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Autonomous Power Expert System Advanced Development

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ABSTRACT

The Autonomous Power Expert (APEX) system is being developed at NASA Lewis Research Center to function as a fault diagnosis advisor for a space power distribution test bed. APEX is a rule-based system capable of detecting faults and isolating the probable causes. APEX also has a justification facility to provide natural language explanations about conclusions reached during fault isolation. To help maintain the health of the power distribution system, additional capabilities have been added to APEX. These capabilities will allow detection and isolation of incipient faults and enable the expert system to recommend actions/procedures to correct the suspected fault conditions. New capabilities for incipient fault detection consist of storage and analysis of historical data and new user interface displays. After the cause of a fault has been determined, appropriate recommended actions are selected by rule-based inferencing, which provides corrective/extended test procedures. Color graphics displays and improved mouse-selectable menus have also been added to provide a friendlier user interface.

This paper contains a discussion of APEX in general and a more detailed description of the incipient detection, recommended actions, and user interface developments during the last year.

INTRODUCTION

Our future presence in space will require larger and more sophisticated working and living environments. Such environments will consist of numerous integrated subsystems that will have to be maintained with a high degree of reliability. Primary among the various subsystems is the power distribution system that supplies electrical energy throughout the space-based facility. The availability of space power will be finite, and the sharing of limited power resources will have to be optimally scheduled. If a fault occurs within the power distribution system, disruption of scheduled power usage will result in a costly loss of mission time and could threaten the operation of other subsystems such as life support.

Figure 1 shows a typical power distribution test bed designed for space-based applications. Electrical energy is collected by solar arrays, converted to 20 kHz power, and transmitted through power lines to the various loads. Power distribution paths are opened/closed by using switching devices known as Remote Bus Isolators (RBI's). Each RBI contains a number of sensors to measure the various operating parameters of the power distribution system such as current, voltage, power, and power factor. Upper level controllers access the sensory data and relay the information to a central Power Management Controller (PMC). When an RBI is tripped because of an overcurrent condition attributed to a fault in the system, the PMC will attempt to restore the lost power by activating alternate RBI's that will reconfigure the power distribution system.

Quick and automatic reconfiguration of the power distribution system by the PMC provides the necessary capability to maintain power distribution when a fault occurs. To preserve the health of the power distribution system, however, the fault must be isolated and appropriate recovery procedures must be performed to repair the problem. Potential power disruptions can also be avoided by detecting incipient fault conditions that are, at present, nonthreatening to the power distribution system but that over a period of time will become a fault. Isolation of and recovery from a fault condition depend on the technical knowledge and experience of power systems personnel. Incipient faults are detected by continuously monitoring sensory data for indications of persistent upward or downward trends in any of the power distribution system measurements.

In a real space environment, with a limited crew size, space power expertise may be unavailable, and with a large number of switching devices, routine maintenance checks and power system data analyses for incipient fault conditions would require a significant amount of crew time. Therefore autonomous control of space power distribution by expert systems with fault isolation, fault recovery and incipient detection will greatly enhance the reliability of the power distribution system and reduce the human workload.

The Autonomous Power Expert (APEX) is a software system designed to emulate a human expert's reasoning processes in order to solve problems in space power distribution. The APEX system automatically monitors the operating status of the power distribution system and reports any anomaly as a fault condition. APEX then functions as a diagnostic advisor, aiding the user in isolating the cause of the detected fault condition and in repairing the power distribution system.

Development work for the current design of APEX was based on the Power Distribution Unit A (PDUA) subsystem shown in figure 1 [Troung 1989]. APEX is currently interfaced to the PMC controller, which communicates with the Power Distribution Controller (PDC). APEX sends a request for data to the PMC. The PMC acquires the requested data from sensors on the power distribution switching devices via the PDC and passes the data to APEX. When APEX has collected the power distribution parameter data, a fault detection phase is initiated.

APEX detects faults by comparing expected values to the measured operating values (parametric values) obtained from the controller. The expected values are calculated by APEX from the scheduled profile data of the loads connected to the PDUA. If no deviations from the expected operating state of the PDUA are found, APEX will again request data from the PMC and re-initiate the fault detection activity with the new data. If an anomaly is found within the data acquired from the PMC, APEX will inform the user that a fault has been detected.

The user can direct APEX to isolate the probable cause of the fault. APEX accesses information and rules contained in its knowledge base, reaches a conclusion, and displays to the user the probable cause for the detected fault. The user can then ask APEX to justify its conclusion and to recommend actions to correct the fault.

