TIGER™: Knowledge Based Gas Turbine Condition Monitoring

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1. INTRODUCTION

Given the critical nature of gas turbines in most industrial plants, their availability is of prime importance. Associated maintenance costs can also be extremely high and hence, it is a high priority to find ways of reducing maintenance costs and increasing the availability of the gas turbine. Routine preventative maintenance techniques have been used for many years to minimise major problems by routinely checking and taking care of small problems. This has produced some good results, but it is desirable to do even better.

As a result, as a major move towards condition based maintenance and condition monitoring of gas turbines, the goal is to monitor the turbine on a regular basis in order to establish when maintenance actions need to be performed based on the condition of the turbine rather than a fixed number of operating hours. The core task of condition monitoring includes two elements: the first is regular and consistent data collection; and the second is the interpretation or analysis of that data. Two of the major approaches to condition monitoring are performance monitoring and vibration based condition monitoring.

The TIGER gas turbine condition monitoring system [1] addresses the performance monitoring aspects. It has the capability to be integrated with vibration based condition monitoring, but its primary focus is continuous real-time performance assessment. TIGER can be considered the most advanced software tool for condition monitoring of the performance of gas turbines available today. It runs continuously on-line to the turbine, sampling the key operating parameters at once per second intervals, it performs a wide variety of checks including limit checking, dynamic response and consistency with model based predictions. It also provides extensive graphical user interface displays to help view the state of the turbine. TIGER includes an extensive trending support system to allow the user to select sets of data and view long-term trends.

The TIGER condition monitoring system has been in continuous use at the Exxon Chemical Fife Ethylene Plant for over two years. It has been instrumental in identifying the underlying problems for a number of situations, one of which resulted in considerable cost benefit to Exxon [2]. This paper gives an overview of the TIGER functionality and its use at Exxon Chemical.

2. THE APPLICATION SITE

The Fife Ethylene Plant is a 650,000 tonnes a year gas cracking facility located in South East Scotland, and jointly owned by Exxon Chemical Company and Shell Chemical Company. The major product of the facility is high grade Ethylene for use in the plastics and butyl rubber industries in both the UK and on the continent. The feedstock is ethane gas obtained from the Shell/Esso offshore facilities in the North Sea. The process is continuous with the Ethylene product being transported by both ship and pipeline to end users in the UK and on the continent. The gas turbine is a 28 mega-watt General Electric Frame Five two shaft supplied by John Brown Engineering (See Figure 1), this is used to drive the primary compressors for the Fife Ethylene Plant. It is a vital item of equipment for the plant. If the turbine fails the entire plant must shut down. This turbine is typical of large-scale industrial gas turbines.

3. THE USERS VIEW OF TIGER

TIGER works continuously with a direct on-line data feed from the gas turbine control system. This data input provides all the key operating parameters for the turbine. TIGER works continuously to analyse this data and evaluate the state of the turbine. At Exxon Chemical, TIGER is located in the Chief Engineer's office. There are a variety of colour mimic diagrams that give a view of the overall turbine or sub-system of the turbine. The Chief Engineer selects the colour view that he considers most interesting for his routine monitoring, normally this is an overview of the total turbine operation. All the main operating parameters are colour coded and at a

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glance he can identify whether there are any major problems or not. Most importantly, there is a small window known as the alarm window, which indicates whether the monitoring and diagnosis system has detected any problems.

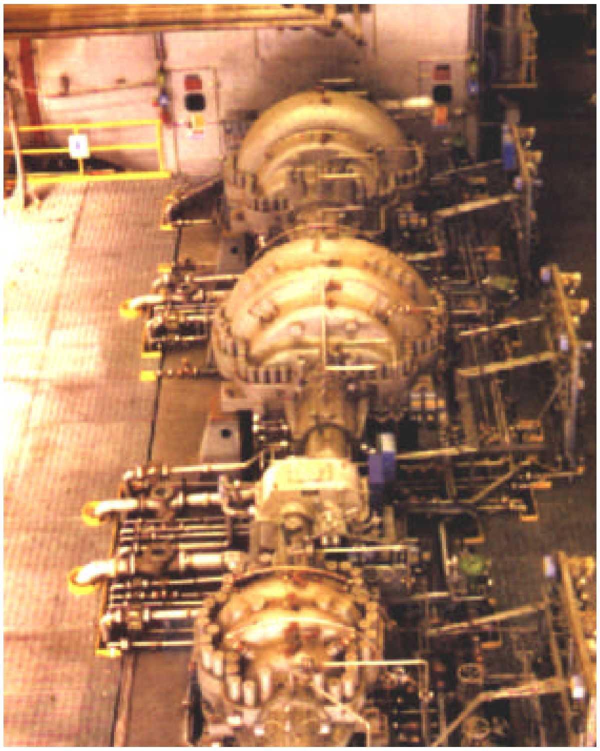

Figure 1: GE Frame 5 and Compressors at Exxon

When a turbine is working well, the engineer can quickly browse through the colour displays to reassure himself that the turbine is operating according to his own intuitive feel. If at any time TIGER believes something is not right it displays a message in the alarm window. The engineer can then go to the alarm page to see what faults are being detected. The amount of information on this page is kept very low.

