Automated Analysis of SCADA and DFR data: Post-fault Diagnosis of Power System Disturbances and Condition Assessment of Plant

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***Abstract*— In order to automate the analysis of SCADA and digital fault recorder (DFR) data for a transmission network operator in the UK, the authors have developed a multi-agent system which integrates a number of legacy intelligent systems for analyzing power system data. The integration achieved through multi-agent systems technology enhances the diagnostic support offered to engineers by focusing the analysis on the most pertinent DFR data based on the results of the analysis of SCADA. It provides an analysis of the disturbances on the power system, and evaluates the performance of the protection schemes.**

The system underwent on-line trials with a UK utility. Since then, further research has identified that voltage transformer (VT) problems and failures can be detected through the automated analysis of DFR data. Also, circuit breaker trip coil signatures have been included in some DFR data sets. These can also be automatically analyzed to determine problems and defects within the circuit breaker mechanisms.

This paper will detail research concerning VT and circuit breaker defect analysis. The algorithms and methods used to analyze the DFR data will be explained. In addition, the paper will specify how these new functions are being integrated as further autonomous agents within the overall multi-agent system. The resulting system aims to provide extensive support for engineers tasked with the management and analysis of SCADA and DFR data. It underpins protection analysis, disturbance analysis, and plant condition assessment. The utility perspective on the benefits of this approach is also provided.

I. Introduction

The proliferation of monitoring equipment on transmission and distribution networks has resulted in an ever-increasing amount of data being made available to utility engineers. Data provided by Supervisory, Control and Data Acquisition (SCADA) systems, Digital Fault Recorders (DFR), microprocessor-based protection relays with fault recording capabilities, travelling-wave fault locators, and condition monitoring systems for circuit breakers and transformers, can aid engineers in making more informed, and potentially more profitable, power system operations and asset management decisions. The belief that monitoring can provide information which can lead to improved management and operation of the power system is one of the commercial justifications for the investment in monitoring systems and meeting the cost of maintaining and running those systems. However, there are a number of barriers to the effective use of this data:

- The raw data is often uninformative: information relating to plant health or the performance of the power system is implicit rather than explicit. Expert interpretation of the data is required;
- As the number of monitoring devices deployed on the network increases, the volume of data they produce, especially under storm conditions, renders manual analysis time-consuming if not intractable; and
- Data from different monitoring systems is related however it tends to be stored in different databases and file systems. Relating and collating this data can be a time-consuming task.

While utilities wish to use monitoring data to inform both power systems operations and asset management decisions, without adequate support for the analysis and management of the data, it is difficult for utilities to fully realize the benefits of monitoring.

SP EnergyNetworks manage, operate and maintain the transmission network in central and southern Scotland. The transmission network comprises a total 272 circuits at 132kV, 275kv and 400kV with interconnection to the transmission network managed by National Grid in England and Wales to the south, the transmission network managed by Scottish and Southern Electricity in the highlands to the north, and to Northern Ireland by a DC link. In terms of monitoring, it is arguably the most the comprehensively monitored part of the UK grid: at the time of writing over 300 DFR units were installed on the network. These units are GPS synchronized and auto-polled at least once every 24 hours with any new records being downloaded to the utility's headquarters. Through a system called PS Alerts, SCADA data from the Energy Management System is made immediately available to staff outside the control room. In addition, a number of circuits are equipped with traveling-wave fault locators, to which engineers have dial-in access.

Engineers at the utility can use these data sets above to build a picture of the power system's response to a disturbance. SCADA data is immediately available and can be used to quickly identify the occurrence of an incident as well as be used as the basis of a basic assessment of a protection operating sequence. Fault recorder data can provide a more

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complete picture, allowing the performance of the protection scheme to be assessed based on voltage and currents seen by protection relays and measured operating times of relays, inter-trips and circuit breakers. The distance-to-fault derived from the calculated impedance seen by the fault recorder can be compared and corroborated with the distance-to-fault derived from traveling-wave fault locator data. For each protection operation sequence on the transmission network, engineers at SP create a report which gives details of their expert interpretation of the data and an assessment of the performance of the protection scheme.

While engineers at the utility are adept at analyzing the data, the volume of data coupled with time constraints on the few engineers with the requisite expertise make manual analysis difficult.