IMPLEMENTATION OVERVIEW

APEX is currently implemented on a Texas Instruments Explorer II workstation in LISP and employs the Knowledge Engineering Environment (KEE) expert system shell. APEX consists of an integrated set of software, including a knowledge base, a database, an inference engine, and various support and interface software. The knowledge base comprises facts and rules that correspond to knowledge acquired from the human expert during problem solving. The database is the basic working area where storage and calculations of sensory data for incipient fault detection occurs. The inference engine is the reasoning mechanism that, during fault isolation, draws conclusions from information stored within the knowledge base. In choosing the appropriate recovery procedures for the isolated fault, APEX also relies on the reasoning capabilities of the inference engine. Conventional software provides the user with an interactive interface to communicate with APEX and to obtain data from various sources such as power distribution hardware and planner/scheduler software.

Knowledge is represented within the APEX knowledge base mainly by frames, semantic triples, and production rules. Frames are structures that describe objects or classes of objects and their relationships. Objects are composed of slots that specify the various attributes belonging to each object. Individual slots of an object can contain declarative information or attached procedural functions. Declarative information expresses facts about the object, whereas procedural functions are programs or a set of procedural steps attached to the slot producing a particular behavior for the object. Within APEX, declarative information is represented by semantic triples that state information in the form of object/attribute/value (ie. attribute of object = value). Production rules are "If-Then" statements that imply either declarative facts or procedural behaviors when the conditional statements contained in the premises of the rule are found to be true. [Sell 1985]

The database contains a historical record of data acquired from the switching devices in the power distribution system. Storage and manipulation of these data are accomplished with conventional techniques and do not require the use of the inference engine. A detailed description of the structure and use of the database is given in the section on incipient fault detection.

APEX employs an inference engine contained in the Knowledge Engineering Environment (KEE) expert system shell [KEE 1989]. The inference engine is the heart of the expert system; it determines how knowledge is represented and processed. By operating on the rules within the knowledge base, the inference engine can reason and draw inferences about the state of the power distribution system. The inference engine rule processing strategies are commonly referred to as forward and backward chaining. Forward chaining works from the given data to a conclusion by examining the premises of the rules to determine if the conclusion of a rule can be inferred. If a conclusion is inferred, the new facts asserted by the conclusion could then cause other premises in other rules to imply even more conclusions. Backward chaining works from a particular goal and tries to either confirm or refute its truth. In the case of backward chaining, rules are selected by first matching the conclusion of the rules with the stated goal. If the true/false values of the premises of the matched rule are unknown, the premises become subgoals, which then can cause other rules to be selected. The goal is asserted only when all of the premises and subgoals of the goal-matched rule are known to be true. In the APEX system, fault detection is driven by sensory data and is implemented with forward chaining. Fault isolation is accomplished with backward chaining by giving APEX the goal of finding the probable cause of the fault.

APEX also consists of various support software that allows communication with the outside world. The user interface enables APEX to communicate with the operator through color graphics display screens and menu selections. Using the menu options, the user can select the detail level of information to be displayed, ask for justification of a particular conclusion, and request recommended action to correct an isolated fault. Other communication links provide data acquisition from the power distribution system via the lower level controllers, and load profile data acquisition from a remote scheduling system [Ringer 1990].

Incipient Fault Detection

Faults are detected by comparing the parametric values (measured operating values) of the power distribution system to the expected values and identifying any abnormal operating parameters. When the detection rules have been exhausted, APEX reports to the user whether or not any faults were detected. If a fault was detected, the user can then ask the expert system to isolate the probable cause of the fault. If no abnormal conditions were detected, the historical data is analyzed for incipient fault conditions.

Incipient detection is based on

statistical linear regression and correlation analysis of the historical data. As new data are received, the parametric values of the power distribution system are stored as historical data under the appropriate attributes for each switching device. Along with each measured value, the expected value that is calculated by the expert system is also saved. The expert system analyzes the historical data looking for any indication of a parametric attribute that has maintained either an upward or downward trend in the data values over a period of time. The following parametric attributes are stored for each device: switch A current, switch B current, line voltage, load voltage, and power.

Since the power system is dynamic and the measured value fluctuates over a period of time during normal operation, a parametric ratio of the measured-to-expected value is used to identify any increasing or a decreasing trends in the parametric data. Thus, if the measured and the expected values are equal, the ratio will be one. If the measured value is higher than the expected value, the ratio will be greater than one; if the measured value is less than the expected value the ratio will be less than one.

