satisfy the following requirements:

- Number of voltages, currents, and contact states must correspond to the type of relay being tested.
- Maximum value of voltage/current must be representable in the maximum number of bits allowed by the simulation hardware (16 bits, in case of DYNA–TEST simulator).
- The fault signal length should be greater than or equal to a predefined number of cycles (usually 8).
- The sampling frequency of the file must be within the limits of the hardware.

The checks for the above requirements are done automatically. If the file satisfies all of the specifications, then it may be saved in the format specified by the I/O device driver. This can either be in ASCII or in MATLAB (binary) form.

Signal Conversion

The following two main sources of data files can be identified: Digital Fault Recorder (DFR) and Electromagnetic Transient Program (EMTP). Files obtained from DFRs are in binary form with manufacturers following different proprietary formats. EMTP output files may be in ASCII and also follow a specific format. These waveform data files need to be presented as an input to the MATLAB software. In this case, the files are first converted to COMTRADE (ASCII) standard. This is accomplished using external conversion software.

Figure 6 shows how the data file input format is presented to the other three modules. Software for converting EMTP output files and files obtained from three commercial DFRs (Hathaway, Rochester and Mehta) have been implemented and successfully interfaced with the MATLAB software. This interface is transparent to the user and the conversion programs are presented as an integral part of the signal processing and file management software.

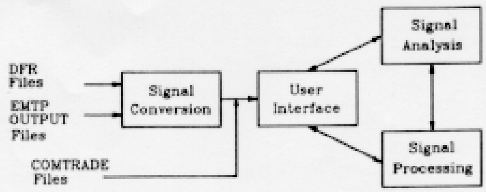

Fig. 6. Data Flow Between Modules

Signal Analysis

Once the transient data is converted to the MATLAB format, various signal analysis and processing functions can be performed. This section describes the signal analysis functions.

The presence of transients greatly affects performance of the relays. Relays are sensitive to signal frequency content and the sampling frequency. The presence of additional hardware, like analog filtering before sampling (for digital relays), also affect the sensitivity to harmonics and the reliability of the relay. Hence, it is important to identify the harmonic content of the signals. This aids the relay engineers in identifying the magnitudes of the harmonics and filtering some of them using the relevant functions in the signal processing modules.

The user is allowed to specify the following parameters.

- Length of signal on which the analysis is to be performed.
- Channels selected from the data file.
- Type of windowing function to be used for reducing the influence of the side lobes and better resolution (Hanning, Hamming, Bartlett and Rectangular).

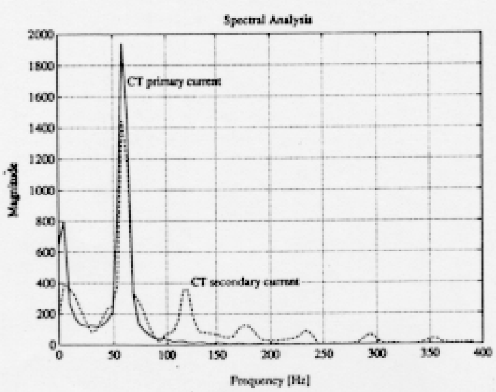

Fig. 7. Spectral Analysis of CT Primary and Secondary Currents for a Single Line to Ground Fault

This function has also been used as a tool for analyzing the influence of instrument transformers on the power system signals. Figure 7 shows the influence of current transformers on the current waveforms. The CTs actually have a distorting effect on the signals. The case depicted is a single line–to–ground fault signal for one of the sections of an actual power system, simulated using EMTP.

Signal Processing

This module fulfills the need of signal processing requirements for the test signals. Different test signal sets can be created from the same data file by performing signal processing. The following is a description of each of the signal processing functions with some examples.

Filtering

This function is very useful in identifying the relay sensitivity to a particular set of harmonics in the input signals. It can be used, together with the spectral analysis, to filter a required set of harmonics. Relay responses can then be compared to draw meaningful conclusions about its performance and sensitivity. Steady–state and dynamic phasor testing can be performed by filtering the harmonics completely, using a low pass filter with suitable characteristics.

The user is allowed to choose the channels to be filtered. In addition, the user can specify the following:

- Filter function (Butterworth filter, Yulewalk filter, Chebyshev filter)
- Filter type (Lowpass, Highpass, Bandstop, Bandpass)
- Filter characteristics like the cutoff frequency and the order.

Figure 8 (a) shows the unfiltered and filtered secondary current in T–domain for the case depicted in Figure 7. Figure 8 (b) shows the primary and filtered secondary current in the frequency domain. The filtering was done using an eighth order Butterworth filter with cutoff frequency 100 Hz.

