BENEFITS AND USE OF SIMPLIFIED AUTOMATED DIAGNOSTICS PROCEDURES UTILIZING DFR AND SER DATA

Bill Andre [a], Don Bjork [a]

Mladen Kezunovic [b], Igor Rikalo [b]

Larry Smith [c], Robin Smyth [d]

Charles Fromen [e], Don Sevcik [e]

[a] Andtek, Inc., Huntsville, AL; [b] Test Laboratories International, Inc., Bryan, TX

[c] Alabama Power, Birmingham, AL; [d] GP&A, Clackamus, OR; [e] Houston Lighting & Power, Houston, TX

Abstract

New developments in automated diagnostics procedures to evaluate substation equipment operation provide significant benefits, and are cost justified when compared with conventional scheduled/unscheduled maintenance practices. In addition to cost benefits, automated diagnostics provide early warning of impending misoperation, avoidance of unscheduled maintenance, reduced man-hours for maintenance inspections, and a greater knowledge of equipment health and reliability.

Records of events and disturbances from Sequence of Event Recorders (SERs) and Digital Fault Recorders (DFRs) at substations today, provide information for automated diagnostics. This paper discusses two software solutions that use this information to determine correct operation, degraded operation , and misoperation in equipment.

The solution by Andtek Inc. has been applied to SER data, and a solution by TLI Inc. has been applied to DFR data. Ways to use or combine both solutions are addressed. Modeling of expected relay response based on expert system rules allows DFR data evaluation by the TLI programs. Modeling of expected substation equipment operation based on operating table logic allows SER data evaluation by the Andtek programs.

The EPRI sponsored development of the software package for demonstrating automated substation diagnostics using DFR data was completed in 1995. The software has been field tested for over two years, and is now being offered as a commercial product. Operating experience to date will be presented.

The EPRI sponsored development of the software package for demonstrating automated substation diagnostics using SER data was completed in 1996. A program package with demonstrated results is now ready and available for use. A summary of the results of using this package will be presented with some lessons learned regarding best selection and use of monitoring points.

I. Introduction

The utility industry has been dramatically affected by deregulation and resulting competition. The main impact observed in many utilities so far is related to major organizational restructuring, staff reduction as well as refocusing of the future research and development activities. Improvement in the operating practice, extension of the equipment life cycle, and emphasis on the quality of the power supply will be among major targets for the future directions. To achieve some of the mentioned goals, it is expected that the utility industry will invest in new technologies, extensive automation and more efficient utilization of its technical personnel.

This paper concentrates on major improvements in utilizing data coming from commonly used substation data recording instruments, namely digital fault recorders (DFRs) and sequence of events recorders (SERs). The traditional role of these instruments was to provide information about analog waveforms and contact status changes associated with power system faults and other disturbances as well as operation of protective relays and switching equipment. Two major improvements are identified as a focus of this paper:

- automation of the data analysis process
- use of the analysis results for improving the monitoring, diagnostics and control practice.

The cost benefit analysis approach to be used to justify the investment in the new applications is also presented as a guideline for evaluating economic value of the improvements.

In order to achieve automation of the data analysis process, two different software packages are developed and their application is discussed in the paper. The DFR Assistant™ is an expert system software package aimed at automating the analysis of DFR data. The DIAGLOG is a model based reasoning software package designed to automate the analysis of SER data. Once these packages are installed and used, it is possible to develop monitoring and diagnostics strategies that can significantly improve the control, and maintenance practices. Options for using the mentioned packages individually and in a combined solution are presented. Discussion of the resulting monitoring and diagnostic benefits and their impact on the system control and equipment maintenance is provided.

The first part of the paper is devoted to a background discussion of the application requirements associated with automated substation monitoring and diagnostic tasks. The next two sections provide descriptions of the software packages for automated analysis of the DFR and SER data, respectively. The next section is devoted to discussion of the possible configurations for both the individual and combined use of the mentioned software. The final part of the paper contains discussion of a methodology that can be applied to the cost-benefit analysis for the new dignostic solutions.

II. Requirements for Event Monitoring and Equipment Diagnostics

It is well known that substation equipment operation can be categorized as follows:

- intended operator-initiated control actions aimed at scheduled switching operation
- fault driven predefined relaying actions aimed at on-line isolation of the faulted equipment
- unexpected equipment operation initiated by random events of unknown origin or unintended operator action

The DFR and SER equipment may be used to help operators, protection engineers and maintenance personnel determine which of the above mentioned scenarios has occurred and what was the final outcome of the operation.

Typical conclusions that are of interest are as follows:

- was the equipment supposed to operate?
- what has initiated equipment operation?
- did the equipment operate correctly?
- was there a degradation in the equipment operation?
- if the equipment misoperated, why has that happened?
- based on the performance, is equipment maintenance recommended?

To analyze the operation of protective relays and related equipment, the traditional role of the DFR based monitoring was to capture substation-wide analog waveforms coming from the instruments transformers as well as some contacts from the relays, communication channels and switching equipment. This level of monitoring is very useful in deciding what kind of event has caused the relay operation, and has the relaying action been successful. The monitoring of circuit breakers, interlocking logic and communication channels is not one of the main goals, and hence fewer monitor points are provided.

The traditional role of the SER based monitoring was to capture substation-wide contact status information from protective relays, communication channels and switching equipment in order to analyze operation of these devices. This type of monitoring is very useful in deciding if the equipment operated correctly since a very detailed analysis of the device operation can be achieved. This analysis can be performed for both the scheduled equipment operation such as operator initiated switching sequences and the unscheduled equipment operation such as protective relay initiated tripping actions.

It is interesting to note that there may be significant overlaps between the data recording and analysis procedures for both instruments. At the same time, there are major differences in the data recording initiation, number and type of the recorded points as well as the level of detail of the event and equipment monitoring carried out by the mentioned instruments.

The main advantage of the DFR based monitoring is the ability to analyze the causes for protective relay operation by observing the waveform disturbances seen by the relay. In addition, contact changes on the communication and switching equipment operated by the relays can also be observed, indicating if the overall fault clearing sequence is correctly executed. Monitoring of the waveform changes occurring as a consequence of the switching sequence steps is also a good indication of how successful the fault clearing was. A benefit of the DFR application is the ability to conclude if the final outcome for a fault occurrence are correct protective relaying and switching actions. However, the DFR monitoring is triggered by the waveform disturbance or relay operation, and hence the DFR data is only saved under these circumstances. Data associated with scheduled equipment operation initiated by operators may not be captured by DFRs. In addition, DFR monitoring of the contacts may not be extensive enough to provide detailed information on the communication channel and switching equipment operation. This is due to a relatively small number of contact inputs provided by the DFR design.

