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From the Editor-in-Chief's Desk

VETOMAC-II in Mumbai

VETOMAC series of conferences are now set to take place once in two years. The first conference of the series was organized by the Indian Institute of Science in Bangalore in October 2000.

The second conference, held at Mumbai from December 16 to 18, 2002, was organized by the Bhabha Atomic Research Centre in association with Nuclear Power Corporation of India and sponsored by the Board of Research in Nuclear Science, Department of Atomic Energy, and the Government of India. The conference was chaired by Dr. Anil Kakodkar, Chairman, Atomic Energy Commission and Secretary to the Government of India, Department of Atomic Energy, and presided over by Mr. B. Bhattacharjee, Director, Bhabha Atomic Research Centre. In all, 90 papers were presented in two parallel sessions.

The participants included a wide range of experts and researchers from research laboratories, educational institutions and industry (listed below).

Educational Institutions: Andhra University, Visakhapatnam; Arizona State University, Tempe; Bhartiya Vidya Bhavan's Sardar Patel College of Engineering, Mumbai; Birla Institute of Technology and Sciences, Pilani; Dr. Ambedkar Institute of Technology, Bangalore; Government College of Engineering, Pune; Gyeongsang National University, Korea; Indian Institute of Science, Bangalore; Indian Institute of Technology, Chennai; Indian Institute of Technology, Guwahati; Indian Institute of Technology, Kanpur; Indian Institute of Technology, Kharagpur; Indian Institute of Technology, Mumbai; Indian Institute of Technology, New Delhi; Jadavpur University, Kolkata; Kuwait University, Safat; Malaviya National Institute of Technology, Jaipur; Motilal Nehru National Institute of Technology, Allahabad; National Institute of Technology, Rourkela; National Institute of Technology, Warangal; P.C.E., Rourkela; Prince of Songkla University, Thailand; Priyadarshini College of Engineering, Nagpur; Pukyong National University, Korea; Rajaramnagar Institute of Technology, Rajaramnagar; R. V. College of Engineering, Bangalore; Trinity College, Dublin; University of Bristol, Bristol; University of Kaiserslautern, Germany; University of Novi Sad, Serbia; University of Wales, Swansea; University Visvesvaraya College of Engineering, Bangalore; Visvesvaraya National Institute of Technology, Nagpur.

Research Laboratories: Bhabha Atomic Research Centre, Mumbai; Central Power Research Institute, Bangalore; Defence Research and Development Laboratory, Hyderabad; Deutches Zentrum for Luft und Raumfahrt, Braunschweig; Indian Institute of Chemical Technology, Hyderabad; Institute for Problems in Machinery, Kharkov, Ukraine; Institute of Armament

:hnology, Pune; Institute of Fluid Flow Machinery, Gdansk; National Aerospace oratories, Bangalore; Structural Engineering Research Centre, Chennai; URA, CNRS, Paris; ram Sarabhai Space Centre, Trivandrum.

ustry: Central Manufacturing Technology Institution, Bangalore; Bharat Heavy Electricals ., Hyderabad; Heavy Water Plant, Manuguru; Quality Engineering Software Technologies, ıgalore; Tata Consultancy Services, Chennai.

Aore than 150 delegates from India, USA, UK, Ireland, Germany, France, Poland, Ukraine, bia, Kuwait, Thailand, and Korea participated in the conference. The conference also anized an exhibition of vibration engineering products. Prior to the conference, a two-day kshop on Rotor Dynamics and Condition Monitoring was conducted by Quality Engineering Software Technologies, Bangalore, from December 14 to 15, 2002.

t is heartening to note that today there is a common platform available for Vibration ;ineering and Science fraternity in India where research and development activities from ia and other countries can be disseminated. In the offing in December 2003 is the National nposium on Rotor Dynamics (along with a workshop) being organised by Indian Institute Technology, Guwahati. VETOMAC-III will be be organized by the Indian Institute of hnology, Kanpur in December 2004. These activities are expected to promote greater raction between educational institutions, research laboratories and industry, which would ıg direct benefits to the industry in terms of management of their assets.

J.S. Rao

Contents

Development of an Online Diagnostic System Software for Turbogenerator Set of Kakrapar Atomic Power Station

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Abstract

An online expert system that works on a turbogenerator to monitor and detect faults, if any, has been developed. It is based on the vibration signature analysis concept using the vibration information as acquired from the turbogenerator's various bearing locations. These signals (20 shaft and bearing vibration signals distributed over six bearing locations supporting HP, LP and generator rotors) are processed and then analyzed using an expert system. The expert system uses Sohre's database and lists five most probable faults, if any, upon analysis. The software also displays continuously trend of important vibration data for better monitoring. The system is installed and operating on 220MW turbogenerator of Kakrapar Atomic Power Station.

1 Introduction

A sound maintenance program has become the need of the day with the advent of high speed, high power rotating machinery. Over a period of time, these machines develop some defects, which may be due to a design fault, or developed during the life of the rotor. Some defects progress slowly whereas some aggravate suddenly, leading to a catastrophic failure that result in total plant shutdown and thereby heavy financial loss[5]. Periodic measurements may be able to detect the slowly progressing faults, but not before substantial damage has already taken place. Periodic offline inspections at frequent intervals are not foolproof, while being prohibitively expensive. To reduce the costs, if the intervals are set far apart, it is highly probable that a defect may creep in and develop into a serious trouble before it is detected with a conventional maintenance program. Catching the defect in its early stage goes a long way in ensuring safe and trouble-free operation of these costly and valuable machines. The failure of bearings and blades of Narora Atomic Power Plant in 1993[5,6] is a recent example of how continuous monitoring and online diagnostics could have avoided the unfortunate incident. An online diagnostic system thus becomes very economical tool for most efficient machine maintenance.

