Multi-Agent Systems for Diagnostic and Condition Monitoring Applications

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***Abstract*—On-line diagnostics and on-line condition monitoring are important functions within the operation, control and management of power systems. Extensive research activities have led to the development of intelligent system techniques that support these functions. However, experience has shown that often more than one intelligent system technique is required to perform the diagnostic or monitoring function. In addition, integration is required between legacy data sources, legacy monitoring systems and the new data capture systems and intelligent systems being applied. Multi-agent system techniques can be used to provide such integration, while enhancing the overall intelligent interpretation functionality.**

***Index Terms*— Decision support systems, Fault diagnosis, Intelligent systems, Cooperative systems, Multi-agent systems, Condition monitoring.**

I. INTRODUCTION

Within the power industry, an increasing amount of condition monitoring and data capture systems are being deployed throughout the power system. This leads to a number of issues arising:

- The volume of data to be interpreted is large, leading to engineers being unable to analyse all the power system and plant faults and events;
- Data sources are dispersed around the network and plant items, leading to significant telecommunications issues and distributed interpretation/processing problems;
- Several data sources may need to be integrated and interpreted to provide a true diagnosis of any problems (e.g. SCADA data and digital fault records for power system diagnostics; load data, DGA results, on-line gas analysis results and other monitored values for transformer monitoring); and
- Further data sources may be added in the future for inclusion in the diagnostic/condition monitoring function.

Therefore, decision support must be provided for diagnostic and monitoring applications which:

- Handles large volumes of data;
- Converts the data into meaningful information; and
- Supplies the appropriate personnel with the right information at the right time. and;
- Provides flexibility and extensibility, allowing additional data acquisition and monitoring systems to be incorporated in the future.

These functions can be achieved through MAS, while overcoming the aforementioned issues.

II. MULTI-AGENT SYSTEMS

Multi-agent systems (MAS) offer a flexible and extensible framework for integrating the necessary data capture systems, monitoring systems and interpretation functions. Nevertheless, MAS do not provide systems integration capabilities only. This technology permits the development of more intelligent and automated diagnostic and monitoring functions.

MAS are comprised of a number independent software modules (agents) which exhibit four key characteristics: autonomy, social ability, reactivity and pro-activeness [1]. In engineering terms, autonomy means that each agent will operate in an unsupervised mode, continually performing its diagnostic function while altering its behaviour as required. Social ability means that each agent can co-operate and communicate with other agents, supporting data exchange, information exchange and negotiation. Reactivity and pro-activeness suggest that the agents are imbued with the ability to react to their surroundings and pro-actively take action to solve problems and ensure that they deliver the correct information or initiate the required control activity. Therefore, agents and MAS encompass all of the attributes required to automate diagnostic and condition monitoring applications.

The authors have designed and constructed two MAS which provide engineering decision support, as described in the following sections. These demonstrate the benefits of multi-agent approaches to diagnostic and condition monitoring applications within the power industry.

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III. MAS FOR AUTOMATED DISTURBANCE DIAGNOSIS

Power system disturbance diagnosis is a critical activity, which is both time consuming and complex. There are a number of data sources employed: SCADA alarms, digital fault records, travelling wave fault locators (if available), etc.

If performed manually, the process commences with the gathering of SCADA from around the time of a disturbance, followed by manual interpretation of this to identify key events. Once the disturbance location is identified, digital fault recorders are accessed and provide fault records. A number of problems arise with the retrieval due to the large volumes of data which must be retrieved from remote sources over sometimes unreliable communications. Once the records are available, they are used to validate protection performance.

MAS provide the capability to improve and accelerate this activity, leading to engineers being presented with fully interpreted disturbances. The integration capabilities allow intelligent systems for the interpretation of SCADA data to exchange their results with the system which accesses the digital fault recorders. By building intelligence into agents, the identification and retrieval of relevant fault records becomes autonomous. Once retrieved, the social ability of the agents allows the fault records to be passed to further intelligent agents which can interpret the fault records and validate the protection behaviour using model based reasoning techniques [2].