For example, in 2003 the DFR network captured in excess of 20,000 records even though the network experienced only a handful of disturbances (under 70). Over the same period the SCADA system generated around 3,000,000 alarms. The last major storm experience by the utility in 2002 resulted in the transmission network being subject to 166 disturbances in 24 hours with most occurring in a four-hour period resulting in 1650 fault records and 15,000 SCADA alarms.

In this paper we discuss the initial trials and ongoing development of Protection Engineering Diagnostic Agents (PEDA), a multi-agent system which aims to automatically analyze both DFR and SCADA data using a number of legacy intelligent systems developed by the Institute for Energy and Environment and staff at the utility. When the development of PEDA began, the authors' aim was to analyze data from a protection engineering perspective, i.e. automate the assessment of protection performance. However, over the course of its development, the way that engineers at the utility use DFR data has extended beyond protection performance assessment and the analysis of disturbances. A relatively small percentage of the fault records captured outside storm conditions relate to protection operation sequences. Engineers at the utility discovered that amongst the large body of data unrelated to protection operations are records containing indicators of plant condition, e.g. records which indicate problems with voltage transformers (VTs). Fault recorders are also employed by the utility as a means of circuit breaker condition monitoring.

In this paper we discuss the automation of the analysis of DFR data from a plant condition assessment perspective, however, below we begin with a brief introduction to the PEDA system.

II. Integrated Analysis of SCADA and DFR Data

Over the last two decades a number of tools and techniques have been developed to help automate the analysis of power systems data and provide engineers with explicit information about the operation of the power system. Various rule-based expert systems have been developed which offer diagnostic support to engineers based on SCADA [1][2] and DFR data [3-6]. The application of artificial neural networks to the classification of faults using DFR data can also be found in the literature [7]. Model-based reasoning (MBR) systems have been demonstrated for the assessment of protection operation based on both SCADA [8] and DFR data [9-13] using different flavors of MBR.

Each of the tools referenced above focus on the analysis of a single type of data. Engineers at SP EnergyNetworks, on the other hand, tend to take a more holistic approach to post-fault analysis, basing their assessment of protection performance and plant health on all the available data, e.g. SCADA, DFR data, traveling-wave fault locator data, and circuit breaker condition monitoring data such as trip-coil current traces.

Earlier research by McArthur et al [14] discovered that, not only were engineers using multiple data sets during post fault analysis, they were also using the results of the analysis of one data set to focus the analysis of another, i.e. the SCADA data to focus the analysis of DFR data. Because SCADA data was available immediately, engineers were using it to identify when and where on the network protection operations had occurred and if there was any evidence of a genuine power system fault. This knowledge was then used to focus the retrieval and analysis of the DFR data. McArthur et al [14] argued that an existing set of tools for SCADA and fault record analysis could be integrated to automate this process and provide enhanced diagnostic support. Based on the automated analysis of SCADA using alarm processing techniques, the retrieval and analysis of fault records from sites where incidents have occurred can be prioritized.

The problem then became one of how to integrate these legacy intelligent systems. While integration in the laboratory was straightforward, in the industrial context a number of practicalities arise: the software and hardware associated with monitoring equipment is liable to change as new monitoring technologies become available; any integration strategy has to allow the addition of new data sources, improved data analysis tools and version changes to manufacturers' software. In 2001 the authors began investigating the use of multi-agent systems technology as a means of building a flexible and extensible post-fault analysis system. The interested reader can find a comprehensive description of MAS technology and its potential benefits from a power engineering perspective in [15]. Below we describe how it has been exploited for the PEDA system.

III. Protection Engineering Diagnostic Agents

Details of the PEDA system can be found in [16-19] but a brief description of the functionality it offers is given here. PEDA integrates a number of legacy intelligent systems with each other, PS Alerts, and the utility's fault record retrieval systems.

A. Legacy Intelligent Systems

The legacy intelligent systems that PEDA integrates are as follows:

- **The telemetry processor:** The telemetry processor is a rule-based expert system that assesses the operation of protection based on SCADA data. From a live SCADA feed, the telemetry processor identifies what engineers at SP EnergyNetworks term ‘incidents’ and ‘events’. An ‘incident’ is a group of alarms that relate to a disturbance on a particular circuit or item of plant. ‘Events’ are alarms or groups of alarms that make up a part of an incident, e.g. alarms indicating protection operation, circuit breaker movement, the initialization of delayed auto re-close (DAR) sequences or communication signals sent between substations. For each incident, the telemetry processor assesses protection performance using knowledge elicited from protection engineers and highlights if further investigation is required. Details of the implementation of the telemetry processor can be found in [17].