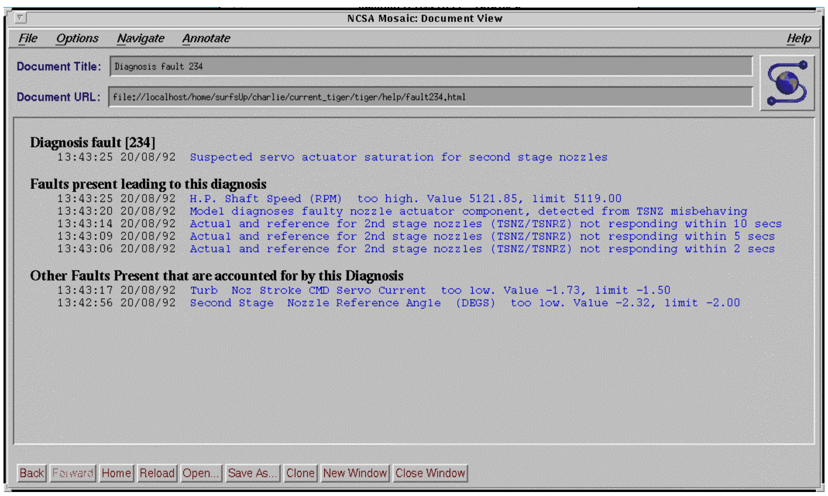

Figure 2: TIGER Fault Manager Display

A major task of TIGER is to consolidate a wide variety of faults and problems detected from different parts of the turbine and by different tools into a smaller number of high-level fault conditions. This lets the engineer rapidly assess the overall state of the turbine and its problems without having to wade through a large number of fault conclusions. If he wants to know more about any faults on the alarm page, he merely selects that fault with the mouse. A new window is presented that shows the derivation of the fault based on the fault conclusions from the various diagnostic tools (See Figure 2).

This shows the hierarchical way in which problems are identified within TIGER and the groupings that can be created to bring fault categories together. Each of these faults can also be selected and the engineer receives further information about the precise cause. In addition, for each root cause there is a link through Hypertext to the manual and documentation relevant for that fault, so very quickly he is able to transition from a high level display of the turbine with a fault indication to the high level fault, a more detailed breakdown of the fault, and finally the relevant manual or supplemental information for each problem (See Figure 3).

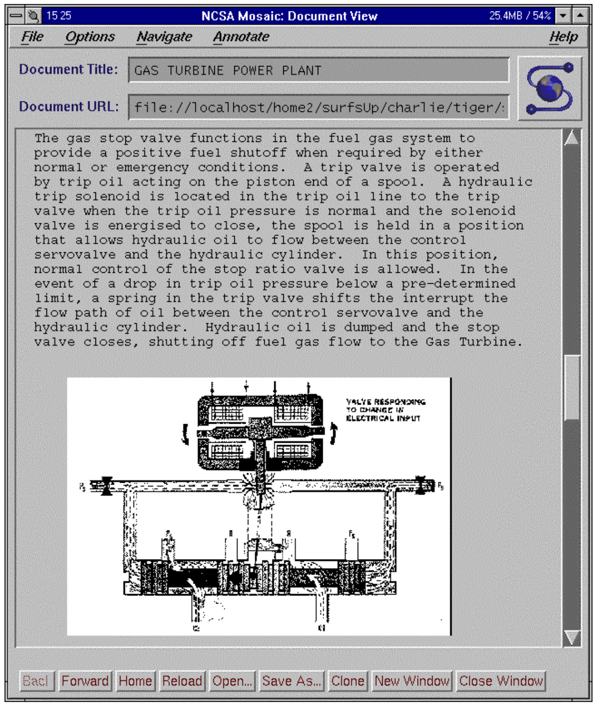

Figure 3: TIGER Detailed Help

If you would like to investigate the raw data, by clicking on the time stamp for the fault a graphical display of the relevant parameters is presented to the engineer. He is then able to browse through the raw data and investigate the exact performance of the turbine. This capability is quite important as it allows the engineer to use his extensive knowledge and experience to investigate more deeply, complex or unusual situations.

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4. TIGER IN USE AT THE FIFE ETHYLENE PLANT

A version of the TIGER system has been in use continuously at the Fife Ethylene Plant for over two years. During this time the system has been cycling once per second and monitoring for faults 24 hours a day. The senior engineers and the mechanical engineering section check the TIGER system several times a day. For example, each morning when they arrive at work, they check the TIGER system to see if there are any faults that have been identified over night. This system automatically saves a snapshot of the data, typically a 4-minute sample, these are then used for post analysis of any incidents which have occurred. Early in its usage, TIGER was instrumental in identifying the cause of a major plant problem.

The Exxon turbine is a two-shaft turbine (See Figure 4). The set of nozzles refer to second stage nozzles that balance the energy between the two shafts. This allows the compressor to run at its optimum speed while providing for variable load on the turbine. When the turbine was running very near full power, occasionally they would have a problem where the second stage nozzles appear to become stuck. The nozzles would deviate from their reference set point, and at the same time, the actuator's servo current would go to its maximum. Even this increase in servo current did not move the nozzles to the requested reference point. The exact cause of this problem was not known at Exxon.