The main advantage of the SER based monitoring is the ability to provide a detailed account of the equipment operation irrespective of the initial causes for the operation. A large number of contact inputs available in the SER design enables wiring of as many contacts as needed to provide good monitoring of the equipment operation including the initiation commands, interlocking and blocking logic, logic timing, special sensor for monitoring mechanical and thermal failures, equipment power supply circuits, etc. This monitoring can be provided under various circumstances such as protective relay operation, scheduled operator initiated switching and unexpected equipment operation. However, the SER monitoring is concentrating on the equipment operation and does not have a provision for concluding what type of event has caused the equipment operation.

III. DFR Assistant™ Applications

The following list outlines main requirements of an automated system for analysis of DFR recordings:

- DFR file analysis logic at a substation level. *It analyzes and classifies DFR data file coming from a single substation. The analysis steps include disturbance detection, identification of the transmission line(s) involved, fault type classification, calculation of fault location as well as analysis of operation of protection relays and associated communication channels and circuit breakers.*
- DFR file analysis logic at a system level. *It correlates data files from all DFRs triggered by the same event. In addition to all of the above steps, the analysis includes filtering of records based on proximity of various DFR locations in the system and fault location.*
- Central database for archiving of analysis results. *The analysis results are stored at a central database and made readily available to different users over the LAN and via Internet.*
- Automatic notification via E-mail and faxes. *The analysis results are E-mailed or faxed automatically to all specified recipients.*

The above mentioned requirements can be met in two different ways. One way is to download events to a central location and then analyze them. The other way is to process events locally at substations and then communicate results of the analysis to the central location for further processing. The next two subsections describe each of these configurations in greater detail.

A. Substation Level Analysis System

Houston Lighting & Power company together with EPRI had contracted Texas A&M University several years ago to develop a system for automated analysis of DFR recording for one of their substations. The development has been completed and system commissioned in 1995. This section summarizes the system configuration and main features [1].

Test Laboratories International Inc. obtained license rights for the software from Texas A&M University with intention to further enhance and commercialize existing technology. Some of the new developments and future directions in this area are presented in the following sections [2-3].

Figure 1 shows the main hardware items and data flow. Local computer interrogates DFR, at pre-specified time intervals, looking for a new recording. The communication between DFR and PC is done via high speed GPIB link that enables transferring of complete records within 20 seconds time intervals. Once the record is archived at local PC, the analysis takes place. Depending on the record size, the analysis is completed in 40 to 60 seconds. After completion of the analysis, the fax message is created and sent to several locations within the company. System dispatcher receives the first fax within 2 minutes after event has been transferred to the PC.

The system, once installed and configured, is completely automated; no operator intervention is needed. This system has "system alive" function that reports its operating status in prescribed time intervals, usually once a day, by faxing a message to corporate office. The dial-up option for retrieving the DFR files from a remote location is still available if needed.

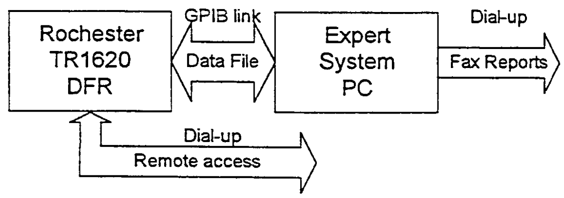

Figure 1. Analysis system configuration in a substation

The system's software consists of several modules. These modules include programs for:

- communicating with DFR
- signal processing of analog and digital channels recorded by DFR
- faxing analysis reports to remote sites
- event file archiving
- rule base expert system for event analyzing and classifying

Figure 2 shows basic steps related to the analysis of a single DFR record for the substation level analysis system. It can be seen that the software is organized in a modular fashion that allows extension in both signal processing capabilities as well as in incorporating additional expertise in the form of the expert system rules.

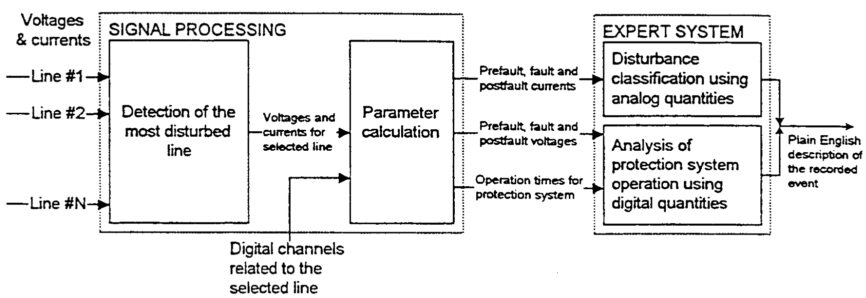

Figure 2. Substation level analysis

An example of a typical analysis report that is being faxed is given in Table I. First section of the report presents general information about recorded event. The second and third sections contain information about fault type, transmission line involved and estimated fault location. The next section presents overview of protection system operation with operating times for relays and circuit breakers. The last section shows analog waveform parameters for a faulted transmission line before, during and after disturbance.

During the initial period of field testing, system was calibrated and adjusted to the specific system conditions at a selected substation. Since the analysis software includes a full blown expert system shell, the addition of new rules to cover changing power system conditions is simplified.

Table I. ***Example of DFR Assistant™ Fax Report***

Date\Time Stamp of Event: 04/04/95, 12:44:44.938
Event number: 017 Sample rate: 5.99 [kHz]
Machine name: S.T.P. Serial number: 20299
Number of pretrigger samples: 1198 (12.0 cycles)
Total number of samples: 2926 (29.3 cycles)
Size of the event in tracks: 10 (320Kb)

EVENT DESCRIPTION

D. Velasco Ckt #27 is the circuit with largest current disturbance.
The disturbance is a **phase B to ground** fault.
The fault is cleared by the protection system at this substation.

FAULT LOCATION

Fault is located **21.54** miles from this substation.

PROTECTION SYSTEM OPERATION ANALYSIS

Backup relay operation starts at **0.0337 sec [2.0202 cycles]**
and ends at **0.0487 sec [2.9202 cycles]**.
The middle 52B contacts operate at **0.0605 sec. [3.63 cycles]**.
The bus 52B contacts operate at **0.0537 sec. [3.2202 cycles]**.
The bus breaker status change after trip is applied is **1.2 [cyc]**.
The middle breaker status change after trip is applied is **1.6 [cyc]**.

LINE CURRENTS AND VOLTAGES

	Prefault	Fault	Postfault	
I0	0.0087	**24.19**	0.001	[kA]
Ia	0.2076	0.801	0.000	[kA]
Ib	0.1868	**22.83**	0.000	[kA]
Ic	0.1672	0.272	0.004	[kA]
V0	0.0008	**0.086**	0.001	[kV]
Va	283.70	272.6	282.2	[kV]
Vb	283.90	**106.4**	282.8	[kV]
Vc	284.70	272.7	283.6	[kV]
Vab	491.20	**327.6**	488.8	[kV]
Vbc	493.10	**342.6**	491.5	[kV]
Vca	492.05	483.5	489.4	[kV]

All above values are peak values.