- **A model-based reasoning engine for the validation of protection operation:** The model-based reasoning (MBR) engine, which is part of an MBR toolset [12], implements a model-based approach to the analysis of DFR data [13]. The MBR engine propagates DFR data through a model of the protection scheme thus predicting the expected behavior of the components of the scheme. By comparing simulated protection behavior with the actual behavior observed by the fault recorder, the MBR engine can identify components of the scheme which may not have operated correctly, e.g. the failure of a trip relay to operate or a missing or late receipt of an inter-trip signal. The MBR engine supports the use of various types of protection relay model, including the detailed dynamic protection models described in [20].
- **A fault record interpretation expert system:** Also part of the MBR toolset [12], the fault record interpretation expert system is a rule-based system with two functions: it converts fault records from the COMTRADE format to the format required by the MBR engine and performs some additional interpretation by classifying the type of disturbance, e.g. red phase to earth, and determining the total fault clearance time.

Each of the tools above offers assistance to the protection engineer by removing the burden of manual analysis of individual types of data, however, as discussed earlier, diagnostic support can be enhanced by using the results of analysis of SCADA data to focus the analysis of DFR data. By comparing when a fault record was captured with the timing and location of power system disturbances identified from SCADA data by the telemetry processor, it is possible to perform a first-cut classification of the DFR data. Records can be classified as:

- **Directly related to an incident**: a fault record captured during an incident from the end of the circuit involved in that incident.
- **Related to an incident**: a fault record captured during an incident from a substation that contains one of the ends of the circuit involved in the incident, however the record does not contain data from that particular circuit.
- **Indirectly related to an incident**: a fault record captured during an incident by a fault recorder in a substation that was not directly involved in the incident. The fault recorder has triggered or been cross-triggered because of the voltage depression created by the disturbance.
- **Miscellaneous fault record**: a fault record that cannot be associated with an incident, i.e. no incidents occurred at the time the record was captured.

By performing the first-cut classification above, it is possible to quickly identify and highlight the fault records which are of immediate interest to protection engineers, i.e. records that are directly related to incidents, without having to analyze the content of the record. The analysis of these records using the fault record interpretation expert system and the MBR engine can then be prioritized based on the relevance of the record to protection engineers, resulting in more timely decision support.

By integrating the tools above, the entire post-fault analysis process can be automated. While an integrated approach to the analysis of SCADA and DFR data is beneficial, the manner in which integration is achieved has to meet utilities’ requirements for flexibility and extensibility.

MAS technology, through the use of standardized agent communication languages and standardized open architectures, can provide a means of building flexible, extensible, distributable software systems [15]. The de facto standards for MAS are the Foundation for Physical Intelligent Agents (FIPA) standards.