Vibration signature and its analysis have been in use for over two decades to correct the machine operation conditions to avoid failures. Hubbell[2] records the operations of the gearboxes of the US Navy surface effect ship power plants using the vibration levels. Hill and Baines[1] demonstrated the application of an expert system to diagnose faults for the rotating machinery health monitoring. Here, the rule base was not well defined.

Most of the defects encountered in the rotating machinery give rise to a distinct vibration pattern (vibration signature)[8] and hence in most cases the faults can be identified using vibration signature analysis techniques. The power plants use peak-to-peak or rms values to monitor the condition of the machine. But it has been found that any defect developed may not show any indication in the time domain data unless it deteriorates to an advanced condition. Whereas the frequency domain signal not only catches the problem early in its growth, but actually tells, with certain probability, the nature of impending faults like misalignment, seal rub, or bearing failure, etc. Sohre[10] collected and compiled through his wide experience of over four decades records of trouble shooting of rotating machinery in the form of several charts. This knowledge base is the most comprehensive that is available in open literature encompassing a wide variety of rotating and reciprocating machines.

The usage of Sohre's database in the application to an expert system for offline condition monitoring of rotating machinery has been discussed by Rao et al.[3], Rao et al.[7] applied this concept to monitoring of an aircraft engine. Rao and Shingote[8] demonstrated how it could be applied in an online mode using simulated fault signals.

Commercially available current condition monitoring software for power plants do not have the capability to analyze the signals and diagnose the faults online using an expert system. They only trend rms values of vibration signals and display their frequency spectra. Significantly, they lack several important features such as data backup, its storage, retrieval and display. Also, they do not provide trending of amplitudes of important frequency components as well as online expert system diagnostics. The software developed here is the first to have all of the above mentioned features. The software not only diagnoses the machine condition with the help of Şohre's knowledgebase, but also manages to backup the acquired data and allows it to be retrieved for review.

2 Outline of the software

The software uses two computers. Housed in the first computer (FDAS computer) is FDAS (fast data acquisition system) which acquires signals from the transducers mounted on the bearing and shaft locations of the turbogenerators. FDAS, after acquiring data, feeds it to another computer (main computer) which houses OLES. OLES (online expert system) deciphers the signals acquired in real time by first converting them from time domain to frequency domain signal and then using this frequency spectrum to infer about any possible fault. OLES also backs up the data acquired to a separate backup directory. It also updates the trend plot data that comprises rms value and the amplitude of various important frequency components of each vibration signal.

The main computer also houses OSBUDD (operator support and backup data dis[ ]that supplements OLES. Since OLES constantly checks for and processes new data se[ ]FDAS, this separate and dedicated operator interface aids the operator in interacting viewing the acquired and processed data. This way OLES is left undisturbed in its ta[ ]checking and processing fresh data in the background while OSBUDD caters to operat[ ]displaying the acquired and processed data in the form of time domain, frequency dom[ ]orbit plot, trend plot, etc. The expert system analysis results are also listed by OSBU[ ]upon request.

The screen of the main computer displays trend plot of any of the 20 vibration si[ ]over a period of last week or last month or last year. By default, trend plot of rms v[ ]of first bearing vibration signal will be available on the screen displaying the last 24 h[ ]data. The displayed trend plot is automatically updated as and when new data is acqu[ ]

3 Details of FDAS

The data acquisition unit is a 8086 microprocessor-based system with the recording b[ ]done on a high speed PC. FDAS acquires vibration data in three situations. First, [ ]programmed to acquire data at a predetermined time during a day, say 0100 Hrs, [ ]Hrs and 1700 Hrs. Second, it acquires the data whenever the rms value of any of th[ ]vibration signals crosses threshold (lower or upper). Third, it can also acquire data [ ]operators' request. In any of these cases the acquired data is transferred to the main [ ]

The acquired data comprise 20 vibration signals. Two process signals acquired a[ ]the Generator Power and Condenser Vacuum. Twelve vibration signals are acquired [ ]bearing sensors (velocity transducers) and 8 vibration signals from shaft sensors ([ ]contacting eddy current probes). The bearing signals are tapped from turbovisory p[ ]and the shaft signals from the online shaft monitoring system. The vibration channels [ ]set with a predetermined threshold level. FDAS is connected to the FDAS PC by a [ ]speed LAN for transferring data.

Each vibration signal is represented by 5000 samples at sampling frequency of 5 [ ]Each process signal is represented by 4000 samples at sampling frequency of 100 Hz. [ ]the vibration signal acquired for a total of a second gives sufficient data for conve[ ]vibration signals from time domain to frequency domain. Each signal also carries inform[ ]regarding whether the signal taken is due to threshold crossing (upper or lower), a[ ]so, which signal crossed the threshold. This information is maintained by OLES wh[ ]updates trend plot data.

4 Working and details of OLES

Figure 1 shows the details of the working of OLES. Functioning of OLES is divided [ ]following distinct tasks:

- Check for fresh data and backing it up
- Analysis of acquired data and updating trend plot data
- Diagnosis of a fault using expert system.