So far, the analysis system proved to be stable and reliable. The number of analyzed records exceeds 300. In most of the cases system provided accurate analysis for a given event. For the cases not analyzed correctly, changes in the system's knowledge base and/or thresholds were made to improve system performance.

B. Centralized Analysis System

Figure 3 shows a hardware configuration consisting of three PCs. DFR Master Station PC communicates with the DFRs in the field over one or more dial-up lines. Transferred DFR event files are automatically archived on a separate PC (DFR Events Archive) over corporate LAN. The third PC (DFR Assistant™) accesses event files from the server, processes them and returns the results of analysis back to the common database residing on the server. In addition, DFR Assistant sends out Email and fax notifications to specified recipients.

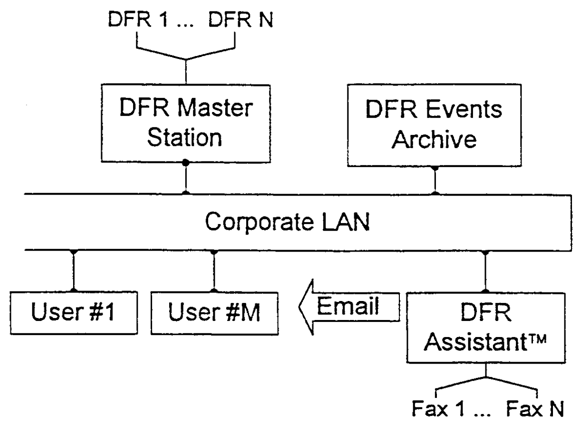

Figure 3. Possible configuration with centralized analysis

The task of the analysis logic in each of the mentioned configurations is to answer the following questions:

- Which DFR has triggered and recorded waveforms for a particular power system disturbance?
- What was the disturbance and what lines were affected?
- Where is the fault located (in the case the disturbance is a fault)?
- Did the protection system operate correctly?

The analysis logic for classification of DFR recordings in all of the mentioned cases consists of the following steps:

- identification of the faulted transmission line
- identification of all records pertaining to the same event
- correlation and analysis of all records identified in the previous step

The event detection and classification analysis is based on several algorithms that take into consideration both analog signals and digital contacts. The analog waveforms are divided into three sections. One section corresponds to prefault, one to fault and one to postfault conditions. Similarly the status change of digital channels is extracted from the record and correlated to the calculated fault inception time.

The following types of input signals are used by the analysis system:

- Phase currents (A, B, C, 0)
- Bus or line voltages (A, B, C, 0)
- Relay trip contacts
- Breaker open/close position
- Pilot channels (send, receive, stop)

Figure 4 shows top level window of DFR Assistant™ [2]. The left hand side presents information about configured DFRs, their connections (e.g., buses, transmission lines), while the right hand side lists DFR recordings that are transferred from the remote substations. The user can easily access the database of processed events by clicking on the toolbar buttons (denoted by H, M, L). Clicking on any of these buttons brings up contents of either high, medium or low priority directories.

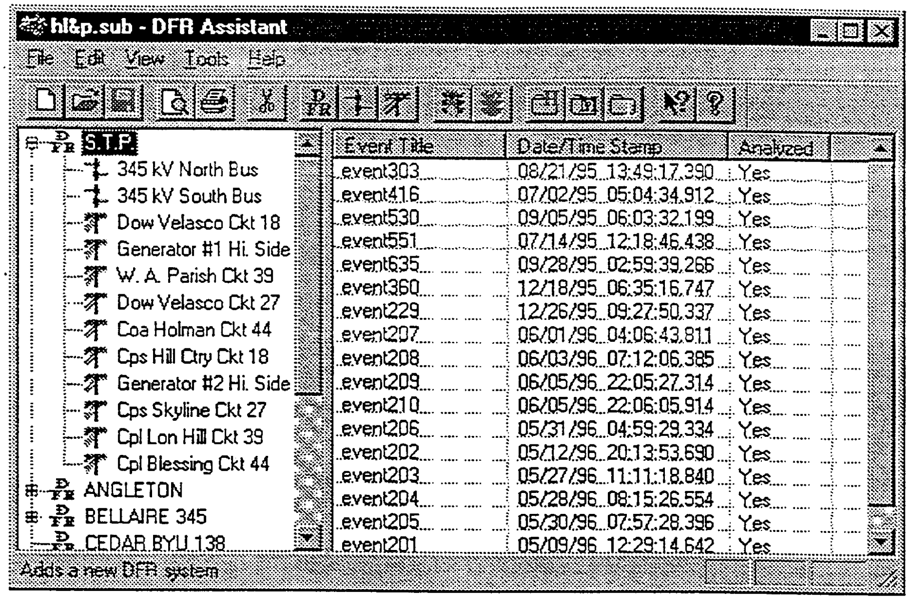

Figure 4. DFR Assistant's top level window

The filtering logic for storing analysis reports into these three directories is based on the following criteria:

- **High Priority**
    - fault confirmed; relay did not operate (failure)
    - no-fault confirmed; relay operated (misoperation)
    - fault confirmed; breaker restrike occurred
    - relay trips and breaker does not open
    - relay trips and breaker opens slowly
    - relay trips and carrier signaling incorrect
    - relay trips but relay pick-up time slow
    - ferro-resonance condition occurs
    - unable to classify DFR record
- **Medium Priority**
    - correct fault clearance by the protection equipment
    - unsuccessful reclosing sequence

- **Low Priority**
    - relay did not operate, breaker did not operate, self clearing disturbance in analog channels
    - DFR manual triggering

Figure 5 shows the window used for analysis report's viewing. This window displays the same type of information as given in Table 1 using a different format.