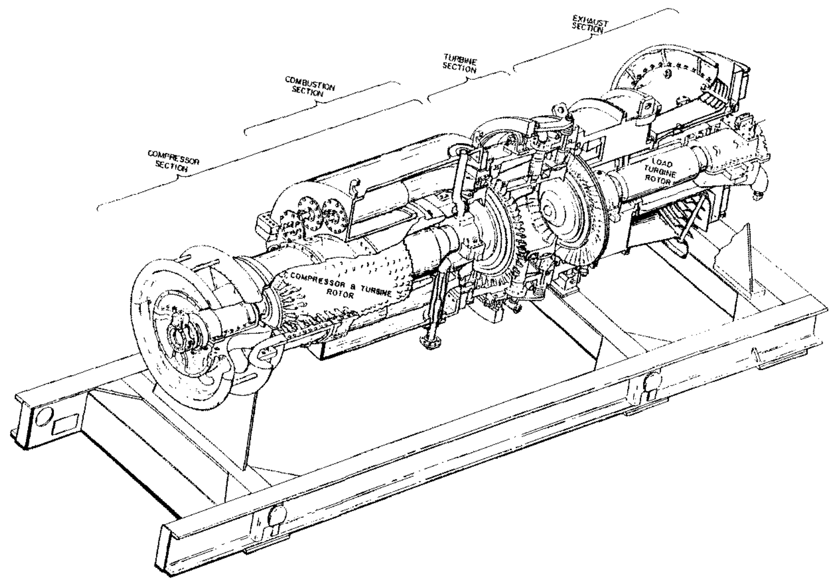


Figure 4: TIGER Exxon Turbine
Sectional view of model series 5000, two shaft gas turbine

As a result, the operators were instructed that any time this occurs, to back off the load on the turbine. The result of this was a restriction on the output capacity of the Fife Ethylene Plant. The PC based data acquisition system was set-up to monitor for this problem and perform a partial diagnosis and capture a snap shot of data whenever it occurred. Within one month of adding these diagnostics to the TIGER system a nozzles sticking incident occurred. TIGER performed the requested diagnosis and captured the snapshot of data. The senior engineer then examined this data and the TIGER conclusions and was able to diagnose the cause of the problem. If the problem was mechanical sticking, there was a risk of an unexpected release of the mechanical problem and the resulting sudden surge of energy could have serious consequences.

The engineer was able to show that the problem was that the servo was not strong enough to move the actuator against the full power of the turbine. This was very important for Exxon. It meant that when the nozzles did stick, there was no risk of a serious incident. The operators were then advised that they could run the plant to full capacity and ignore the nozzles sticking problem. It is important to realise that this problem had been effecting Exxon for 3 years but was diagnosed within one month of introducing TIGER.

The month following the change of restriction to the operators, the plant set its first production record for several years. This increase in production is worth a considerable amount to Exxon. The real proof of the benefit to Exxon however was the fact that all the employees at the plant received a special gift as a congratulations for setting the production record. This is considered a real benefit [3].

Over the past 2 years TIGER has helped to identify and provide diagnostic support for over a dozen problems.

4.1 Diagnostic Tools

The TIGER diagnostic mechanism uses 3 independent tools; the fault manager is used to co-ordinate the conclusions of these tools. It should be noted that each tool runs independent of the others. This means that they can all work in parallel, each examining different aspects of the turbine for an early detection of problems. This also means that for each application, the appropriate subset of these tools can also be selected. The tools are as follows:

1. KHEOPS

Kheops [4] is a high-speed rule base system. It is used primarily for limit checking. This allows the user to set a lower set of pre-alarm or limits for each parameter. The user adjusts these limits by a simple menu driven interface. Although the primary usage of Kheops is as a limit checking system, it is in fact a full powered rule based expert system language.

The Kheops limits used within TIGER go beyond normal limit checking. This is because of the ability within Kheops to express different conditions for the limits. Hence, in many cases, for example monitoring the fuel values, different limits apply depending on the operating regime of the turbine. In addition, any specific fault rules that want to be inserted can be used through Kheops. The Kheops system is capable of very high-speed execution. Response time is less than 15 milliseconds is possible.

2. IxTeT

The IxTeT [5] functionality is a very powerful capability to monitor the dynamic reaction of the gas turbine. It is also a unique capability in TIGER that is not found in other condition monitoring systems. Essentially within IxTeT the user is able to specify a sequence of events. The system then monitors to ensure that the sequence is properly followed. For example, when the load set point increases on the turbine, we expect to see the fuel valves open and shortly after the temperature increase, resulting in an increase in shaft speed. This causal sequence can be encoded easily in IxTeT situations. The tool then detects that the starting incident has occurred and ensures that the cascade of subsequent events is maintained properly.

Time limits can be specified to ensure the system response is adequate. This is helpful in detecting a wide range of problems. For example, if a servo is partially blocked and resulting in slower movement of the actuator, the IxTeT system can detect this by the delayed time response. A fundamental element of any dynamic system is its causal reaction to events. IxTeT is designed to monitor these situations.

In addition, specific situations can be described that can be recognise faults. For example, a specific causal graph can be implemented in IxTeT to detect nozzle sticking or dirty servos. Hence, IxTeT can be used to either describe the normal causal reaction or look for specific patterns resulting from known faults.

3. Model Based Prediction and Diagnosis – Ca~En

Ca~En [6] is a model-based supervision system devoted to ill-known dynamic systems often encountered in engineering domains. The Ca~En representation formalism intends to overcome the limitations of both explicit and non-explicit causality approaches for its originality is to be able to combine empirical causal knowledge together with first principles of the domain when available. The Ca~En formalism is based on a two-levels representation scheme for the description of a physical system:

- an analytical equation level which allows one to represent algebra-differential equations.
- a causal graph level in which the paths presume of the perturbation flow causality. The influences supported by the edges of the graph allow for representing causal-dependency-type knowledge.