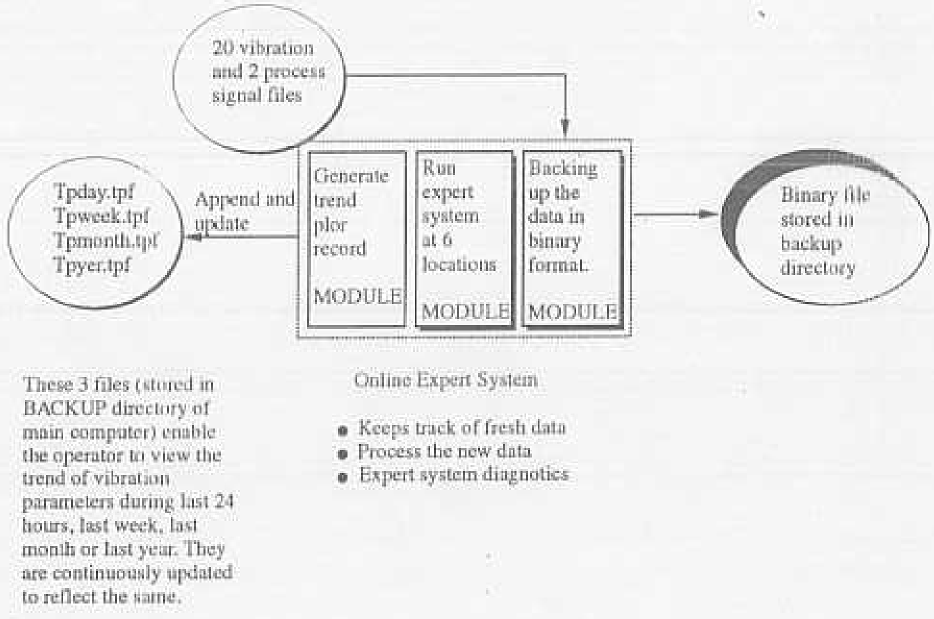

Fig. 1 Working of the OLES.

4.1 Checking for fresh data and backing it up

OLES keeps track of fresh data sent by FDAS. The OLES has an in-built function that keeps checking for new arrival of input time domain files from DAS. This function, when it detects arrival of new set of data, kicks off the data processing cycle that starts with first converting the input time domain text data to binary format. These 20 time domain signals in binary format are stored to a backup directory in a single file whose name is representative of the date and time at which the data was received. The file name is constructed as follows.

The file Tddttttt.bar is stored in Mmm subdirectory of Yyyyy directory in the backup directory named BACKUP. Here, dd: the date, ttttt: the time, M: month tag, Y: year tag, mm: the month, yyyy: the year. For example, a signal acquired on 23rd of May 1998 at 01:45:28 will be named N23014528.bar and stored in M05 subdirectory of Y1998 directory in the BACKUP directory.

In the main PC only one directory named OLESDATA is allocated for the recently acquired time domain data. This data is overwritten by the next acquired data, whereas in the BACKUP directory all the acquired data is stored to a well-defined directory structure.

4.2 Analysis of acquired data and updating trend plot data

The fast Fourier transform is performed on each of the 20 time domain signals value computed from the time domain signal and amplitude of vibration at pr frequencies of interest obtained from frequency domain signal of the 20 signals in a special trend record format as shown in Fig. 2. This information is usef purpose of trend monitoring. The already existing trend plot data stored in plot files stored in BACKUP directory is updated by OLES. Two other param Generator Power Output and Condenser Vacuum are also stored along with data. The trend data is segregated in four separate files, namely, the previous da last week file, the last month file and the last year file.

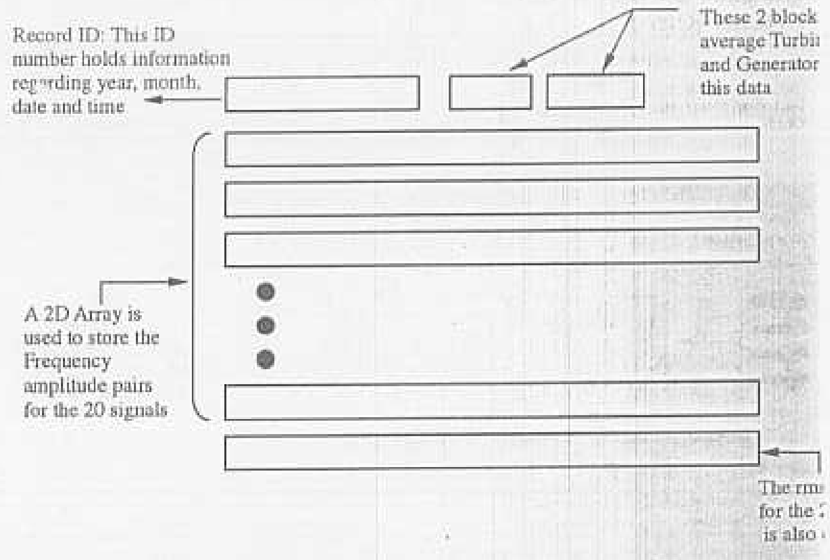

Fig. 2 Structure of a trend plot record.

4.3 Diagnosis of a fault using expert system

After performing FFT on the time domain signal and updating the trend pl calls the expert system module which first identifies the presence of important components in the frequency spectrum of all the shaft and bearing vibration sig information is then input to the expert system module which after taking into ac type of signal (bearing or shaft), direction of signal (horizontal, vertical or axial), the probability of existence of each fault in the signal being analyzed. The expe uses the probability table compiled by Sohre[10]. It is well known that a partic generates a typical frequency pattern. If the frequency components identified m that of the frequencies generated by any of the known faults, then the current signal may be generated due to the fault whose frequency pattern is found to be matching. In this way the presence, if any, of a fault in the signal can be detected. But a particular frequency can be generated by more than one fault. By attaching probability values to each fault depending on presence of frequencies as given by the Sohre's database, the overall probability of each fault in the given signal can be computed.

5 OSBUDD software

OSBUDD basically works on the backed up data processed by OLES. The purpose of the OSBUDD is to allow the user to view in various formats the data already acquired and processed by OLES. Refer to Fig. 3, showing details of working of OSBUDD.