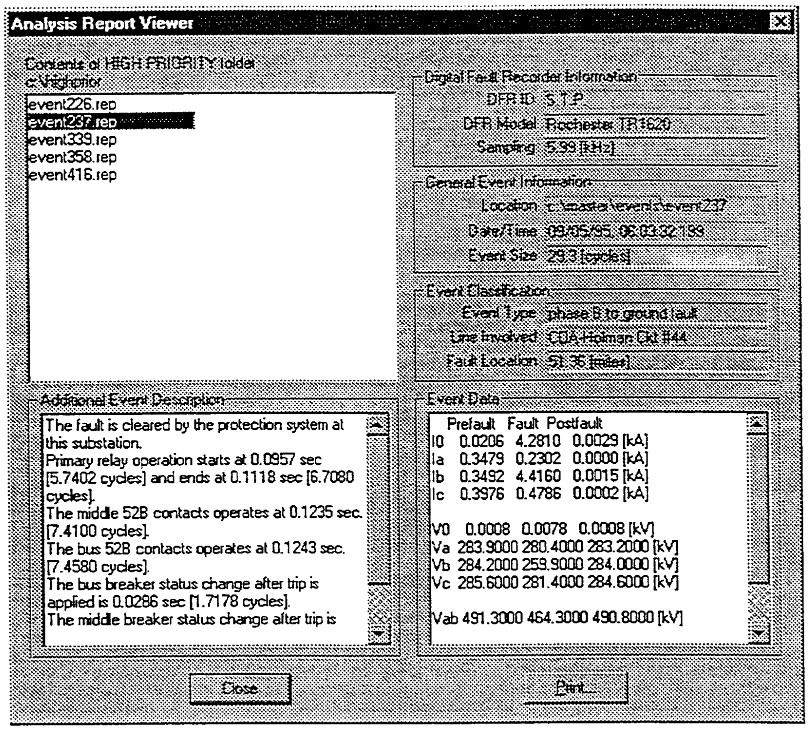

Figure 5. DFR Assistant's analysis report view

IV. DIAGLOG Applications

A. The DIAGLOG System

DIAGLOG is a Diagnostic Logic system implemented through a personal computer. It uses Sequence of Event Recorder files to perform an automated event diagnosis based on a comparison of observed reporting data with an expected set of data values. The expected data values are produced from a logic model of the expected equipment operation. Whenever observations are made from a sequence of event record, a comparison is made between the observed values and the expected values. When the two values agree, the substation equipment is considered to have operated correctly. When they disagree, a diagnostic report is provided [4].

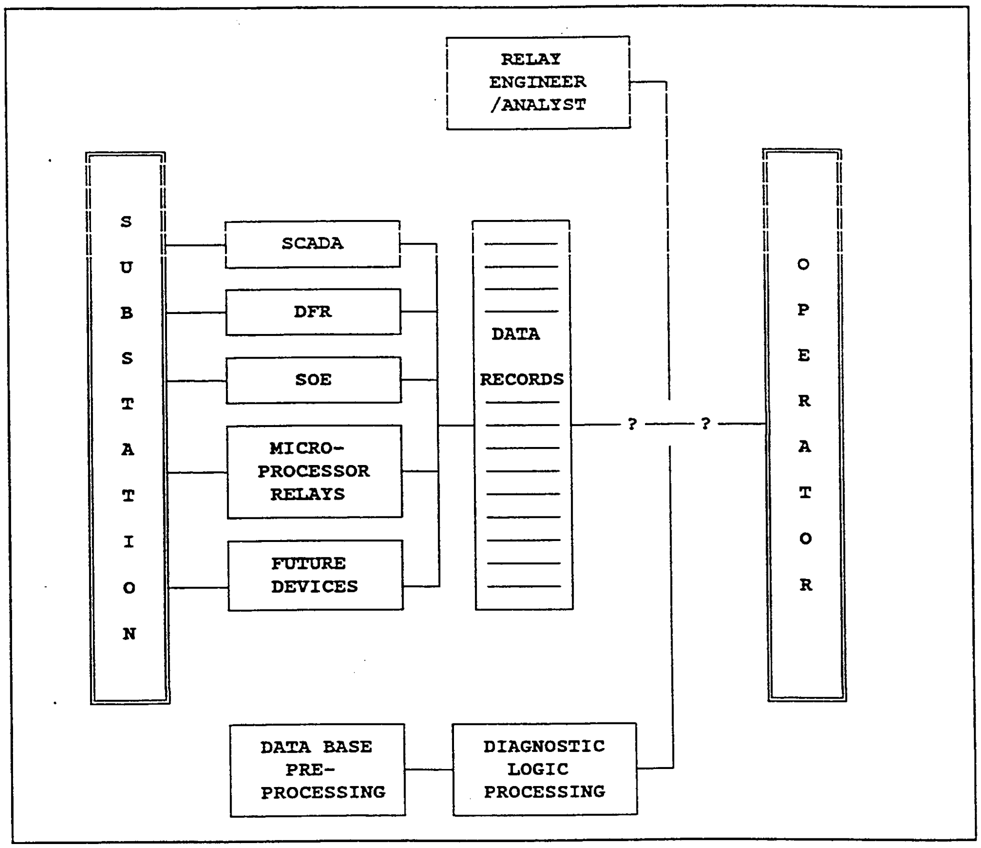

Figure 6. Where DIAGLOG Fits In Substation Operations

The evaluation of the equipment operation is based on how good the comparison is between the two sets of values. When differences are found to exist, then the appropriatness of the equipment operation is questioned, and a diagnostic Exceptions Report is made on the differences that were found. With this a troubleshooting procedure is automatically performed to locate the origin of the misoperation.

The automated diagnostics fits into substation operations (Figure 6.) where the data records from reporting equipment needs to be evaluated, and used effectively without being discarded because it is too voluminous or not quickly interpreted for easy use by the information users.

The reporting data must be evaluated and filtered to isolate information associated with each event, and to determine if a meaningful event exists. Following this process, each event identified for diagnostic reporting from the event recorder is converted to an appropriate logic format in a file where the diagnostics can begin. DIAGLOG performs automated data preprocessing as the next step for event diagnosis to proceed.

To achieve simplicity, speed and ease of operation, it is important to combine an automated reporting system with an automated diagnostic procedure. The essential elements of the DIAGLOG System for automated operation include the following:

1. Preprocessing programs to screen Reporting Data
2. Diagnostic programs to Evaluate Equipment Operation
3. Models of the Expected Equipment Response
4. A Summary and Reports of Diagnosed Events

B. The DIAGNOSTIC MODEL

In order for the diagnostics to be performed there must exist a substation model which describes the expected operation of each functional device in the substation. This logic model is a key feature in allowing the diagnostics to determine which substation equipment worked properly and which did not. The level of diagnostics achieved is directly related to the level of modeling performed and the number of station alarm points that are monitored and reported. Figure 7 shows how the model is in the DIAGLOG programs.