Both levels can manage imprecise knowledge. A Ca~En program hence represents a formal model of the physical system built from knowledge about the physics underlying the behaviour of the system. This model can be viewed as an implicit behavioural model of the physical system. Ca~En has two processing modules:

- a simulation module which produces the explicit behaviour of the physical system in terms of the values of the inner variables across time according to the behaviour of the exogenous variables. Imprecision is managed with interval values, which implies that predicted graphs are curve envelopes.
- a diagnosis module which accounts for fault detection and isolation of faulty components. Fault detection is based on models of normal behaviour. The on-line simulation of these models provides a way of implementing a discrepancy detection procedure as the basis of the reasoning leading to monitor the behaviour of the system and detect early deviations from the nominal behaviour. Our diagnosis algorithm then falls into Reiter's model-based diagnosis framework [7] and uses the Ca~En causal graph as the System Description (SD). It relies on the collection of conflict sets, i.e. sets of components which cannot behave normally altogether according to the observations, and the use of an incremental hitting set algorithm. The diagnoses are given as sets of faulty components labelled by their corresponding date of failure.

The Ca~En diagnosis system conclusions rely on a reasoning based on the physics underlying the behaviour of the system, i.e. physical laws and empirically known causal interactions. When a fault is detected, it is viewed as the violation of some of these principles which then help isolate the faulty component(s). As a consequence, there is no need to anticipate the faults, which is highly intractable in most complex engineering domains. On the other hand, as variables and parameters take interval values, one can easily adapt the models granularity to the requirements of the faults. Hence Ca~En has a wide coverage of faults, from those radically changing the behaviour of the physical system to those causing smooth deviations.

4.2 Fault Coverage

The TIGER system covers most common and expected faults in the following areas:

- fuel system and fuel valves
- compressor
- second stage nozzles
- steam injection
- combustion problems
- turbines
- inlet guide vanes
- steam helper turbine

4.3 Fault Manager

The three primary tools in TIGER work in parallel, each has a particular strength and a particular class of faults and problems that it monitors for. Depending on the exact behaviour of the turbine and the sensitivity chosen for some of the fault conditions, these tools can detect a wide variety of minor fault conditions. The fault manager is used to filter the minor fault conditions and only present to the engineer those conditions that he considers interesting. In addition, it provides a means of consolidating the conclusions of the various tools. This provides two important capabilities:

The first is that it provides a mechanism for the reinforcement of fault conclusions, for example the Kheops tool may detect that there is a high shaft speed, a short time later the IxTeT tool may conclude that the second stage nozzles are not responding in their expected response time. At approximately the same time the Ca~En model based prediction would conclude that the nozzles are not following the expected response giving the operating parameters of the turbine. These three together both explain the cause of the high shaft speed for the compressor but also give confirmation that something is not quite correct with the nozzle movement system.

The second aspect is that in some cases it can eliminate minor faults as being unimportant or accounted for by some other action. For example, if Kheops detects that the compressor shaft speed is too high, but IxTeT concludes that the second stage nozzles are reacting slowly but still within acceptable response times, then the fault manager will suppress the high compressor shaft speed message as it is likely that the shaft speed will go back within limits very quickly. The fault manager is one of the unique capabilities of TIGER and is a major advance in the use of multiple knowledge-based tools to filter information to only that which is relevant for the engineer.

4.4 User Interface

The TIGER user interface is built upon one of the most advanced user interface graphics tools available today. It is possible to draw sophisticated images of elements of the turbine, schematics and plant diagrams (Figure 5). In addition, all aspects can be dynamically colour coded, for example: the display of the turbine exhaust can change colour as the spread increases to give a rapid visual indication; the vibration limit displays also change colour as the vibration levels go into alarm. This provides a very flexible and informative interface into the overall state of the turbine.

4.5 The Trending System

A major element of condition monitoring is to detect and monitor the gradual, but long-term, deterioration or change in performance aspects of the turbine. The TIGER system includes an extensive trending sub-system. TIGER can be configured through the user interface to collect whatever historical information at any desired frequency the user requires. For example, an hourly or daily snap shot of the vibration levels can be captured. These can be trended over any chosen period of time such as one week, one month or one year.

In addition to the pre-configured trend data, it is possible to go back over the historical data that has been captured and stored and construct new trends if this is desired after a specific event. Trend graphs are accessible through the standard TIGER user interface graphics display system. It is also possible to bring together the trend of sub-components with the operating state of the turbine such as which fuel valves were opened or closed, or the shaft speeds to provide a more accurate comparison of the historical data.

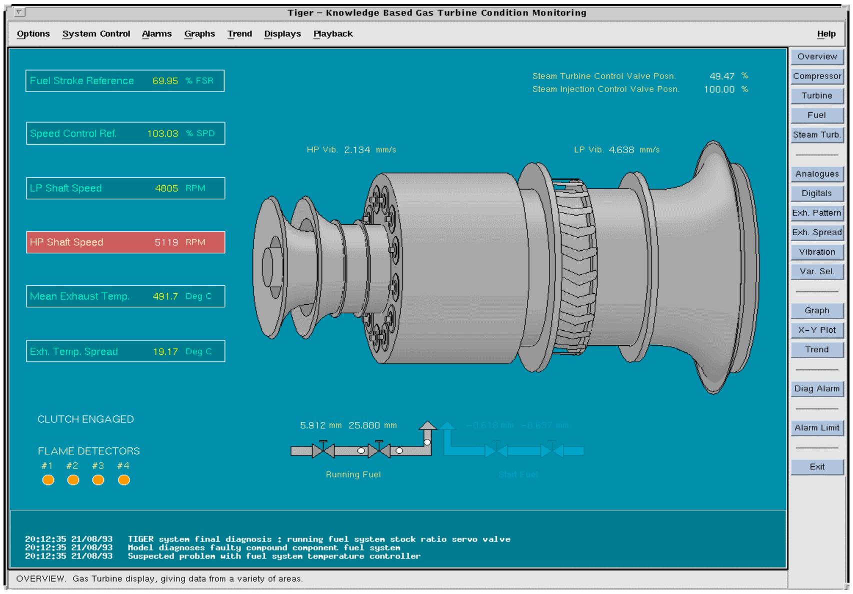


Figure 5: TIGER User Interface – Top Level

The trending system also includes a number of mathematical calculations such as the rate of change of a parameter; the time to alarm; and the expected value at a future time. This expected value calculation is useful to assess for example, whether the vibration level would be considered too high at the next shut-down or whether the vibration level could be left for a longer period of time. As part of the user interface, short-term trends, i.e., the last 4 minutes or 30 minutes in a real-time manner, can be displayed for any of the parameters.