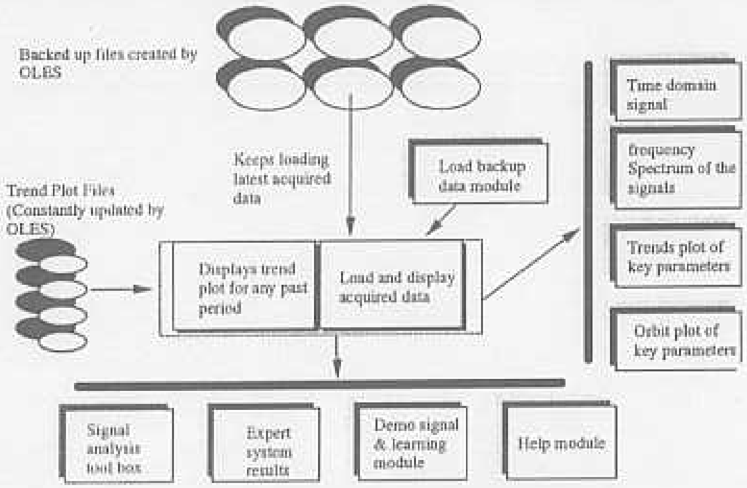

Fig. 3 Working of OSBUDD.

OSBUDD has following modules as shown in Fig. 4.

- Plots
  - Time domain
  - Frequency domain
  - Trend
  - Orbit
  - Waterfall

- Analysis
  - Expert system
  - Signal processing
- Load backup data
- Configure
- Assistance
  - Demo
  - Help

The *time domain signal* menu displays the time domain signal in the backdrop of b of different colors indicative of severity of vibrations. For example, a cyan color band starts at vibration velocity of 3.5 mm/s indicates "allowable" vibration category. Be that, a yellow color band which starts at 9.2mm/sec indicates "not allowable" vibr

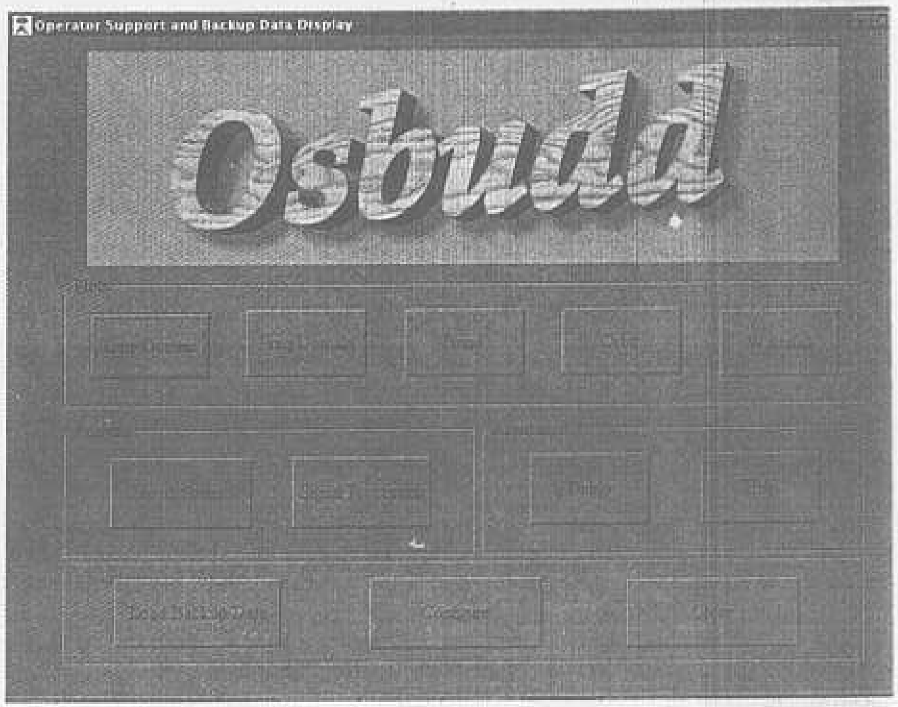

Fig. 4 The OSBUDD menu screen.

category, and so on. These ranges are arranged according to ISO standards for 3000 rpm machines. The numbers on the x-axis are the sample numbers of the time domain data and the amplitude value of the samples are displayed on the y-axis. Cursor position can be changed by using arrow keys or buttons provided at the left side of the signal or simply double clicking the left button of the mouse at the position of interest. The sample number and corresponding amplitude value of the current position of the cursor is also displayed there. Any other signal of interest can be chosen for display, using *Signal Selection* module available at the top left corner of the screen. The same can be achieved using two triangular buttons provided there. The axis limits of the time domain display can be set using *Change Limits* button. To get a magnified view of a part of the signal operator can click right button of the mouse. *Refresh* button brings back the original display. A sample time domain signal display is shown in Fig. 5.