Providing this automated means of performing disturbance diagnosis significantly reduces the data retrieval, collation and interpretation burden on protection engineers.

A key issue within this research was the design of MAS for power engineering applications, therefore the authors have developed a methodology to facilitate this. The key steps in this methodology are:

- Requirements Capture/ Knowledge Capture
  The first step is to understand the end use of the MAS through a high level requirements specification, and to ensure that any relevant knowledge, cases, experience and rules are captured. This permits intelligent system technologies, such as rule-based reasoning and case-based reasoning to be embedded within the agent. This transforms it into an "intelligent agent".
- Task Decomposition
  The high level requirements specification and knowledge underpinning the MAS are transformed into a hierarchy of tasks and sub-tasks. It is important to note that the tasks may include functions performed by existing monitoring and analysis systems, therefore this methodology caters for legacy systems.
- Ontology Design
  The ontology is the vocabulary used by the agents to exchange information and data. As such, it is a data dictionary that supports co-operation and social ability. This is critical to the operation of the MAS.
- Agent Modelling
  From the task hierarchy and ontology design, the identification of independent and autonomous agents can be achieved. Once identified, their core functionality is designed.
- Agent Interactions Modelling
  Once the agents have been identified, the interactions between different agents must be defined. This has an impact on their core function, therefore the previous step and this one are iterative.

- Agent Behaviour Functions
  The necessary software functions to allow the agent interactions are designed, and the control mechanisms designed which allow autonomy, reactiveness and pro-activeness.

As an example, for the MAS under consideration the high level task hieracrchy was:

- Perform SCADA interpretation:
  - Identify incidents;
  - Group incident related SCADA; and
  - Identify incident events.
- Assist with DFR retrieval:
  - Manage automated polling of DFRs and retrieval of new records; and
  - Prioritize retrieval of records from DFRs in the vicinity of an incident to avoid records being overwritten by new data.

- Interpret retrieved DFR records:
  - Extract key indicators of disturbance type, e.g. fault type, clearance times.
- Analyse protection performance:
  - Validate protection operation; and
  - Diagnose protection failures.

Once the remaining steps of the design methodology were followed, the resulting Protection Engineering Diagnostic Agents (PEDA) system was designed, built and operates as shown in Figure 1. Each agent has the necessary intelligence built into it to perform its core tasks. For example, the *Incident and Event Identification* agent uses knowledge based systems technology [3][4], and the *Protection Validation and Diagnosis agent* uses model based reasoning [2][5].

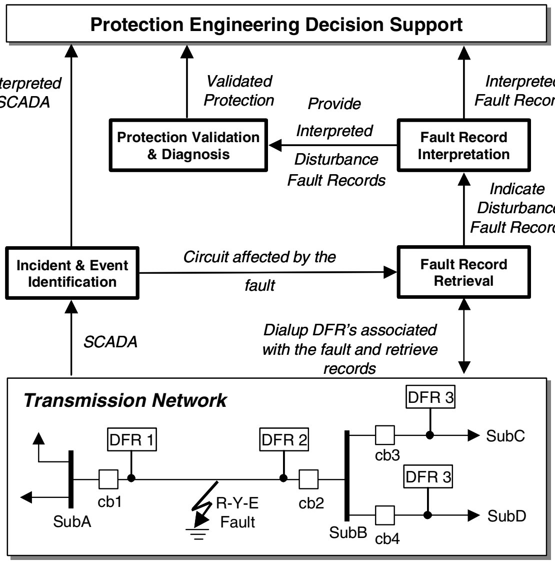

Figure 1 – Protection Engineering Diagnostic Agents

The PEDA multi-agent system shown in Figure 1 was built and tested in the laboratory. Currently, it is being implemented as an on-line post-fault analysis system for ScottishPower PowerSystems in the UK. This activity is highlighting the operational and practical issues associated with industrial deployment of multi-agent systems. Based on this, our multi-agent system development approach will be enhanced and tuned to support application of the technology within the electrical power industry.