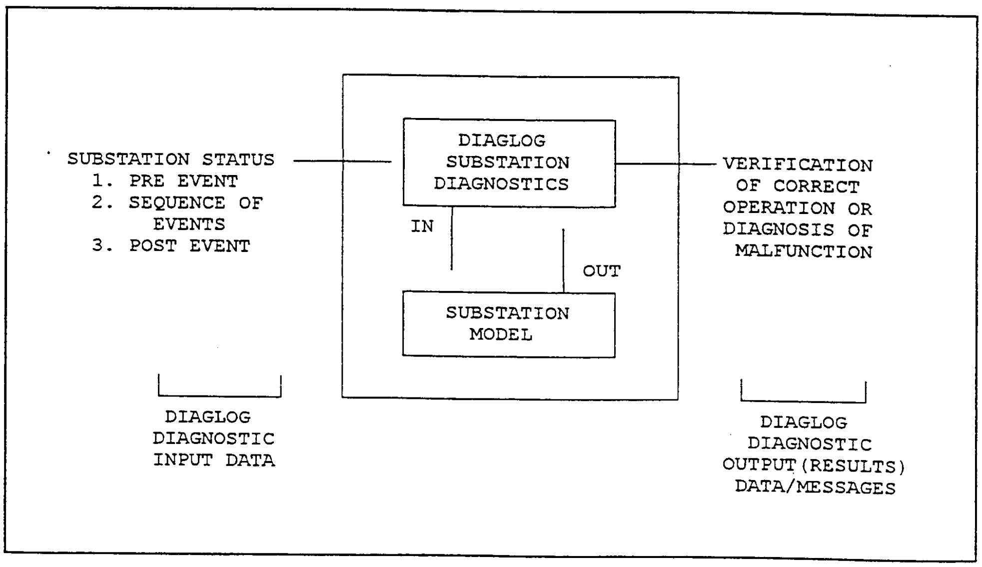

Figure 7. DIAGLOG Program Package

A top level model, which uses a limited number of monitor points at each Line Terminal, can usually be assembled to process the existing SER alarm points. Additional points can be installed as required for a more detailed model. The model is exercised by the diagnostic programs and uses the SER alarm reports.

The inputs and outputs of the model logic are related to substation status data base information on a point by point basis. Ideally, one desires to acquire all of the direct fault/event information on a real-time-stamped basis. In addition, it is desirable to acquire in real time the status and indicator information for equipment at any relevant neighboring substations not directly involved with the event. This is to verify that equipment which should not change state remained so during the event

Each module in the diagnostic model, representing equipment operation, requires specific information to enable the logic of the module to be developed and exercised by the diagnostic program. Fortunately there is a well structured set of logic procedures for describing the module logic.

An individual module of logic is constructed in a Truth Table or Operating Table form where the module logic input variables are listed in rows followed by the listing of the module logic output variables. For each expected operating case or condition, the logic values of the variables are listed in columns. Each module is defined at a level where the logical operation of a device can be easily described. The identification and selection of the module variables will determine what points it is desirable to have an event recorder report, and what preprocessing is needed to assign a logic value.

Several modules are combined to form a single diagnostic model. Collectively the modules describe how the substation equipment is expected to operate when an event happens. For a given event, the DIAGLOG diagnostic program will calculate the expected status for model observations, and will compare the calculated status with the actual reported observation. This information will allow the diagnostic program to determine which modules operated correctly and which ones did not.

C. Substation Application

The DIAGLOG models can be applied to substation equipment in a manner which allows each line terminal in the yard to be modeled individually and then combined into a single model for the substation. The 230 KV line terminals at the Miller Substation of Alabama Power Company were modeled. The Sequence of Events Recorder (SER) at the substation provided the raw data files used in running the DIAGLOG Diagnostics program package. When the DIAGLOG user programs are called, a screen is provided for the user to select the raw data reporting file for diagnostics. the following is a typical screen showing a selected file.

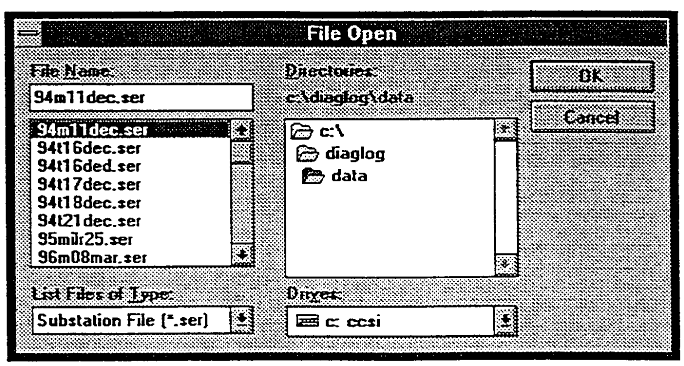

Figure 8. Report File Selection

Any file naming convention can be used. Here all file names use the extension .ser to denote the SER file record. The file name highlighted in Figure 8. is 94m11dec.ser. This denotes a record taken during 1994. The m denotes the Miller Station, and 11dec is the day the file was recorded denoting 11 December.

When the file is selected then the records are automatically processed to determine if any significant events have occurred. the need to actually review or inspect raw data records is eliminated while the value of any significant information is still retained. If no significant information exists when a user selects the file name, then a screen message would appear stating that "No Events Exist" for that file.

Once the record evaluation is finished, the substation model is automatically run to evaluate every operating event that was detected. If records are evaluated on a daily basis, then a small number of events usually exist. The diagnostic summary report for the substation will show a condensed one line report for each event.

The one line report will indicate if any maintenance alerts exist, and if there were any unexpected reporting values which would indicate an equipment item did not operate as intended. An example of a typical summary report is shown here to illustrate how a completed diagnostic will first appear (Figure 9.).

In this summary report, a single event is reported for the MLRTOP (Miller Top Level) model running for the Miller Station. This event indicates that two maintenance related items were detected, but there was no unexpected equipment actions that indicated a failure to operate correctly. Usually no immediate attention is needed if maintenance items are indicated, and any maintenance that is indicated can be detected early and scheduled at a time when it is convenient or more economical to perform.

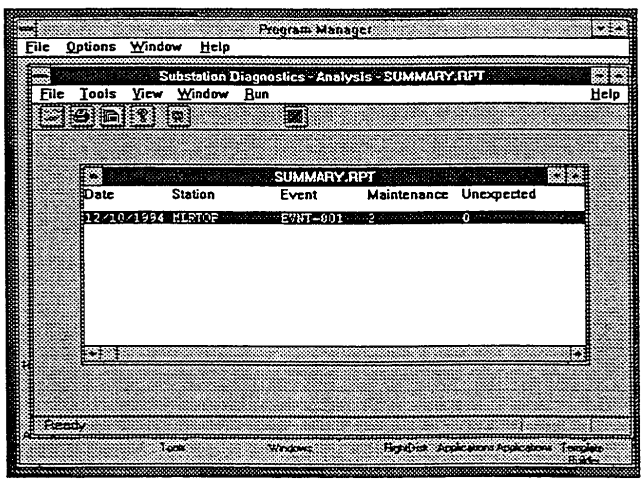

Figure 9. Summary Report

At substations there should not be much time or work spent performing the diagnostics. For this reason a choice of report levels of informations is provided when one needs to look a little further into the diagnostics. For the case above in which an event showed two maintenance alert observations, one can proceed to look at the lowest level of additional information offered. By doing a double click on the highlighted event line, a report selection is provided (Figure 10.).

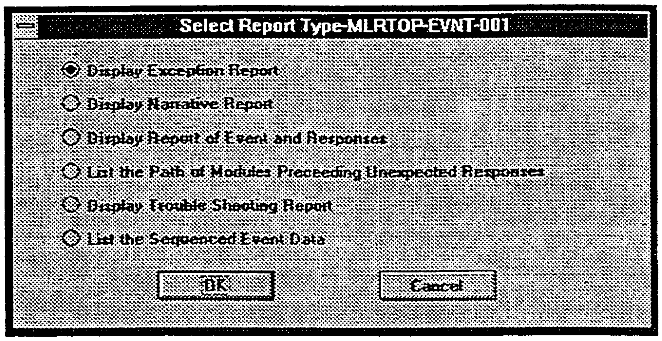

Figure 10. Report Selection

In this list of reports, the Exception Report is provided to tell only those items which were considered exceptions to a normal event, and that includes any maintenance alerts.