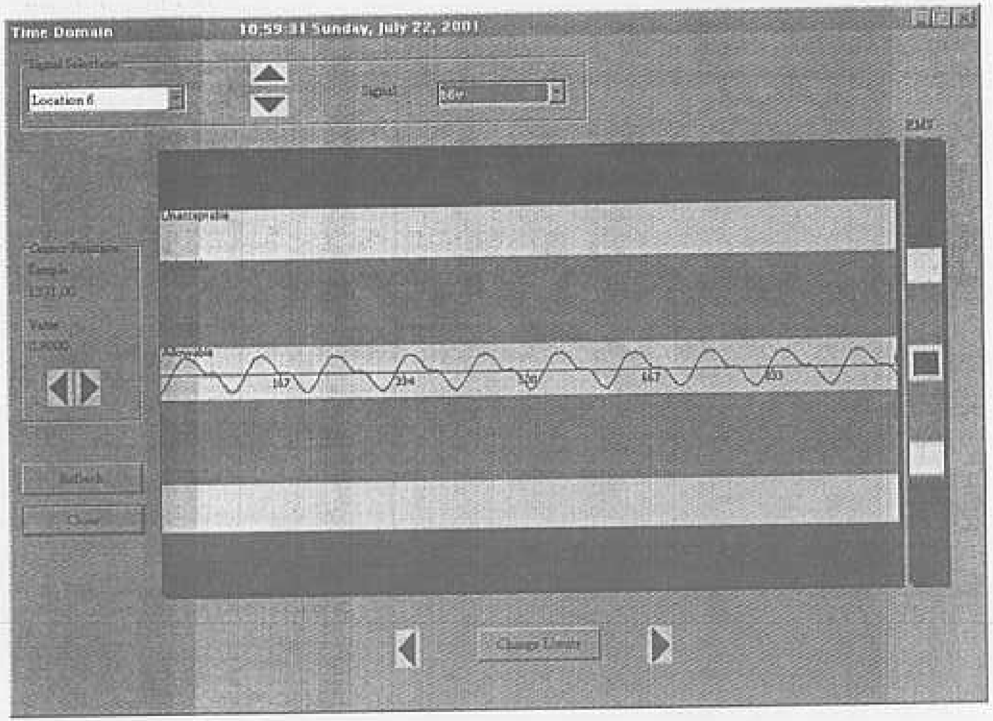

Fig. 5 Screen snapshot of time domain signal.

The frequency domain signal menu shows the fast Fourier transform of the time domain signal. Radix2 algorithm is implemented on 4096 samples of the data collected. The inherent noise in the signal is minimized by auto correlating the signal before transforming it.

The frequency domain signal is shown enclosed within the background of different ba[r] corresponding to healthy values. These healthy values are decided using past recorded d[a] There are two bands, one corresponding to allowable limits and the other for not satisfact[ory] limits. The x-axis values are frequencies and the y-axis values are the correspond[ing] amplitudes. Other things are similar to the time domain signal. A sample frequency dom[ain] signal display is shown in Fig. 6.

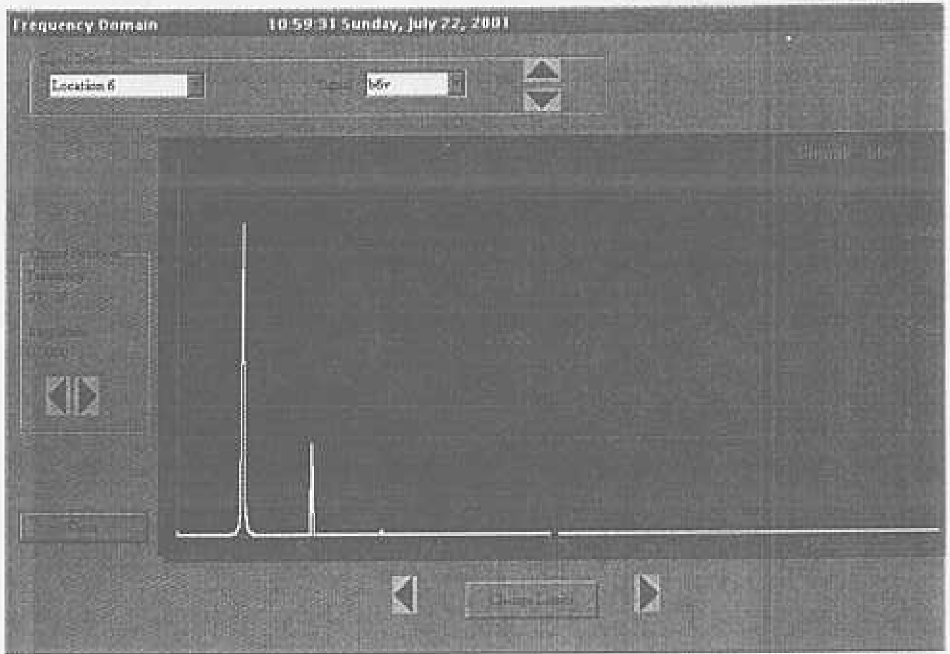

Fig. 6 Screen snapshot of frequency domain signal.

The trend plot loads trend plot data previously stored by OLES in trend plot files [a]nd displays default trend plot. An operator can modify the display to show trend plot [for] any specified period. The trend may be of rms value of a particular signal or it may [be] of any frequency of interest like 50 Hz. The trend plot of the bearing vibration signal [in] all the three directions is shown together so as to correlate variation in these signals. [A] toggle button is provided to swap the display to show both shaft (vertical and horizon[tal]) signals together. The trend plot is always shown in conjunction with Generator Power [a]nd Condenser Vacuum so that if disturbance in trend in rms or frequency value is due [to] transient changes in above two process parameters, possibility of any fault can be tentativ[ely] ruled out. Mostly, when these two parameters are within limits and if the trend of [the] signal is disturbing, then the possibility of any fault creeping in should be looked into. T way these trend plots help in better and comprehensive interpretation of the condition of the machine. Screen snapshot of trend plot is shown in Fig. 7.