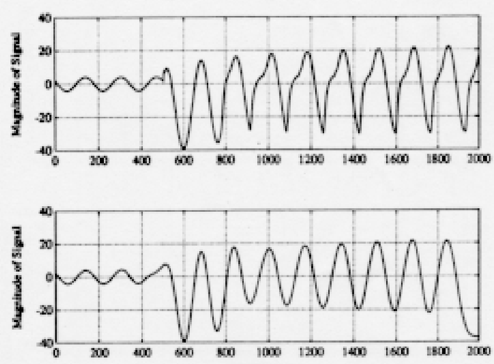

Fig. 8 (a). Unfiltered and Filtered Signal in T–Domain

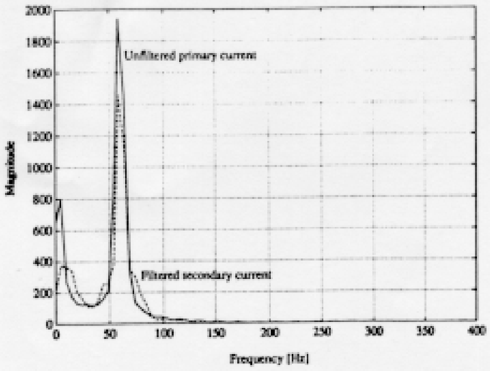

Fig. 8 (b). Primary and Filtered Secondary Current in Frequency Domain

Change Sampling Frequency

The DFRs usually offer a limited set of sampling frequencies in a particular range. The available frequencies vary with different manufacturers. Variations can also be found in different models of DFRs from the same manufacturer. The hardware design of the simulators may require signals sampled at a particular frequency. For example, the DYNA–TEST digital simulator developed at Texas A&M University can accept signals having sampling frequency in the range of 3kHz to 40kHz.

If the sampling frequency of the record does not belong to this set, then the sampling frequency conversion need to be performed. This may not be necessary in case of records obtained from EMTP, since the simulation time step can be adjusted to be in this range. In many cases, the data file may need to be transported to other simulators having different sampling frequency ranges. This provides an opportunity to compare the performance of various relay test equipment available for relay testing. In this case, the change of sampling frequency may be required.

The user needs to specify only the new sampling frequency. All of the calculations are transparent to the user. The flow chart in Figure 9 shows the user interface available.

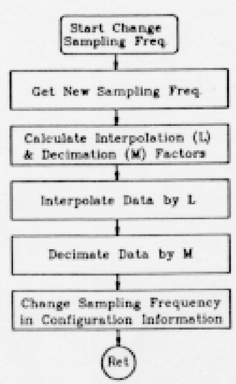

Fig. 9. Change Sampling Frequency

Prefault Length Extension

Protective relays are constantly monitoring the signals to determine the condition (steady–state or faulted) of the power system. Hence, sufficient prefault length is needed for the relay to get initialized with the steady–state condition of the signals. Usually 8 to 10 cycles of prefault length is needed, but it may be greater when testing the relay under power swing conditions. The records obtained from DFRs have, typically, about 2 cycles of prefault length. This can be extended using this function to the desired number of cycles. No limit is presented as to the number of cycles to which the extension can be done. Prefault length extension may not be necessary in case of records obtained from EMTP simulation, since the duration of steady–state can be specified.

Prefault extension is done for a user specified period by calculating the steady–state parameters of the limited prefault portion already present in the waveform. At least three zero crossings is mandatory for such a computation. Figure 10 (a) shows the actual waveform obtained from a DFR. Figure 10 (b) shows the waveform with 6 cycles (0.1 s) of prefault added to the existing signals.

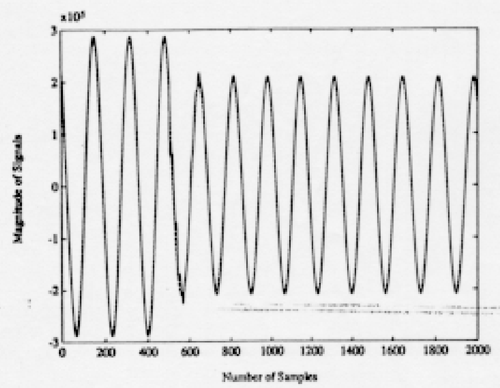

Fig. 10 (a). Waveforms Before Prefault Extension

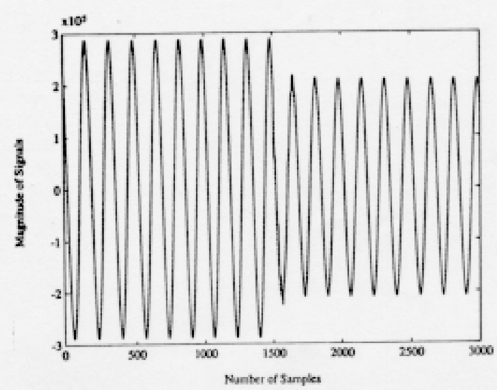

Fig. 10 (b). Waveforms After Prefault Extension of 0.1s

Create/Modify Contact State

The contact/status are digital signals used to indicate various relay and circuit breaker states. In data files obtained from EMTP simulations, there are no contact states. Such cases require creation of status channels. DFR records usually have a contact channel, but these may require modifications. Both of the functions are fulfilled by this routine. Figure 11 gives a description of this software routine.

Change Signal Polarity

Signals recorded using a DFR may have a 180° phase shift due to a wrong connection used in recording. The signal polarity may have to be reversed to obtain the actual power system signal. This is accomplished by this software function.

CONCLUSIONS

The results of the software development presented in this paper lead to the following conclusions:

- Commercial equipment for relay testing, in general, is not capable of performing full scale transient testing.
- Digital simulators have both hardware and software capabilities to support transient testing of protective relays.
- Signal processing and file management software are necessary software tools for transient testing of protective relays.

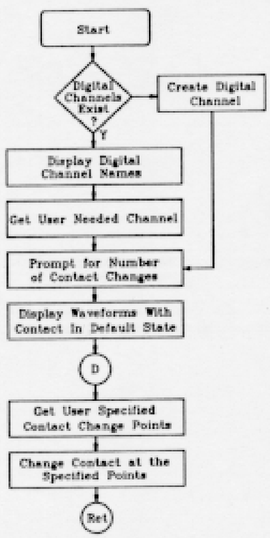

Fig. 11. Create/Modify Contact State

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