Once the data have been stored in the database, correlation coefficients are calculated for each parametric attribute of each switching device. The correlation coefficients are calculated in the following manner [Trivedi 1982]:

The mean value of a variable is found from

$$\bar{a} = \frac{1}{N}\sum_{1}^{N} a_n$$

the time variance from

$$\sigma_x^2 = \overline{X^2} - (\overline{X})^2$$

the parametric variance from

$$\sigma_y^2 = \overline{Y^2} - (\overline{Y})^2$$

and the covariance of X and Y from

$$\overline{XY} - \overline{X}\,\overline{Y}$$

where X is the time values and Y is the parametric values.

The correlation coefficient r, then, is

$$r = \frac{\overline{XY} - \overline{X}\,\overline{Y}}{\sigma_x \sigma_y}$$

where the standard error is

$$S_y = \sigma_y \sqrt{1 - r^2}$$

the slope is

$$m = \frac{\overline{XY} - \overline{X}\,\overline{Y}}{\sigma_x^2}$$

and the Y-intercept is

$$b = \overline{Y} - m\overline{X}$$

A high correlation coefficient, caused by a parametric ratio trend, indicates that a temporal relationship exists. The value of the correlation coefficient lies between zero and one. A zero indicates that there is no correlation between the time and historical parametric data; however the closer correlation coefficient is to one, the stronger the time and parametric value correlation. APEX currently will consider an incipient fault condition to exist if the correlation coefficient of a parametric attribute is higher than .75.

Once an incipient fault condition has been detected, the user can view the results of the statistical analysis and also have APEX isolate the probable cause of the incipient condition. Figure 2 shows a typical display indicating a definite increasing trend in the ratio between measured values and expected values. The trend was detected within the switch A current parameter of switching device RBI.3/3. Along with the plot of the linear regression results, the correlation coefficient, slope, standard error, and y-intercept are displayed for the user. A set of isolation rules for detected incipient fault conditions can access the database and examine correlation coefficients of the various parametric attributes of each switching device.

USER INTERFACE

The goal of the user interface is to provide access to APEX which is intuitive, and requires only a small amount of training. Communication between APEX and the user is accomplished with easy to use mouse-selectable menus, and color graphics and text displays. The user interface screen presents a color display that is divided into three areas as shown in figure 3. The top portion of the screen is the control menu that allows the user to select the desired APEX function. When a function is selected, mouse-selectable options for that function appear in the options menu located in the lower portion of the screen. As APEX performs the selected function, the control menu is replaced by a status display window indicating the operational steps being executed. Fault detection and fault isolation results are shown within the main display area by means of color diagrams and text explanations.

The control menu contains the following six mouse-selectable functions: MONITOR, DETECTION, ISOLATE CAUSE, RESET SYSTEM, LOG FILE, and EXIT. The MONITOR selection causes APEX to continuously acquire and check parametric values from the power distribution system. When either an active or incipient fault is detected, APEX stops monitoring and displays a "fault detected" message in the upper left corner of the user interface screen. Once alerted, the user can display the fault detection analysis performed by the MONITOR function by selecting DETECTION in the control menu. When ISOLATE CAUSE is selected from the menu, APEX will access the fault isolation rules to determine the probable cause of the detected fault. The RESET SYSTEM function clears the working space of the APEX system to prepare APEX for monitoring the power distribution system. If the user wants to record the session with APEX, a file can be opened/closed and printed with the LOG FILE function. The EXIT function allows the user to either terminate APEX, switch over to the power system data simulator, or to communicate with a remote planner/scheduler.

Recall that when a function is selected, the options menu provides the user with available options for that function. For example, when the user selects the ISOLATE CAUSE function, APEX will display the probable cause of a detected fault and the options menu will contain CONTINUE, WHY?, RECOMMEND. The CONTINUE option will allow the user to exit from the ISOLATE CAUSE function and continue APEX operations with the control menu. If the user selects WHY?, APEX will display the reasoning process leading to the probable cause conclusion. The RECOMMEND option allows the user to request recommended action procedures for correcting the fault; this option also has a user confirmation/rejection sub-option during any procedural step requiring autonomous action of the APEX system, such as reconfiguring the power distribution system.

The graphical displays in the main display area consist of a set of hierarchical diagrams that represent three different levels of information. The diagram in the main display area shown in figure 3 represents the overall power distribution system. When an active fault is detected, in the diagram the area of detection is outlined in red and a red flashing cursor appears next to the area. For an incipient fault condition, the area is outlined in yellow and has a yellow flashing cursor. The yellow indicates that a parametric value is probably going to go out of tolerance if preventive action is not taken. The user can get a more detailed diagram of an area by choosing the particular area of interest and clicking the mouse. Figure 4 shows the user interface screen after the user selects on PDUA of the top level diagram. In this PDUA subsystem diagram, the user can easily see the location of the detected parametric abnormality at the switching device level. Figure 5 shows the switch level diagram after the user clicks the mouse on one of the switching devices, such as RBI 3/3. Each switch level diagram displays the actual measured data values enabling the user to see which parametric attribute is out of tolerance.