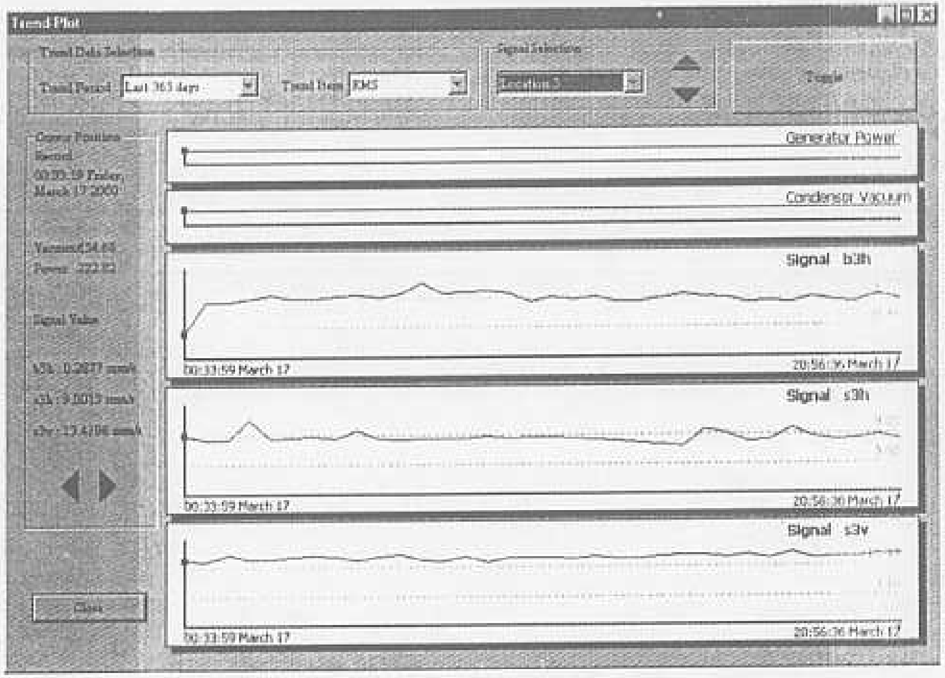

Fig. 7 Screen snapshot of trend plot.

The orbit plot displays locus of the rotor center drawn using a pair of vertical and horizontal shaft vibration signals. The menu allows to chose any location for which the orbit plot is to be drawn. The plot can be of use to diagnose some faults from the shape of the orbit.

The waterfall plot menu displays waterfall plot for the coast up data that can be acquired during startup process of the turbogenerator. The frequencies are shown on the x-axis, the rpm reading on the z-axis and the amplitude on the y-axis (vertical). The peak at the first critical speed is clearly seen. Speed range over which the waterfall is to be viewed can be set as also the angle of view and frequency range of interest. A simulated waterfall plot is shown in Fig. 8.

The expert system menu displays a list of five most probable faults that the current signal may indicate. Since the expert system analyses the signal accounting for the relative dominance of amplitude of various frequency components in all the three directions and also the type of signal (shaft or bearing), all the bearing and shaft signals available at a location are

used in the analysis. Hence, the expert system analysis results are available locatic An operator may view the analysis results at different locations by choosing any l from the location selection box provided (Fig. 9).

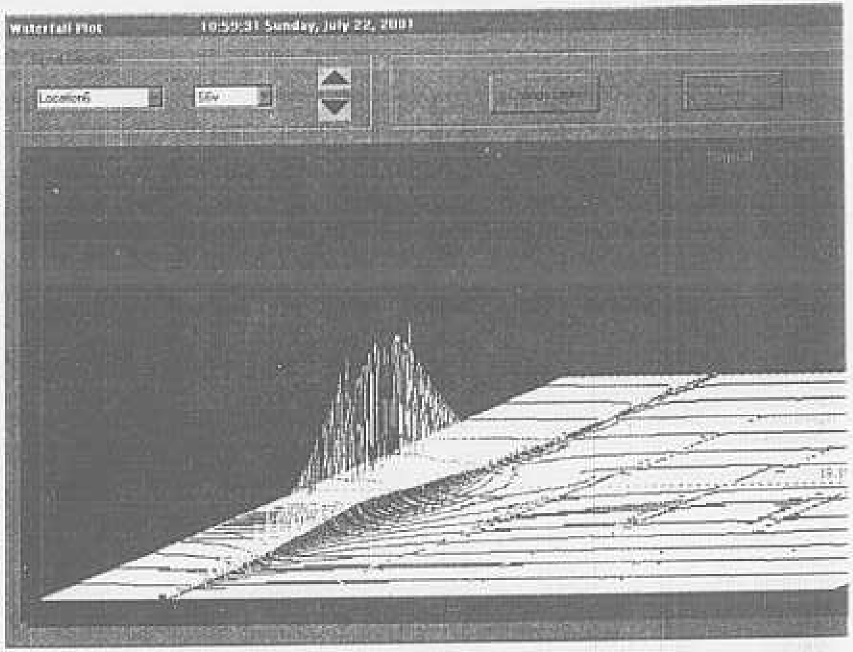

Fig. 8 Screen snapshot of waterfall plot.

The signal processing menu is in itself a dedicated signal analysis toolbox that allows o to test the quality of each signal (Fig. 10). It has the following menu options:

- Coherence
- Correlation
- Correlation factor
- Cross spectrum
- Convolution
- Signal/Noise ratio
- Phase plots

This toolbox helps the operator to assess the extent of linear dependence of onc over the other, similarity between two signals, and discern the frequency range ir the noise or disturbance is most significant.

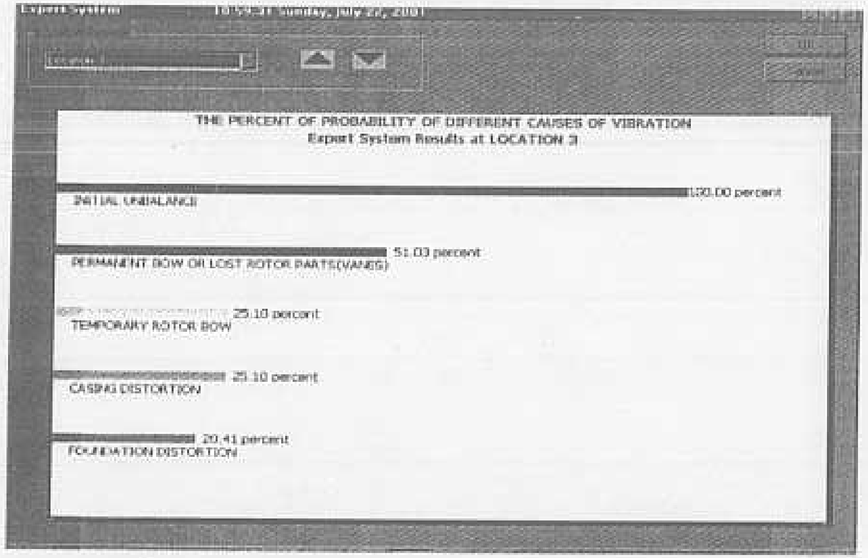

Fig. 9 Screen snapshot of expert system results.