The Narrative Report includes the Exception Report information together with that which responded to the event at the substation.

The Report of Event and Responses goes further to also include everything that the substation model was observing. This includes things that properly made no response.

The Path of Modules report will tell everything that operated correctly up to the point where unexpected operation existed.

The Troubleshooting Report is only invoked when an event exhibits incorrect operation.

And lastly, an option is provided to list only that portion of the reporting data record which lists the particular event data which triggered the diagnostic evaluation.

The majority of reporting events are for correct operations in which the equipment responding to the event behaved as expected. The DIAGLOG diagnostics will confirm the correct operations. And for those events which contain maintenance alerts, the equipment is still considered to perform in an acceptable manner at the time of the event.

For those occasions when there is an incorrect operation of equipment, the emphasis is placed on the diagnostic reports which detect and identify what has gone wrong with the equipment.

To illustrate the diagnostic response that is provided when there is an equipment failure, the next section on Reports for an Incorrect Operation is illustrated using the previous example where a primary trip coil failure is introduced into the reporting event. This Test Report was run by the diagnostic program; and shown here is the results obtained when all other event information remained exactly the same.

D. Reports for an Incorrect Operation

The The Summary Report now shows not only the previous maintenance alert, but now also an unexpected operation (Figure 11.).

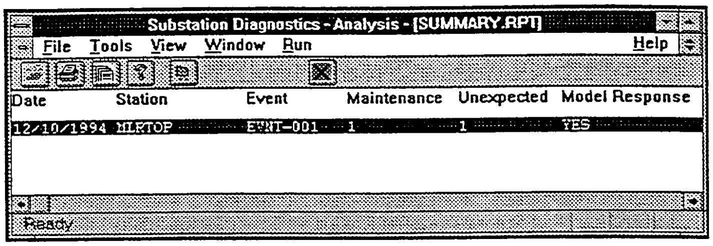

Figure 11. Summary With Unexpected Operation

The Yes value under the Model Response heading confirms that the diagnostic model has responded to the reporting data for the event. The Exception Report, the Narrative Report and the Troubleshooting report will track the unexpected observation.

Display Exception Report

The Exception report focuses on showing only what changed during the event, and now lists the items that did not behave as expected.

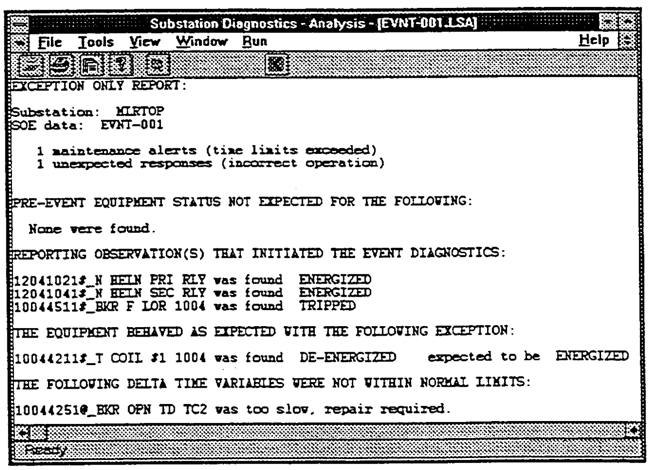

Figure 12. Exception Report

The Trip Coil # 1 for Breaker 1004 is now shown as being found de-energized when it was expected to be found energized. And since the # 1 coil did not report energized, there was no Delta Time variable calculated for the Breaker opening from the time of the primary trip coil. None of the reporting observations that initiated the event diagnostics were changed from before. The North Helena Line primary and secondary relaying were found energized, and the Breaker Failure Lockout Relay for 1004 was found tripped (Figure 12.).

Troubleshooting Report

When an exception occurs, a person can go directly to the Troubleshooting Report to find out what all was associated with the particular exception. The complex interactions between equipment and the possibility of one or more problems being present are good reasons to read the Troubleshooting Report. For this example the report was able to go directly to the problem.

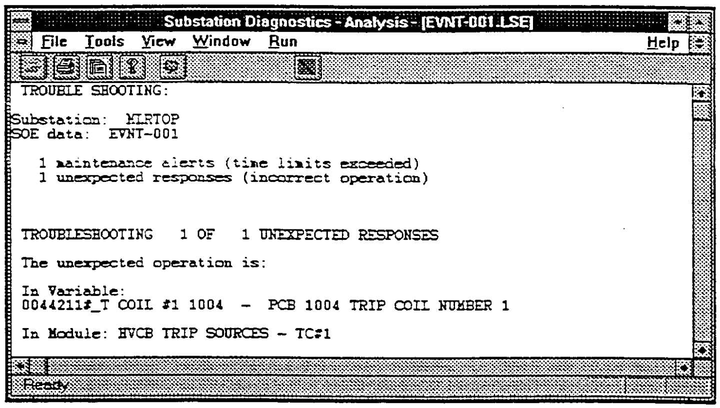

Figure 13. Troubleshooting Report

The Troubleshooting Report confirms that there is one unexpected response that it is dealing with, and goes on to say what variable in the model it is associating with the incorrect operation. It points to Trip Coil Number 1 for Power Circuit Breaker 1004. The operation of this equipment is described in a Module (operating table) in the diagnostic model which is called HVCB TRIP SOURCES -TC#1.

The Troubleshooting Report will locate the problem down to the specific equipment item that is not operating correctly. If the reporting data contained too few monitoring points to let the diagnostics point to the exact location of the problem, then the Troubleshooting Report would list those equipment items that could have been associated with the problem. Here the information was sufficient to say exactly where the problem was located.

The diagnostics would normally be concluded at this point. But for the sake of completeness the other available reports associated with the event will be presented and a few comments provided to show where an unexpected operation is described.

Display Narrative Report

The second half of the Narrative Report for this event is shown here which identifies the equipment operation on the North Helena Line.

Recall that in addition to the #1 trip coil not reporting operated, there also was the time delay in the Breaker 1004 opening. Trip Coil #2 operated even though Trip Coil #1 was out of the picture. By examining the list of the observed responses that were as expected, one can see what was missing. When the North Helena Primary and Secondary Relaying responded to the event, The Trip Coils #1 and #2 were shown energized for each breaker except 1004. The T COIL #1 1004 response is missing from the Expected

Response list.