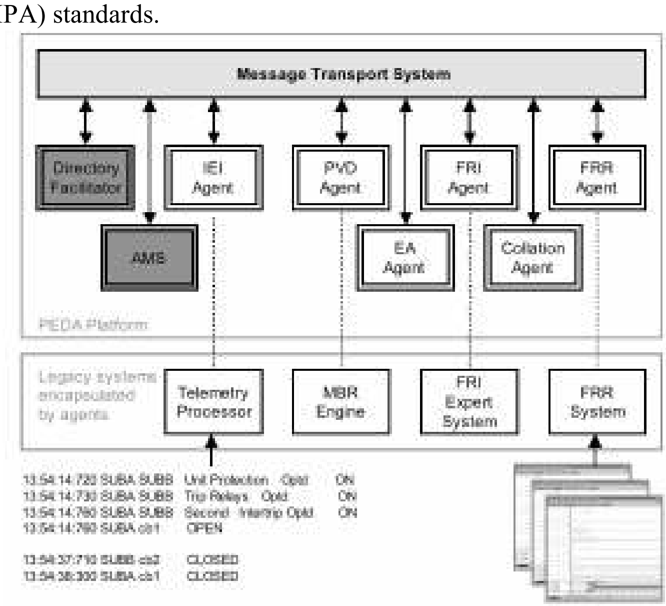

Figure 1: PEDA in relation to the FIPA Agent Management Reference Model

The architecture of the PEDA system is based on the FIPA Agent Management Reference (Figure 1) model which defines “the normative framework within which FIPA agents exist and operate. It establishes the logical reference model for the creation, registration, location, communication, migration and retirement of agents”. It includes two utility agents: the agent management service agent (AMS), which is compulsory, and the directory facilitator (DF) agent, which is optional. The AMS acts as a white pages, maintaining a directory of agents registered with the MAS. The DF acts as a yellow pages, maintaining a directory of agents and the services they can offer other agents. An agent can use the DF to search for other agents that can provide services that will aid it in fulfilling its own particular goals.

B. PEDA's Functionality

PEDA achieves its functionality by wrapping the legacy intelligent systems as autonomous intelligent agents which support the FIPA standards for interoperable multi-agent systems.

In addition to the information discovery agents required by FIPA, PEDA comprises the following data management and analysis agents:

- An Incident and Event Identification (IEI) agent which encapsulates the telemetry processor;
- A number of Fault Record Retrieval (FRR) agents which interface with the fault record retrieval system used by SP PowerSystems;
- A Fault Record Interpretation (FRI) agent which encapsulates the fault record interpretation expert system of the MBR tool-set;
- A Protection Validation and Diagnosis (PVD) agent which encapsulates the MBR tool-set's diagnostic engine;
- A Collation Agent which gathers information from the agents above and stores it in a relational database; and
- A number of Engineering Assistant (EA) agents which engineers can configure to inform them of new diagnostic information as soon as it becomes available.

Full details of how the agents interact, the standards they employ and how they were designed can be found in [19]. However, for the sake of brevity, the process PEDA executes can be summarized as follows.

When a fault record has been retrieved, the FRR agent asks the IEI agent if there was an incident on the network at the time the record was generated. The IEI agent replies with the details of the any relevant incidents. The FRR agent can then perform the first cut classification of the DFR data before sending it to the FRI agent and PVD agent for analysis. The results of all analyses and the fault records are sent to the collation agent which stores them in a relational database. This database has a web-based front end which allows engineers to access the information generated by PEDA. The web front end gives details of all the incidents that the telemetry processor has identified and all the records that are related, directly and indirectly to the incident. By clicking a hyperlink on the web browser the user can view the records. As a result, records are classified and made available over the utility's intranet within seconds of being downloaded from the substation.

IV. PEDA's Deployment and Lessons Learnt

After testing the full version of PEDA, described above, on historical SCADA and DFR data in the laboratory, a subset of the system's agents were deployed at SP EnergyNetworks in 2004. For initial testing the IEI agent, 9 FRR agents, the collation agent, and its database and associated web server were installed at the utility. The FRI agent and PVD agent were not deployed at that stage. The utility wished to test a commercially available, and thus commercially supported, fault record classification tool. Based on their experience with that tool a decision would be made whether or not to include that in PEDA rather than the tool developed at the Institute for Energy and Environment. Research has now restarted concerning the implementation of the Institute's fault record classification tool.

Model-based validation of protection operation requires a database of protection settings and models of the protection schemes in service to be maintained. The utility wished to explore the possibility of using existing protection settings databases rather than having to maintain a dedicated database for the PVD agent. As a result, the PVD agent was not included in the initial roll-out.

Results of the initial trails have already been reported in [19]. From the research perspective, in addition to demonstrating the efficacy of the integrated approach, the trials demonstrated that MAS technology had matured to the point where it could be used for data analysis applications in power engineering and could display the robustness utilities require. The trials also illustrated some of the ancillary benefits of MAS: the technology lends itself to incremental/staged roll out of functionality as well as the removal of redundant functionality. Initially 9 FRR agents were deployed, one for each type of fault recorder and version of the DFR unit manufacturer's software. As the firmware on a particular model of recorder was updated, the FRR agent associated with that model and previous software version was easily removed from the system without affecting the other agents.

During the deployment of PEDA additional knowledge elicitation meetings were held with the utility's chief expert in fault record analysis to investigate the kinds of additional information that can be gleamed from both the fault records relating to incidents and the miscellaneous fault records. These meetings also helped researchers at the Institute for Energy and Environment to identify areas where the automated analysis of DFR data could be extended in the future.