RECOMMENDED ACTIONS

After APEX has isolated the probable

cause of a detected fault or an incipient fault condition, the user can to ask for fault recovery recommendations. APEX will analyze available information about the current operating conditions with respect to the fault and display appropriate actions to be taken. Recommended actions pertain to both short- and long-term recovery. Short-term recovery determines if the fault can be tolerated for a period of time, if the power distribution can be reconfigured, or if load shedding is necessary. For long term recovery, the repair procedures needed to correct the fault are determined after short term actions have been implemented.

Short-term recovery analysis is based on a set of "recommended action" rules for the particular fault condition. Information about available power sources, current configuration of the power distribution system, the scheduled run times of the loads, and the effects of the fault on the system are all considered during the analysis. If enough power is available and the effects of the fault are minimal with respect to remaining scheduled run time of the affected loads, then the fault can be tolerated and the loads are allowed to run to completion. If the fault is seriously affecting the amount of power reaching a particular load and an alternate path for power distribution exists, then the system can be reconfigured automatically, or with user confirmation, to allow the load to run to completion. When the fault cannot be tolerated and alternate power distribution paths are unavailable, then the schedule for the loads is replanned by a remote scheduling agent; this results in load shedding and a new schedule.

After short-term recovery, the fault in the power distribution system needs to be repaired. The appropriate procedures needed to repair the power distribution system are determined by long term recovery, which is also based on a set of recommended action rules. In some cases, the cause of the fault is localized to a group of possibilities, and additional troubleshooting procedures are displayed to intelligently guide the user to further isolate the exact location and to make repairs.

CONCLUDING REMARKS

The APEX system consists of an integrated set of software agents, including a knowledge base, database, inference engine, data acquisition interface to the power distribution hardware, and a communication interface to a remote planner/scheduler. During the past year, advanced development of the APEX system has included addition of incipient fault analysis, an improved multilevel color user interface and a new recommended action facility.

Incipient fault analysis adds a unique health monitoring capability to prevent faults by continuously monitoring all parametric values in the power distribution system. APEX can warn the user of potentially threatening fault conditions before power distribution interruptions are experienced. This continuous health monitoring will of relieve human operators of labor-intensive mission control operations. Moreover, the type of continuous monitoring that APEX provides eliminates problems that can occur with human monitoring such as errors caused by fatigue.

The color capability of the new user interface enhances the information display and provides a friendlier man machine interface. Location and type of detected faults are immediately recognized when flashing combined with color coding appears on multilevel displays. In addition, the user interface contains mouse-selectable menus that present appropriate options for accessing information and obtaining fault recovery/prevention assistance.

The new recommended actions feature determines the most appropriate procedures for recovering from and preventing power distribution faults. The procedures are determined by rules stored in the knowledge base and the reasoning capability of APEX. Recommended actions consist of both short- and long-term recovery procedures necessary for maintaining the health of the power system. Execution of short-term recovery procedures restores power to scheduled loads, and execution of long-term actions effectively repairs isolated areas of the power distribution circuit.

In future space applications, APEX can be applied to help maintain the operational health of the power distribution systems.

APEX will be able to diagnose fault conditions and recommend appropriate recovery procedures when experienced power system personnel are unavailable. By allowing APEX to autonomously monitor and analyze power distribution system data, faults can be detected before serious problems develop and costly power interruptions occur. Increased reliability of space power distribution and a substantial reduction in the human labor required for routine monitoring of system operations is the goal of the APEX project.

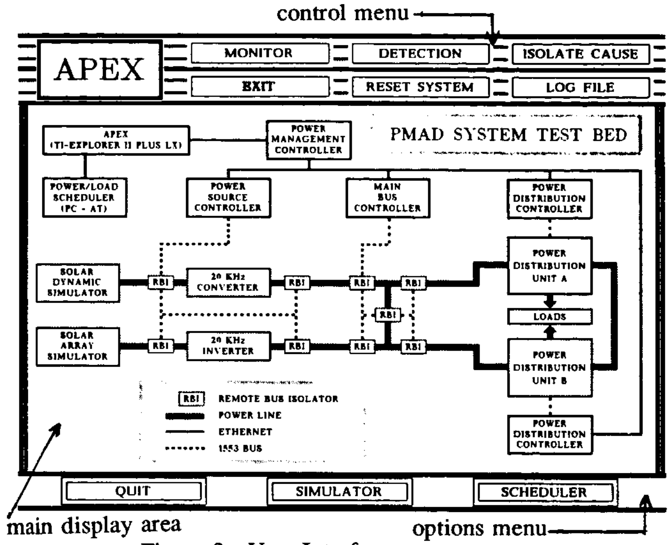

Figure 3. User Interface
(with power system diagram)