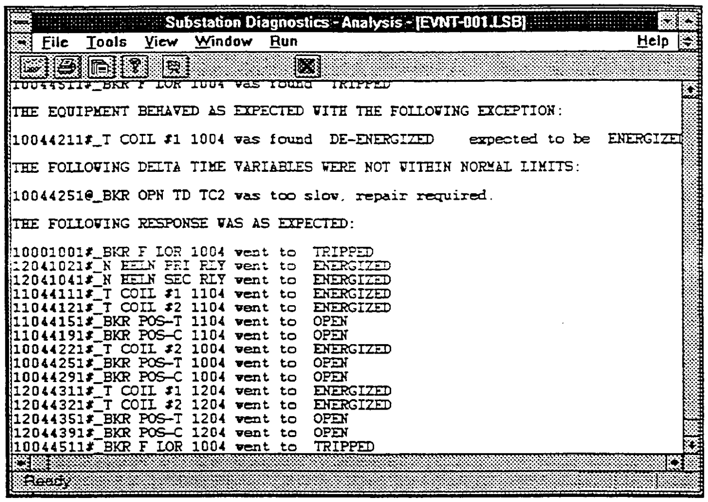

Figure 14. Narrative Report

In a situation such as this, the full Narrative Report for the event could be saved for maintenance purposes.

E. Graphical Modeling Methods

A recent development has been accomplished as an extension to the regular method of building DIAGLOG models. This involves Graphical Modeling procedures, and is an entire subject of discussion by itself. It is an important area of development that should be mentioned here since it may prove to be very beneficial in the future. The original procedure for building the modules that make up the completed model involves the building of an operating table or truth table for each of the functional equipment devices that are expected to operate when required. That procedure is strait forward, and can describe functional operations independently of the actual wiring connections or circuitry.

The Graphical Modeling approach allows the engineer or model developer to visualize the devices on the screen, and then wire or connect each of the devices to construct the actual single line diagram equivalent of the engineering drawing or schematic. The concepts for building and connecting elements were reported at the 1996 EPRI Substation Diagnostics Conference. At present the graphics work has progressed to where graphical designs at the device level involving several elements can now be saved and used at a system level design screen where a single item on the screen will represent the integrated device design. Only the inputs and outputs are identified on the screen at the system level design.

When the Graphical Modeling methods are used, then the developer will be able to take advantage of the best features provided by both a graphical as well as a logic table procedure. Small example graphic designs are presently available.

V. Combined Solutions

This section concentrates on various options for combining the two software packages in one application. One obvious option is to use both packages and run them on the same computer. In this case the user will have to select related data files so that the analysis is performed on "corresponding" files obtained from DFR and SER recordings.

Other more automated options include:

- Common graphic user interface (Option 1)
- DIAGLOG package enhancement using data from DFR Assistant™ (Option 2)
- DFR Assistant™ package enhancement using data from DIAGLOG (Option 3)
- Extended analysis logic based on correlation of data / results from both packages (Option 4)

The common graphical user interface can be designed to have data from both software packages controlled through a multi area window. An example of the window design is shown in Figure 15.

Section #1 • DFR Assistant™ Menus • DIAGLOG Menus	Section #2 • Header file of the DFR record • Header file of the SER record
Section #3 • DFR results from DFR Assistant™ • SOE reports from DIAGLOG™ software	Section #4 • Fault type • Fault location • Fault clearing assessment

Figure 15. Common User Interface for a Combined Solution

The window section #1 can be used to provide a choice for data types to be shown in the other windows. The displaying options are discussed in the earlier descriptions for each of the packages. One example is to have DFR Assistant™ and DIAGLOG menus that allow selection of different DFR and SER records. A pointer logic based on the time stamp information can be developed to extract DFR and SER records corresponding to the same time interval of a given event. The window section #2 will then be used to display the header information of both records. The window section #3 can be used to combine the results of analysis of the sequence of event data coming from both packages. The data in this window section can be selected through the DFR Assistant™ and DIAGLOG menus given in the window section #1 to reflect the level of detail available to support the results. The window section #4 can be used to display the results of the processing and analyzing the analog data. This window section can be controlled through the DFR Assistant™ menu given in the window section #1. For example, one level of detail can be presentation of the fault type, location and clearing description. The next level of detail can be representation of the RMS values of the prefault, fault and postfault voltages and currents.

The next two options of enhancing either the DIAGLOG or DFR Assistant™ packages with the analysis results from the other package is shown in Figure 16.

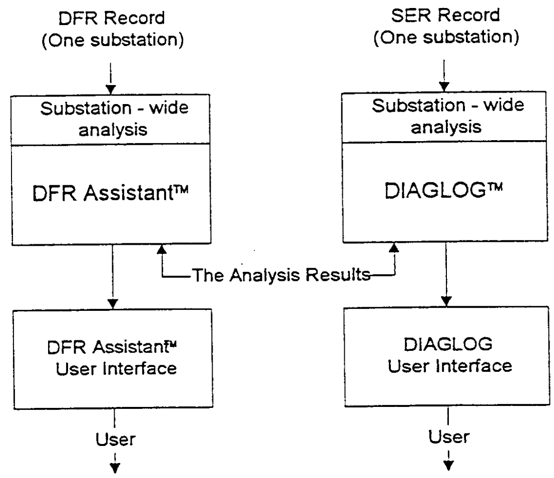

Figure 16. Software package enhancements

It should be noted that this still assumes existence of both packages, but the analysis of each of the corresponding packages is enhanced based on the preprocessed data received from the other package.

For example, the DFR Assistant™ analysis result that identifies the type of fault and fault location can be utilized as an input to an additional logic module in the DIAGLOG software that identifies an expected fault clearing, relay tripping and breaker switching sequence. The relaying communication channel state changes can also be anticipated based on this information. This additional information and logic expansion would enable DIAGLOG software to provide more comprehensive diagnostic results.

Likewise, the DFR Assistant™ logic can be expanded to accommodate additional information on switching sequences that is readily available from the DIAGLOG processing. This information can be combined with the rules based on the parameters obtained from the processing of the analog inputs in the DFR record to further verify the switching sequence by observing the corresponding changes in the analog signals.

It should be noted that the main difference between the first and the second two options for combining packages is in the design of a common user interface with no logic change (Option 1) and a logic change based on the exchanged data with no change in the user interface (Option 2, 3). Obviously, options 2 and 3 can be further merged in one option where the enhancement in the logic of either one or both packages can be supplemented with a design of a common user interface.

Finally, an option (4) for further combining of the two packages can be implemented as shown in Figure 17.