V. Extending the Functionality of PEDA to Consider Assessment of Plant Condition

When the development of PEDA began in 2001, its intended function was the automated analysis of SCADA and DFR data from a protection engineering perspective. However, as the utility's engineers' expertise grew it became clear that DFR data was being used for much more that the analysis of protection operation and recording of power quality issues.

In this paper we discuss two such additional uses of DFR records: the identification of problems with voltage transformers (VT) and the use of DFR data as means of assessing circuit breaker health.

VI. Identifying DFR Records Related to Abnormal VT Behavior

In addition to the classification of power system disturbances [3-7], evaluation of the performance of protection [3-6][9-13], and the assessment of power quality [6], DFR data can also be used to identify problems with voltage transformers (VT). To the authors' knowledge there has been no work published which proposes or examines the use of DFR data to this end other than the identification of VT ferroresonance during fault clearances [6].

Engineers at SP EnergyNetworks have gained experience in identification of a range of VT problems from DFR data that would be classed as miscellaneous by PEDA. These include: flashover of the VT's spark gap, faulty VT fuses and precursors to failure which can be seen in DFR data, in some cases, several days before failure of the VT occurs.

By way of an example Figure 2 shows an example voltage waveform from a VT with a faulty fuse. Fuse problems tend to cause an intermittent reduction in the peak voltage. If alerted by the DFR data, engineers can schedule the inspection of the VT.

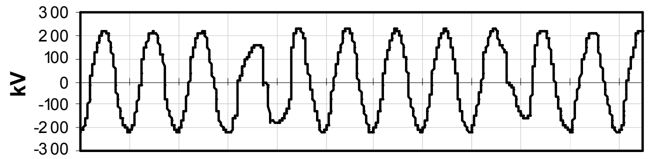

Figure 2. Voltage trace captured from a VT with a faulty fuse.

As can be seen in figure 2, the faulty fuse causes intermittent reduction to the magnitude of the voltage waveform. In very rare cases, they may cause protection to operate unnecessarily causing a temporary unplanned circuit outage.

Permanent failure of a VT may have more serious consequences, tripping a circuit or even a generator. The financial consequences of such an event can be severe. Moreover, should the VT fail catastrophically, it may endanger personnel working in substation. Importantly, precursors to the failure of a VT can sometimes be seen in DFR data.

Figures 3 and 4 show a sequence of traces captured from a VT before it finally failed (Figure 5) causing a circuit outage. In the case below, the precursors to failure (Figures 3 and 4) were captured several days before the failure of the VT.

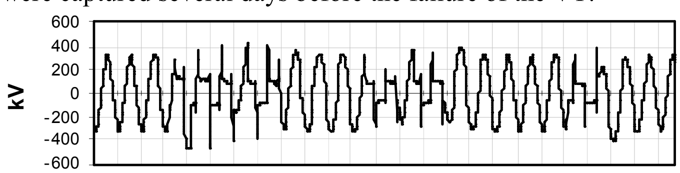

Figure 3. 1st voltage trace recorded 3 days before the VT failed.

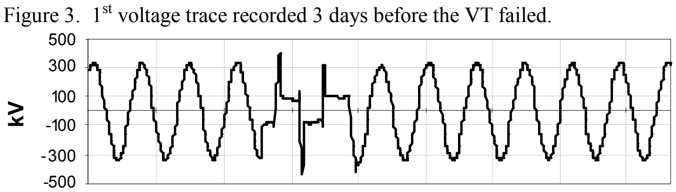

Figure 4. 2nd voltage trace recorded 3 days before the VT failed. Note the similarity between trace in this figure and figure 3.

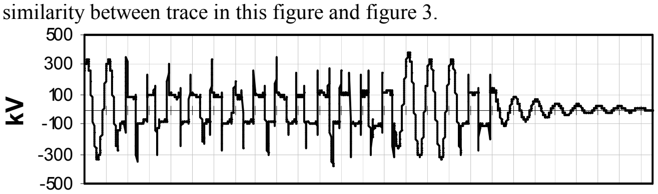

Figure 5. Voltage trace recorded during the failure of the VT. The VT fails and its output falls to zero.