IV. MAS FOR CONDITION MONITORING

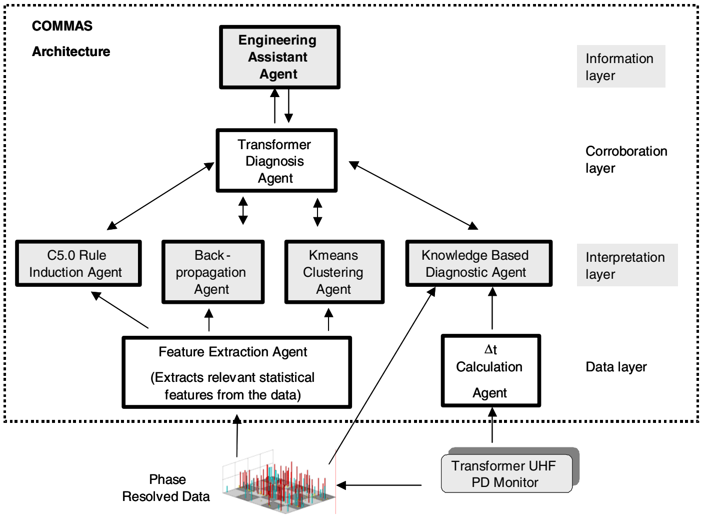

Figure 2 – COMMAS for Transformer Monitoring

A MAS has been developed to aid in the condition monitoring of power transformers. The design of the system followed the methodology described in the previous section.

Through the initial requirements analysis the following key functional requirements were identified:

- Raw sensor data, from various sensors, must be conditioned and tested for any significant deviations (such as the exceeding of certain limits and unexpected rates of change);
- When significant deviations are identified, diagnosis of the failure must occur through interpretation of the data;
- It must be ascertained whether there is a sensor failure or an actual plant failure. This is achieved by corroborating the interpretation results and sensor data with other relevant data sources; and
- Once diagnosed, key information and remedial advice must be presented to the relevant engineers.

An additional requirement, which is essential for longevity and practical implementation, is that the architecture must be scalable and support the introduction of new sensors, data sets and interpretation techniques as they become available. This suggests that each of the required functions should be standalone, with the ability to co-operate and exchange data/information as required. Therefore, the requirements are supported by a multi-agent approach to condition monitoring.

This led to the design of a “layered” condition monitoring system, where functional modules are grouped by their overall goal. Architecturally, the condition monitoring system uses distributed agents that have no constraints on their physical location. This allows data handling agents to be on the plant or close to it. Importantly, modules are designed such that only relevant data and information enters the telecommunications system, thereby avoiding the current practice of sending all data to a central point.

The layers are:

- The data monitoring layer;
- The interpretation layer;
- The corroboration layer; and
- The information layer.

The resulting system will integrate various monitoring technologies and data sources, such as oil temperature measurements, electrical loading (from voltage and current sensors), dissolved gas analysis results (on-line or periodic measurements), UHF PD measurements, tap changer position and additional relevant data such as records of maintenance and servicing. However, the key focus of the current research is to harness UHF monitoring of partial discharge within transformers, through a combination of laboratory based experiments and field experiments [6].

This research has led to the development of COMMAS [6][7], the Condition Monitoring Multi-Agent System. Each of the layers of this condition monitoring MAS contains a number of agents performing different functions. The social ability and co-operation between the agents leads to the final diagnosis and conclusions. The functionality of the agents within each layer is described below.

- Data Layer:
  Feature Extraction Agent: This agent extracts statistical features from the raw UHF partial discharge data, which are used in the identification of problems.
  Δt Calculation: This agent uses time-of-flight calculations to identify the exact location of any discharges and defects.

- Interpretation Layer:
  C5 Rule Induction Agent: The C5.0 rule induction algorithm was used to extract rule patterns from a database of laboratory results. This agent uses the resulting rules to identify the probable defect type e.g. bad contact, floating particle, surface discharge, etc.
  Back Propagation Network Agent: A back propagation neural network was used to identify the probable defect, and this was wrapped as an agent.
  K-Means Clustering Agent: This agent uses the K-means clustering algorithm to identify the probable defect type.