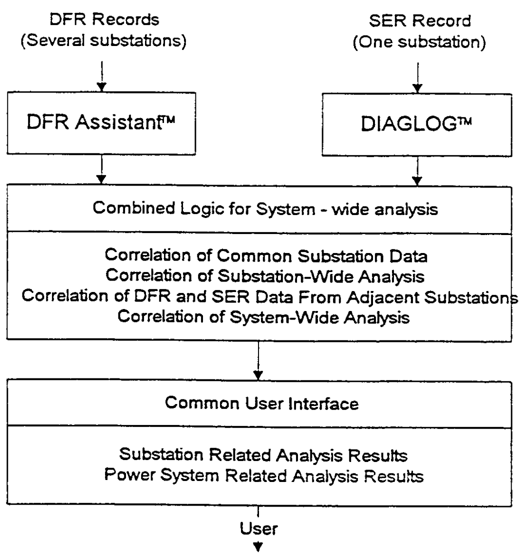

Figure 17. System Diagnostics using combined Automated Analysis of DFR & SER records

It is obvious from Figure 17 that this option represents a full integration of the data, processing and analysis logic and user interfaces. It is foreseen that this integration can produce further enhancements over options 1-3 at both the substation-wide and system-wide levels. At the substation level the total data available in DFR and SER records can be used to establish inferential checks to further verify the likelihood of occurrence of the given events. In addition, the logic of both packages can be merged to enhance the temporal account of the sequence of events where the analog and contact data are used in a cause ⇒ effect mode to further verify the correctness of the equipment operation.

At the system level, combination of the DFR Assistant™ and DIAGLOG logic can provide additional information about power system events that may not be observable by the existing sparse allocation of either DFR or SER recorders. Also, full verification of the operation of the relaying schemes can be provided if any of the mentioned recorders are located at both ends of the line. Furthermore, a quick selection of the most relevant DFR and SER records can be performed in the case when several DFR and/or SER records are generated at the same time from different substations affected by the same power system event.

These options for combining the two software packages require various degrees of the software integration; with the option 1 being the least involved and option 4 the most involved.

VI. Cost Benefit Analysis

There are costs associated with providing a diagnostic capability which can be justified when the alternatives to the diagnostic can be shown to not be as effective. Although there are other factors besides cost that can justify providing a diagnostic capability, this discussion focuses on the cost benefit and attempts to quantify certain cost boundaries for the diagnostics.

The reference used for comparison is the maintenance policy of using scheduled replacement or overhaul to avoid unscheduled equipment failures during normal operation. Whenever the cost of incurring equipment failure during operation is greater than the cost of scheduling repairs when equipment is out of service, then a minimum cost can be determined by selecting the operating life T for scheduled repair that will minimize the overall average cost per hour of operation.

The following terms are used:

- C_u = Cost of an unscheduled equipment renewal
- C_s = Cost of a scheduled equipment renewal
- X = Cu / Cs the ratio of unscheduled to scheduled costs
- T = Time of optimum renewal
- C_d = Cost of Diagnostics to provide incipient failure detection
- R(t) = Reliability function of equipment
- R_d = Reliability of the Diagnostic System detection

The cost ratio X is the principal driver in determining the cost savings that can be achieved for using a diagnostic system. If the diagnostic system provides the capability to detect incipient failure, then the total cost of an equipment failure during operation as measured by C_u for unscheduled renewal can be avoided. Then only the lesser cost of doing a scheduled renewal is experienced.

A useful equation for determining an upper cost boundary for providing diagnostics was developed by Andtek Inc. as a management tool in comparing costs. This equation gives the ratio of C_d the diagnostics cost to C_s the scheduled renewal cost as a function of the X cost ratio.

$$\frac{C_d}{C_s} < \frac{\int_0^\infty R(t)dt}{\int_0^T R(t)dt} [R(T)(1-X)+X] - 1$$

This equation is in its general form where the reliability function R(t) is that of the equipment being evaluated.

If the diagnostics system will detect every incipient failure with 100% Reliability, then no correction is needed to the cost boundary equation. When the Diagnostics detects failure 99% of the time or 90% of the time, then a correction factor is needed. The upper value of the cost boundary C_d / C_s will be reduced. The amount of the reduction is given by the following expression.

$$(R_d - 1)(1 - X)$$

Here the term Rd is the reliability of the diagnostic detection system. If the detection reliability is high then a greater cost for diagnostics C_d can be justified. The following table provides some selected solution values of C_d / C_s for given values of X.

Table II. Diagnostic Cost Boundaries

X (C_u/C_s)	C_d / C_s (R_d=100 %)	C_d / C_s (90 %)
1	0.00	0.00
2	0.72	0.62
3	1.30	1.10
4	1.62	1.30
5	2.00	1.60
10	3.30	2.40
15	4.50	3.10

Table II shows that a significant cost for diagnostics can be justified when the boundary for comparison is a minimum cost scheduled renewal maintenance procedure. Whenever the cost of providing the diagnostics falls below these boundary values, then the difference can be considered a cost savings or avoidance when compared to not installing the diagnostics.

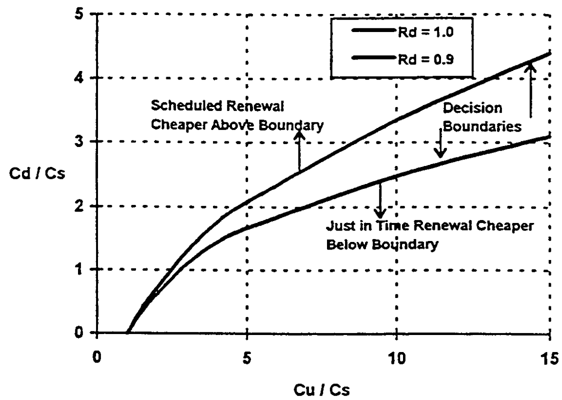

Figure 18. Diagnostic Cost Boundaries

For example, assume the cost of repairing an equipment that failed in service was $10,000 due to severe damage to itself and other equipment. But the cost of repairing the same equipment that did not fail in service was $5,000. The X value for unscheduled to scheduled cost is 2. From the table the C_d / C_s value is .72 as an upper boundary. Then the cost to provide the diagnostics should not exceed .72 x 5,000 or $3,600 to be competitive with the best results from an optimum scheduled maintenance policy. If the actual cost of providing the diagnostics were only $1,600 then a cost savings of $2,000 would be realized compare to operating without the diagnostics.

REFERENCES

[1] M. Kezunovic, I. Rikalo, C. W. Fromen, and D. R. Sevcik, "Expert System Reasoning Streamlines Disturbance Analysis," *IEEE Computer Applications in Power*, Vol. 7, No. 2, pp. 15-19, April 1994.

[2] M. Kezunovic, I. Rikalo, "An Advanced System Solution for Automated Fault Analysis Using DFR Files," *Fault and Disturbance Analysis Conference*, Virginia Tech, Arlington, Virginia, November, 1996.

[3] DFR Assistant™ Product Description, *Test Laboratories International Inc.*, 1996.

[4] B. Andre, R. Smyth, L. Smith, "User Friendly Features for Automated Diagnostics" *Substation Equipment Diagnostics Conference,* International Hotel, New Orleans, Louisiana, February 5-7,1996.