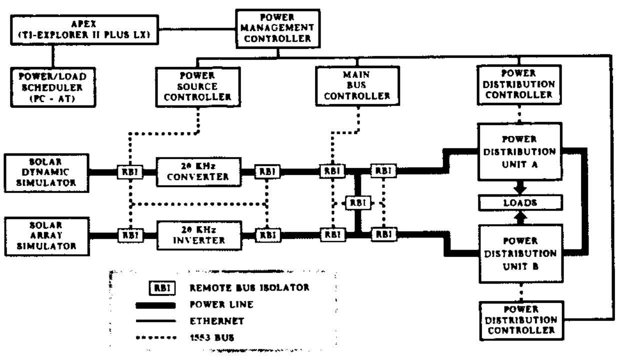

Figure 1. Power Distribution Test Bed

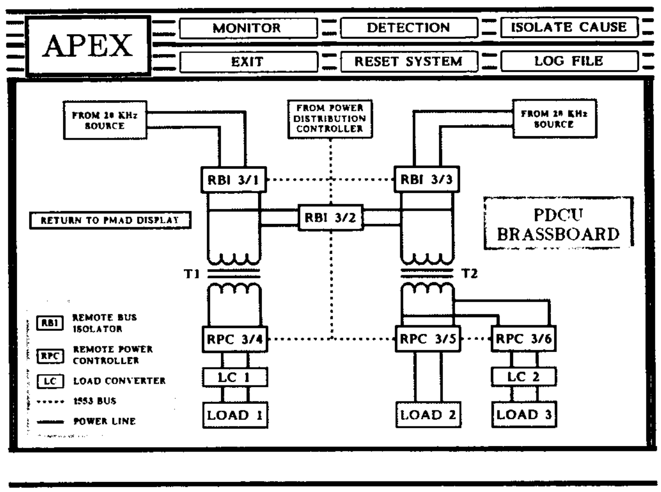

Figure 4. User Interface
(with PDUA diagram)

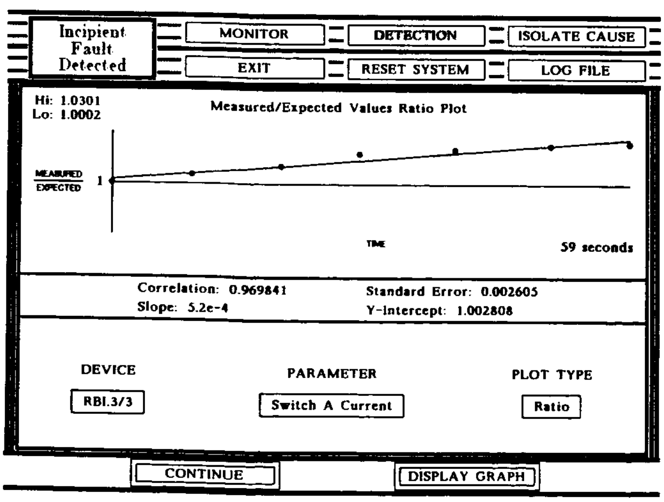

Figure 2. Incipient Fault Condition Analysis

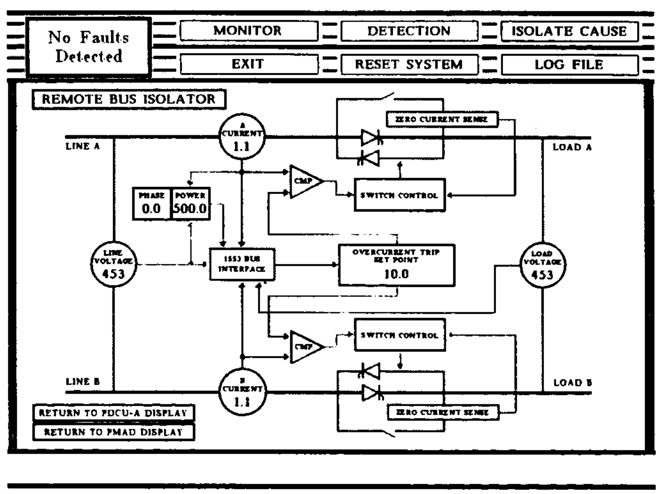

Figure 5. User Interface
(with switch diagram)

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