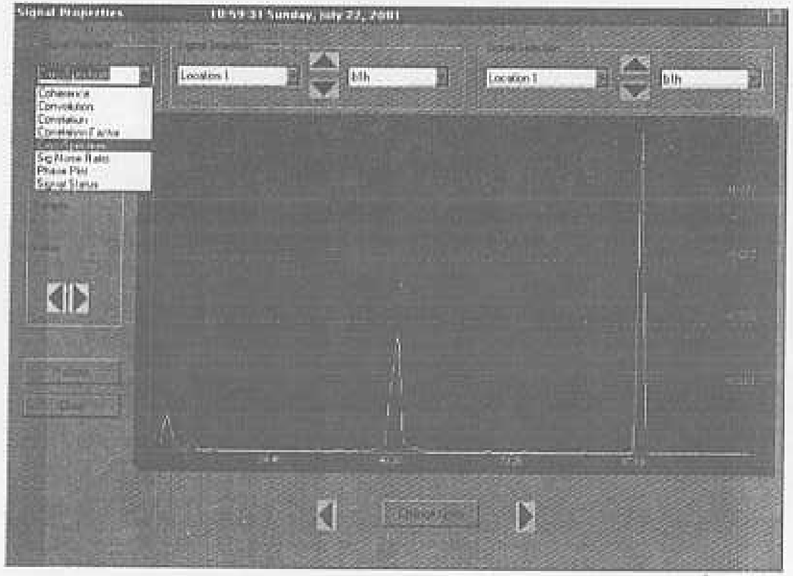

Fig. 10 Screen snapshot of signal properties tool box.

The load backup data loads backed up data stored in the BACKUP directory by · This data basically is time domain signal at all locations acquired at a particular tim user then can review this data like any normal data. This facility is provided to all operator to check any previous data. Sometimes from the trend plot a particular insta data may necessitate a closer look and a review. Noting the time and date of the int data sample from the trend plot the operator may use *Load Backup Data* menu to lo instance of data that may be analyzed from a different perspective. Expert system a for this data can also be viewed.

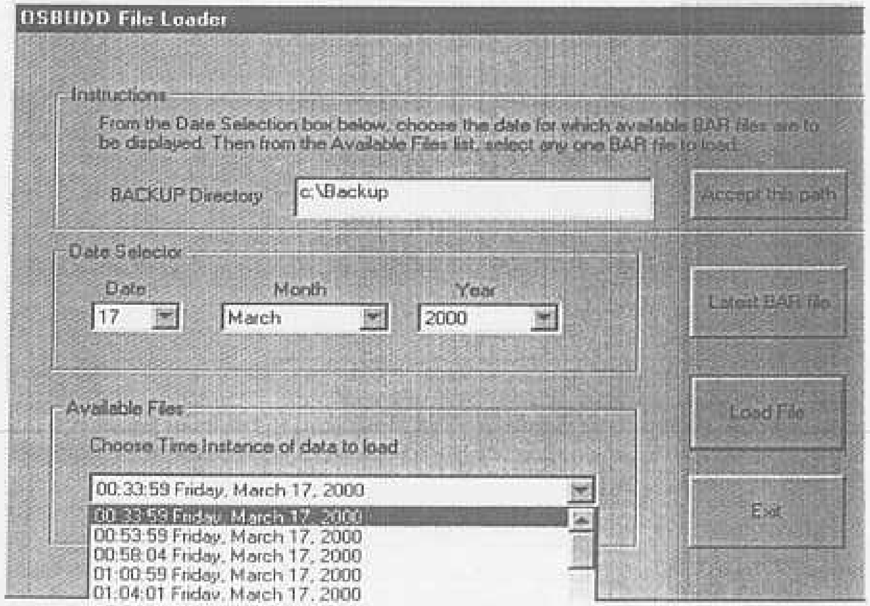

Fig. 11 Screen snapshot of backup data loader.

The menu first allows an operator to modify the default path of the BACKUP dir (Fig. 11). Normally the path as earlier mentioned is C:\BACKUP. However if the back data is to be loaded from other storage device such as a CD, then the operator may n the source directory path in the edit box provided at the top. This is helpful when data accumulates in the BACKUP directory of the computer and needs to be transl to another auxiliary storage device to make space in the local disk. Having specific source directory path, the operator can choose the day, month and year of the da interest from the *Date Selector* provided in the dialog box. Once this is set, a list of inst of data acquired on the selected date is made available in the Available Files list Choosing the appropriate time instance of data from this list box the operator can the data by clicking on the Load File button. The dialog box has another option of loading latest data acquired by OLES.

The *demo* module assists the operator to know more about various faults commonly encountered in turbogenerators. About 23 faults are described in detail along with the simulated time domain and frequency domain plot for the fault signal (Fig. 12). Simulated signal is generated using established frequency pattern of a given fault. A list of predominant frequencies and their corresponding relative amplitudes is also displayed. This may help the operator to understand the typical time domain plot and predominant frequency contents of the vibration signal generated by a specific fault. Acquaintance of vibration signature of various common defects using this module is expected to arm the operator with basic knowledge to better deal with what is observed in practice.