A key aspect in the usage of the TIGER system is the ability to capture snap-shots of the data anytime an incident occurs. For example, the nozzle-sticking problem was first diagnosed by using the four-minute data buffer capture. The user can configure the system to determine which incidents or situations they would like to retain the data for. This flexible mechanism means that it is simple to capture data related to minor fault situations for a more detailed analysis. In addition, any unusual events on the turbine can trigger a data capture for a detailed analysis by the engineering staff. At Exxon Chemical a four-minute snapshot is automatically triggered once each day. This provides a resource of historical data for later trend analysis or checking the state of the turbine at different times of the year to detect early signs of problems that were not anticipated. This historical data can also be used by the modelling mechanisms to fine-tune the parameters and predictions for the turbine.

5. SUMMARY OF TIGER'S FUNCTIONALITY

5.1 Data Acquisition

The TIGER systems data acquisition has been configured for a number of different turbines and controllers. They are;

- General Electric's Speedtronic Mark IV Controller at Exxon
- LARRI panel controller to a General Electric turbine
- Any system that can transmit data via a serial link
- Any real-time database accessible over a network

The TIGER system can be run in playback mode and also on-line mode. The playback mode can be via a specified file or via a whole sequence of such files played back continuously. The on-line mode reads data from a serial port connected to the TIGER system and runs forever.

For the Exxon application the TIGER system receives 80 analog and 80 digitals at once per second update intervals. Essentially these values cover the key parameters for the main part of the turbine, this includes the speeds of both shafts, the thermocouple readings, the fuel valve settings, the turbine set points and information on supporting systems such as the steam turbine. In principle the TIGER system can support a much large number of analog and digital inputs. The maximum number of inputs possible will depend on the needed diagnosis time of the system, and also the depth of diagnostics. The Kheops tool would allow for over 1000 parameters to be evaluated every second. The other diagnostic modules could then be activated only when there is a problem.

There is nothing specific or directly tied to these data inputs for TIGER, that is it can easily be extended to incorporate other or different parameters. For example, in the Exxon turbine, the flame detectors are only 4 digital signals representing either flame detected or not. It would not be difficult to extend or modify TIGER so that it can work with the flame intensity instead. The TIGER system can also be used if there is only a sub-set of this information available. TIGER provides a variety of support for filters to eliminate noise or extraneous variation of the incoming data.

5.2 The Graph Program

The graph program (See Figure 6) shows the output of analog and digital channels showing 240 points at any one time. There are six separate graph areas each of which can contain 6 different graphs with up to 8 channels at the one time. The scaling for the graphs is via pre-set values stored as limits in a file, or by auto scaling to the entire data range being shown at that moment. If there are only two graphs it is possible to do a high/low plot between the two values at each time point. The graph scrolls in real-time as on-line data comes to it.

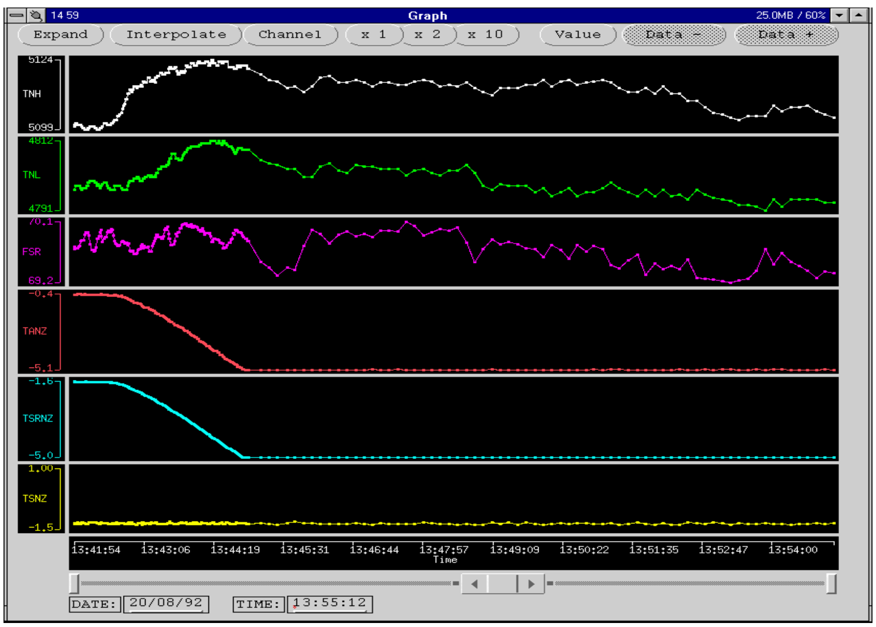


Figure 6: TIGER Data Graph Showing Nozzle Sticking Data

Choosing the particular channel to display can be done in a number of different ways. The channels can be scanned through by: incrementing and decrementing; the name of the channel can be selected; a predefined graph definable by the user can be brought up from a menu; or the particular channel can be chosen from a menu containing all of the channels.