Knowledge Based Analysis Agent: Experience and advice, from experts in the area of UHF diagnostics, has been formally captured. It will be embedded within an intelligent agent employing knowledge based reasoning approaches for the diagnosis of defects.

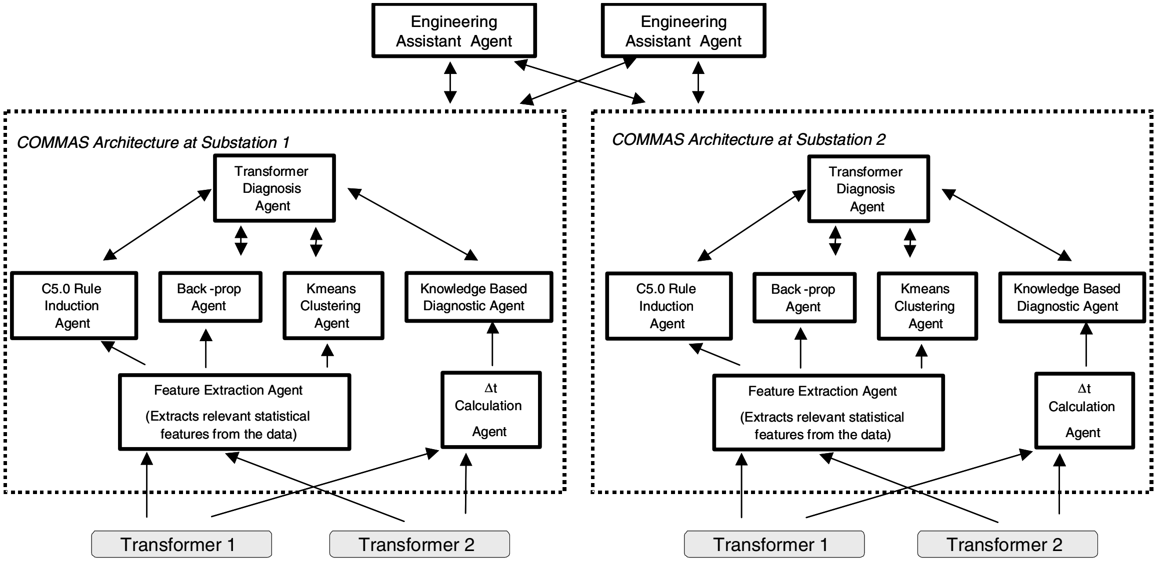

Figure 3 – COMMAS Implementation in Multiple Substations

- Corroboration Layer:
  Transformer Diagnosis Agent: This agent uses the outputs from each of the PD interpretation agents, along with their confidences, to find corroborative evidence of a particular defect type. This agent will eventually corroborate the diagnosis generated from other monitoring techniques, such as on-line gas analysis, acoustic sensors, etc.

- Information Layer:
  Engineering Assistant Agent: The engineering assistant agent formats the results in the most appropriate way for the engineer who is using the system. It is configured for the particular engineer using it, and delivers the exact information they require to perform their operational role. In this system, a graphical 3-D model of the transformer is shown with the defects indicated at their location. These can be selected to find out further information about the transformer, its maintenance history and other relevant information.

Figure 3 indicates how the COMMAS architecture can be replicated across a number of substations, with two transformers in each substation. COMMAS has been designed to be extensible and flexible, easing the integration of many substations and many plant items. It is at this stage of deployment that the *Engineering Assistant Agents* become a critical decision support aid for the operational engineers.

V. CONCLUSIONS

This paper has discussed multi-agent systems for diagnostic and condition monitoring applications in the power industry. The paper demonstrates that MAS offer system integration capabilities to enhance such functions. However, this technology also permits greater autonomy and intelligence to be embedded within diagnostic and monitoring applications, offering advanced levels of decision support to engineers. Consequently, multi-agent systems can underpin the next generation of power system operation and asset management functions, by rapidly providing engineers with advice and meaningful information upon which to base their operational decisions.

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