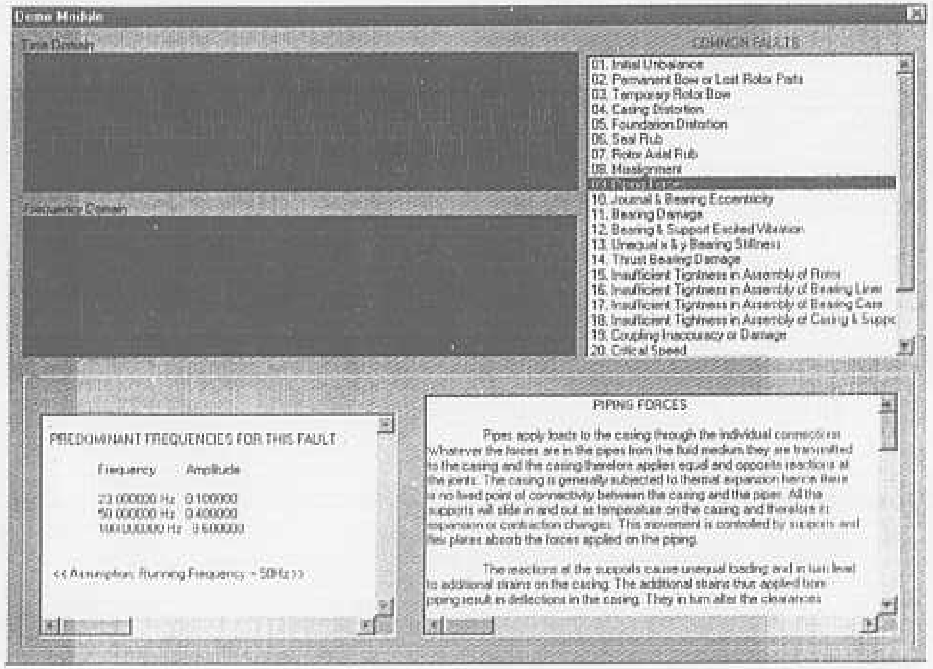

Fig. 12 Screen snapshot of demo module.

The *help* module gives a detailed information about everything the software has to offer. It also describes the overall working of the complete software. Each module is explained in detail. One of the most interesting features is the *Interactive Mode* that allows the operator to click on any part of the dialog box of any module and get information about it. For this purpose the dialog boxes of each module are displayed in the help files.

The *configure* menu option is used to customize the display settings like the defau and y-axis limits of the time and frequency domain signals as well as the trend also helps in setting the healthy limits of some of the predominant frequencies. can be done for the severity bands in the case of time domain plot. The main c menu box is shown in Fig. 13. Using this various menu options can be configu example, the configuration of trend plot can be done through the trend plot confi box as shown in Fig. 14.

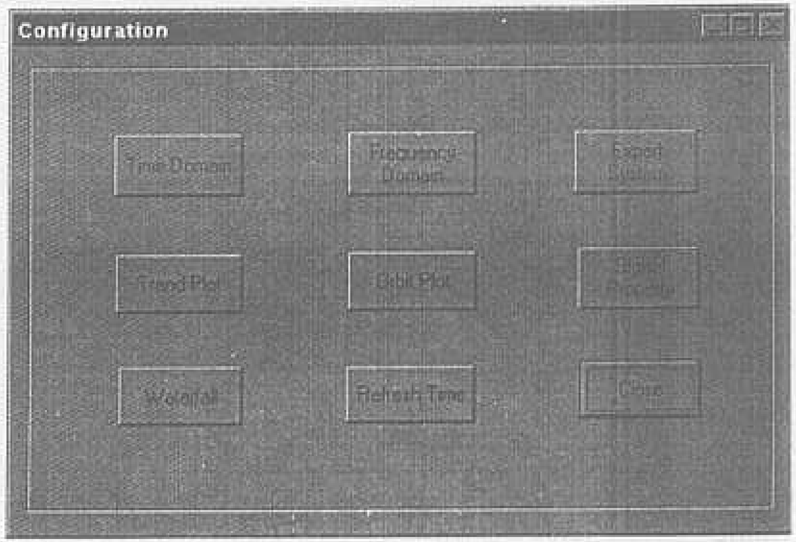

Fig. 13 Screen snapshot of configuration menu dialog box.

6 Conclusions

Comprehensive online condition monitoring and diagnostic system software for tu erators of Kakrapar Atomic Power Station (KAPS) is developed. The software de is housed in two computers. The online analysis of the vibration signals, trendin vibration parameters and early detection of a possible impending fault is the key fe this software. FDAS acquires the data from the transducers mounted on various and shaft locations of the turbogenerator, OLES analyses it and OSBUDD pr user-friendly interface. The data is continuously trended and displayed in various such as time domain or frequency domain, orbit plots, etc. A systematic backup acquired data is maintained in the backup directory. This enables viewing and anal the data at a later date.

Another key feature of the software is the use of an expert system utilizing the kn base compiled by experts in this field. This expert system gives prompt advise re the possibility of the most probable faults so that the operators can plan an appropriate maintenance schedule well in advance and minimize the down time.

The software has been installed at KAPS and running successfully since then. The plant maintenance personnel are using it to monitor the condition of the turbogenerator.

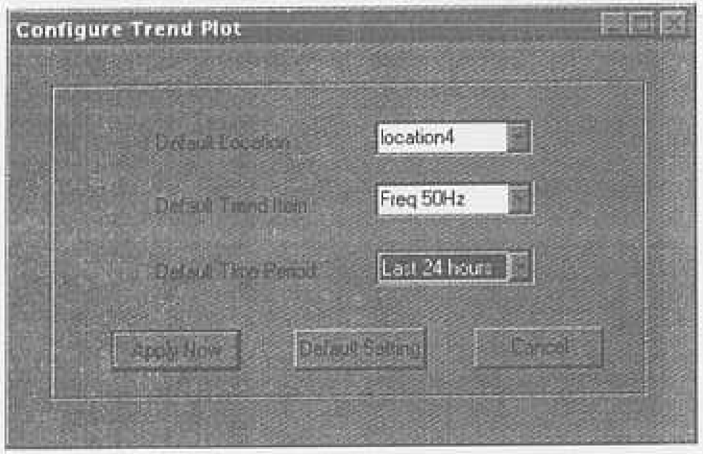

Fig. 14 Screen snapshot of trend plot configuration dialog box.

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