The data can be interpolated to fill in any gaps in the sampling rate, and once interpolated it is possible to filter any particular graph. This allows us to view filtered and non-filtered data for the same channel on the same graph. The parameters of the filter are stored in a file and this allows them to be configured by the user. At any point the user can press on a particular graph and find the value of the particular channel at the point he has chosen.

If there is more data on the graph than can be viewed at one time, then it can be scrolled The scaling of the graphs can be changed to 1, 2 and 10 times and it is possible for any of the 6 specified graphs to expand this up into a larger graph on both the X and the Y axis.

The graph program is used to display the channels the output from the Ca~En qualitative model and the output from the trend system.

5.3 Digital Changes And Controller Alarms

Part of the data coming from the turbine controller will be digital. The TIGER system distinguishes between two different kinds of digital values; contact values within the controller, and alarm values. Both of these can be displayed and used to co-ordinate the faults from different diagnostic modules. The particular digitals and alarms are put in a separate window to distinguish them. The digital values are fed to the IxTeT recognition facility that is running on a symbolic form of the analog values.

5.4 Controller Values

The controller values screen shows numbers representing the value of each analog and digital channel. These are colour coded according to a set of static limits to indicate normal - which is green, too low -yellow, and too high - red. This allows the engineer at a single glance to determine areas of the turbine that are not operating normally. This is particularly useful for the digital set as remembering what is the normal setting can be difficult.

5.5 Ladder Logic Analysis

The ladder logic analysis runs continuously examining the alarms that are given by the controller. If an alarm occurs that it knows about the diagnosis of, it will run and produce an output indicating why that alarm has occurred in terms of the digitals it can reason about.

5.6 KHEOPS Real-Time Rule base

The Kheops rule base examines a single time slice of data. It looks at analog values and some digital values. It checks all 80 analogs and 80 digital values every time they are updated. The digital values are used to determine the state, so that, for example, running fuel is examined and not start fuel. When the analog values are examined they are compared against predefined limits which are adjustable by the user. The user can then alter the rule base to suit his needs. When an analog value goes beyond a predefined limit an error message is produced which is sent to the fault manager and displayed on an individual window on the screen.

5.7 IxTeT Situation Matching On Symbolic Form Of The Analog Values

The TIGER system monitors the analog values, filters them and then examines the derivative. Any change in the derivative indicating that the curve for the analog is going from steady to increasing, or steady to decreasing, or back to steady, will be made into a token that is sent to the IxTeT situation. The sensitivity of any given channel to being tokenised is controllable in two ways; firstly from a file containing the limits, and secondly there is an overall sensitivity control which can be adjusted dynamically by the user.

The IxTeT situations that have been implemented include a number of ones using the following channel abstractions built on top of IxTeT. We monitor TSRNZ and TSNZ (this is the nozzles and their reference). To see if they are following in 2, 5 and 10 seconds we monitor.

- The inlet guide vanes within two seconds.
- The start fuel valve within two seconds.
- The run fuel valve within two seconds.
- The LP shaft speed, with respect to its reference, within two seconds.
- The temperature reference and the average temperature within two seconds.
- The supply gas for start fuel within two seconds.
- The supply gas for run fuel within two seconds.
- The speed of the helper, with respect to the speed of the HP shaft, within ten seconds.
- The steam fuel, with respect to its reference, within two seconds.

A very useful thing to monitor for dynamic systems is whether one parameter “follows” another for example, does the valve position change with its reference. For this purpose, we provide a “follows” function. The “following channels” function is build on top of other abstractions which allow us to describe particular characteristics of a single channel. The abstractions build on a single channel are step, pulse, and oscillate, and they are built in terms of each other and then on the base events increasing, decreasing and steady. There are also base events indicating changes in digital values.

As well as these “following” and other abstractions, we have complete temporal patterns of various dynamic changes within the turbine. These dynamic patterns are typically built up using the abstractions we have. We monitor helper turbine step up in output and increase in the reference for the LP shaft behaving normally. We also monitor oscillations which follow each other with the same frequency on channels TNH, TNL, WQR, FSR. This is a general facility that can be parameterised for other channels too. Generally the temporal patterns you specify are to show normal operation and if the system does not follow this temporal pattern then we can generate an error, but not say where the error occurred.

5.8 CA-EN Models

5.8.1 Building Models

A Ca~En model is defined as a set of causal relations among the variables of a process, and a set of equations relating variables defined on interval domains. These constitute the two representational levels of the Ca~En formalism, so called the causal level and the global constraint level. When applied to the Ca~En simulation algorithm, a Ca~En model provides a behavioural picture of the physical system according to the behaviour of the input (exogenous) variables.

A Ca~En model can be built out of deep knowledge and/or empirical knowledge about the physics underlying the behaviour of the physical system.

Empirical knowledge should state cause-effect interactions among variables (e.g. when the fuel stroke reference increases, then the first stage shaft speed rotation increases as well). Order of magnitude knowledge can be added (e.g. increases much more or increases by a certain numerical coefficient) as well as temporal knowledge like delay of propagation and response times which are not necessarily exact but can be given as intervals. Pure correspondence relations among variables (e.g. when the chimney smoke is coloured blue, the concentration of a polluting product is high) could also be given although they have not been used in the turbine applications.

Deep knowledge can be in the form of algebraic equations (linear or non linear), first order linear differential equations or recurrent equations (linear or non linear).

Empirical knowledge is implemented at the causal level. Deep knowledge is implemented both at the global constraint level and at the causal level.