Engineers aim to identify incipient faults and take the appropriate action before the faults become permanent and result in the removal of the device from service or an unplanned outage. However, knowledge of potential problems with EHV plant is also important for the safety of staff entering substation compounds. In the utility's experience, VT failure can occur with and without warning. When the precursors to failure do occur, it may only be hours or a few days before failure occurs. Hence, it is imperative that those records be identified as quickly as possible.

A. Rule-based classification of records related to VT problems

Through knowledge elicitation it was discovered that engineers had simple rules of thumb that they applied when visually inspecting data in order to classify a record as being generated by a VT problem. If a disturbance in voltage is seen on the one phase, no change of phase angle is seen between unaffected phases and no change in current is detected on the phase experiencing a voltage disturbance, then the DFR unit has capture a record relating to a problem with a VT.

In order to test the effectiveness of this rule of thumb, the authors added additional rules to the rule-based fault record interpretation expert system. These rules, along with some simple signal processing techniques, embody the rationale described above. To test the rules for identifying VT problems the expert system was presented with a set of records known to relate to VT problems mixed with records capturing transient faults, permanent faults and through faults.

While this simple approach allows records relating to VT problems to be identified quickly and could be used to alert engineers of potential problems, it does not discriminate between different classes of VT fault. Given that different problems seem to exhibit recurring, recognizable fault signatures, the authors are currently investigating the use of machine learning techniques, normally used in natural language processing, to allow engineers to highlight signatures and then alert them when similar signatures are seen in other records.

VII. Circuit Breaker Condition Assessment Using Trip Coil Current Traces Captured by DFR Units

Engineers at the utility also use selected DFR units to record circuit breaker trip coil current by installing a Hall probe on the trip coil current line and recording the associated trace using a spare or additional analogue channel on the DFR unit.

Figure 6: A trip coil current signature captured for a 400kV breaker using a DFR analogue channel

Recording the trip coil current (Figure 6) can provide an effective and inexpensive means of basic circuit breaker condition monitoring. Both [21] and [22] described the physical process in the trip circuit that results in the trace above as well as the different classes of fault that can be diagnosed from the trace.

SP EnergyNetworks already use trip coil current traces to assess the condition of 11 kV and 33 kV distribution circuit breakers as part of their breaker maintenance and testing regime. In that case, trip coil traces are captured on handheld units by maintenance staff when they exercise the breaker. Researchers at the Institute for Energy and Environment have taken a data mining approach to derive rules for the analysis of trip coil traces [22][23] for distribution breakers. While experts at the utility certainly have knowledge of the idiosyncrasies associated with different models of distribution breaker, how those are reflected in the trip coil current trace was not necessarily known. As a result an approach which combined knowledge engineering with data mining was used.

The authors are currently investigating the use of similar techniques to [22][23] for the automated analysis the trip coil current traces captured by DFR units for transmission breakers based on the utility's archive of DFR data. A similar situation exists, engineers certainly have knowledge about the breakers' operation and failure modes and, while the engineers know what rough shape of trace to expect, what classifies as subtle deviations from normal is not known.

A potentially applicable approach is described in [24] for learning models of plant behavior for anomaly detection and condition monitoring. The technique, which is based on learning hidden Markov models (HMM), could be used to learn nominal behavior from example traces for a particular breaker and then identify records where the anomalies in the trip coil trace have been detected and further investigation is warranted.

VIII. Extending PEDA to include additional DFR data analysis agents

At the time of writing the authors are in the process of extending PEDA to include the FRI and PVD agents as well as the techniques for identifying records related to VT problems and developing anomaly detection techniques for trip coil current traces. It is in this respect that MAS technology comes into its own. As discussed earlier, MAS offer a standardized open architecture; agents can easily be added to or removed from the MAS. Either the FRI agent could be extended to incorporate the rules relating to VT problem identification or an additional agent with that functionality could be added. Similarly, a new agent with the ability to perform anomaly detection of trip-coil current traces could be added to the system.

IX. Conclusions

Power systems monitoring data can provide useful information about the performance of the power system in response to disturbances, however, support for analysis is required. As engineers tend to use multiple data sets and analysis techniques in order to interpret and relate all the data then to automate the entire post-fault diagnosis process, a method for integrating previously disparate automatic analysis systems is required. Through demonstration at a utility, MAS technology has been shown to be a strong candidate.

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