In the case of the FEP turbine application, the knowledge and information available comes from two sources, the controller (Speedtronic Mark IV) documentation and recorded data obtained from the Exxon turbine in real operation. The first source provides equations relating controlling and controlled variables with precise structure and parameter values. On the other hand, the second source provides relationships whose structure and parameter values can be obtained by identification and parameter estimation methods (we used the toolbox System Identification of MATLAB [8]). Parameters values can be estimated as interval values to account for imprecision, noisy data and genericity related to the turbines of a given series. The set of relationships is in the form of a set of algebraic (linear and non linear) and recurrent (linear) equations to be interpreted in terms of Ca~En causal influences and global constraints. Algebraic and recurrent equations are the easiest to translate into Ca~En primitives.

As an example, we give the equation model and the causal graph corresponding to the FEP nozzle system (Figure 7). Equations are recurrent equations expressed in a sampled time scale. X(k) expresses the value of variable X at the sampled time k. The delays hence appear explicitly; i.e. X(k-1). These are therefore immediately implementable in the form of Ca~En influences.

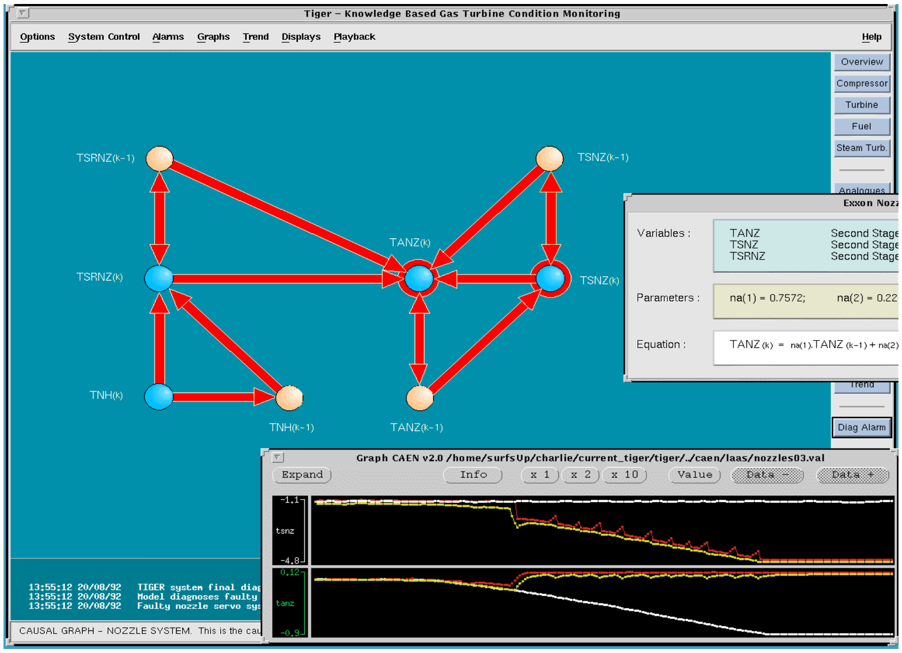


Figure 7: Ca~En Causal Graph and Predictions

Variables

```
TNH :    High pressure shaft speed
TSRNZ :  Nozzle reference position
TSNZ :   Nozzle position
TANZ :   Nozzle stroke CMD servo current
```

Equations

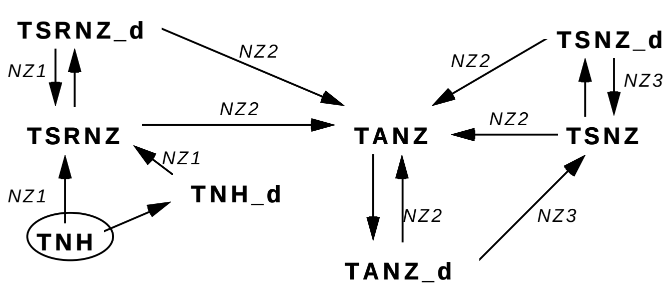
```
(NZ1) corresponds to the main controller.
(NZ2) corresponds to the nozzle servo component.
(NZ3) corresponds to the nozzle actuator component.

TSRNZ(k)  =  TSRNZ(k-1) + (nr(1) + nr(2)) * TNH(k) + nr(3) * TNH(k-1)  (NZ.1)
TANZ(k)   =  na(1) * TANZ(k-1) + na(2) * (TSRNZ(k) + TSNZ(k)) -
              na(3) * (TSRNZ(k-1) + TSNZ(k-1)) - na(4)                  (NZ.2)
TSNZ(k)   =  ns(1) * TSNZ(k-1) + ns(2) * TANZ(k-1)                      (NZ.3)
```

Parameter values

```
nr(1) = -0.1074,   nr(2) = 0.2136,   nr(3) = 1.21
na(1) = 0.2577,   na(2) = 0.1396,   na(3) = 0.0131,   na(4) = 0.4232
ns(1) = [0.2032 0.2372],   ns(2) = [0.0555 0.0823]
```

Causal graph:



It is interesting to notice that the knowledge and information available for the other application (APU) comes from completely different sources. It was provided by the experts which specified the turbine on the one hand and by the experts which designed the turbine on the other hand. The knowledge available was then in the form of :

- relations derived from physical laws (flow conservation law, pressure decrease through a valve, etc.).
- numerical knowledge : several parameters of the relations were numerically specified within a tolerance interval.
- characteristic curves recorded on the test bench.

One of the difficulties came from the fact that the kind of equation knowledge provided was often too precise (and therefore mathematically complex) for building a model dedicated to diagnosis. Several meetings were necessary with the experts to decide on the phenomena which could be neglected and to obtain appropriate approximated equations. This analysis phase required a real involvement into the electro-mechanics of the turbine domain.

After the dialogue with the experts phase, the equation model was obtained from an analysis of the equations and recorded graphs. A first task was to obtain a consistent set of equations by discarding all redundancies. A second task was to estimate numerical intervals for the non-specified parameters. This was done by using the recorded graphs. Note that the obtained equation model has a restricted zone of validity (in the neighbourhood of a stabilised pump speed of 6100 rpm and the following environmental conditions: pressure P0=1 bar, temperature T0=15 C, altitude Z=0m.

This outlines two major difficulties in building deep models of physical systems which are related to the fact that the knowledge available is not necessarily at the right level of abstraction and that it might be difficult to abstract the knowledge without falling into too much trivial models. The second one is that most of the deep knowledge available about complex physical plants concerns nominal operating conditions. This means that it is extremely difficult to get a model valid on a wide operation range (for the turbines, this means that the model might not be usable to monitor a starting up phase) and even more difficult to get realistic fault models showing the required precision.

This can be compensated by IxTeT chronicles. The IxTeT models have a weaker expressive power than the Ca~En models, when the same knowledge is available, but are productive to use when limited causal knowledge is available.

5.8.2 Fault Detection With Ca~En

The Ca~En fault detection procedure is based on models of normal behaviour. The on line simulation of these models is at the basis of a discrepancy detection procedure which allows us to track the physical system. This is performed by comparing the predicted and observed values of variables across time. In that way, static as well as dynamic discrepancies are detected. The comparison consists at each instant t and for every observed variable X, in checking whether the observed value Xo(t) (a real number) belongs or not to the predicted value Xp(t) (an interval). If not, variable X is said to be alarming at time t. At the graph level, this interprets as the observed trajectory going out of the predicted curve envelope at time t. [9].

5.8.3 Fault Diagnosis

The Ca~En system goes further than just fault detection and performs fault isolation using Reiter's model-based approach [7]. Having detected an inconsistency, a diagnosis is a minimal set of components for which the invalidation of the normal behaviour assumption yields (SD, COMP, OBS) consistent, where SD is a formal description of the system including assumptions of normal behaviour for the set COMP of components and the components in COMP are the elementary diagnosis units. In the Ca~En diagnosis module, the causal graph acts as the SD and the influences themselves are the elements of COMP. Faulty influences are internally turned back to faulty components. It relies on the collection of conflict sets, i.e. sets of components which cannot behave normally altogether according to the observations, and the use of an incremental hitting set algorithm. The diagnoses are given as sets of faulty components labelled by their corresponding date of failure.

The diagnosis process is initiated as soon as a variable is detected as misbehaving. The conflict generation procedure traces backward the causal graph, following the intuition that the influences which may be at the origin of the misbehaviour of a variable X are those related to the edges belonging to the paths going from the input nodes to the node of X. The last version of the algorithm also accounts for non-misbehaving variables at this stage. The conflict generation procedure avoids generating useless conflicts by using the concept of explained misbehaviour variable. The misbehaviour of a variable is explained by those of its parents in the graph if it perfectly matches their misbehaviour given the temporal delay associated to the causal influence between them.

The diagnosis generation is then based on generating the minimal hitting sets of the collection of conflicts generated by the above algorithm. As new symptoms for a given fault can appear across time, it is important that the diagnosis procedure is incremental. In Ca~En, we use Levy's algorithm [10] which is an incremental revised version of Reiter's original one. For more details, see [11].

The diagnosis conclusions provided for the nozzles sticking scenario outline the following fault messages which show the misbehaving variables as well as the proposed diagnosis candidates.

```
FAULT MESSAGES
1       Time 18:36:42
        Variable tanz misbehaves
        CURRENT DIAGNOSIS
                {tanz sensor, nozzles servo, nozzles actuator}

2       Time 18:37:09
        Variable tsnz misbehaves
        CURRENT DIAGNOSIS
                {nozzles servo, nozzles actuator}

        END OF DIAGNOSIS
```

As the servo and the actuator run in closed-loop, it is normal that the system cannot discriminate between those two components.

6. BENEFITS OF USING THE TIGER SYSTEM

Perhaps the key benefit of TIGER is that it acts as a gas turbine engineer monitoring the system every second, 24 hours a day, every day of the year. Most engineers make a regular check of the operation of the turbine ensuring that key variables are within their limits and looking at trends and recent patterns of the turbine to ensure that everything is okay. TIGER performs this task automatically.

TIGER is able to detect problems at an early stage before they become significant.

TIGER is able to show the trend of parameters of short or long periods of time, enabling more accurate condition monitoring. The TIGER system captures the key data for an incident and allows the engineer to go back and examine this in more detail.

The TIGER system monitors the dynamic response of the system. This is a unique capability. This can be used to ensure that the servo actuator systems are reacting properly. It can be used to ensure that the control system, and more importantly, the key transducers effecting the control system are correct. It has very powerful user interface environment to develop graphical displays of the state of the turbine giving a quick look analysis of the state. It supports a fault log and data log to enable long-term analysis of problems.

7. SUMMARY

This document has given an overview of the TIGER system in use at Exxon Chemical at Fife Ethylene Plant in Scotland. It has given a summary of the plant and the usage of the GE Frame 5 two-shaft turbine. It has given an overview of the functionality of the TIGER system and a description of how it is being used at Exxon.

7. ACKNOWLEDGEMENTS

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