Proceedings of Engineering of Intelligent Systems (EIS 2004)
February 29 - March 2, 2004
Island of Madeira, Portugal

APPLICATION OF MULTI-AGENT TECHNOLOGY TO FAULT DIAGNOSIS OF POWER DISTRIBUTION SYSTEMS

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ABSTRACT

When a fault occurs in a power system, the protective relays detect the fault and trip appropriate circuit breakers, which isolate the affected equipment from the rest of the power system. Fault diagnosis of power systems is the process of identifying faulty components and/or sections by analysing observable symptoms (telemetry messages). As the domain itself is characterised by dynamic situations, extensive telemetering, complex operations, and distribution of lines and substations over a large geographical area, it is difficult to tackle fault diagnosis problems through the strength and capability of a single intelligent system. This paper describes an experimental multi-agent system developed for and aimed at a computer-supported fault diagnosis in electricity distribution networks. The system is based on a hierarchy of five agents that cooperate with each other to diagnose a fault. The results obtained suggest that agent-based approach is very efficient and with a good potential for real-time application.

Keywords: agents, multi-agent systems, fault diagnosis, electricity distribution networks

1. INTRODUCTION

1.1 Electricity distribution networks

The electricity distribution industry is one of the largest in the UK, serving 27 million customers. In England and Wales there are 12 regional electricity companies responsible for distributing and supplying electricity to customers. Electricity is received from the transmission network at 132 kV and is transformed down to lower voltages, i.e. 33 kV, 11 kV and 240 V, as it is distributed across a region. 132 kV and 33 kV are referred as High Voltage (HV) and 11 kV and below as Low Voltage (LV). Domestic customers receive their supply at 240 V and some large industrial customers can take their supply at either 11 kV or 33 kV.

On the high voltage networks (132 kV, 33 kV), the circuits are usually equipped with automatic circuit breakers that report their operation to the control centre via the Supervisory Control and Data Acquisition (SCADA) system. These circuit breakers are fitted with an auto-recloser, this means that when they open automatically due to fault, after a short delay they will reclose in an attempt to restore the supply. If the fault is transient, the circuit breaker will remain closed and the power will be restored, but if is permanent then the circuit breaker will reopen again to disconnect the supply.

With the low voltage networks (11 kV and below), often only outgoing source circuit breakers, on 11 kV feeders from major substations, are telemetered. Below the source circuit breaker the network is radial with many branches that lead to the 11kV/415 transformers supplying the customers. These branches are protected by protective devices, such as fuses, which are not telemetered.

A control engineer who works in the control centre directly controls the networks, based upon indications and alarms available to him/her and through the use of the telecontrol command schemes. When a fault occurs in the network, no direct information is obtained on what type of fault has occurred and where it is. Rather, telemetry messages obtained in the control centre indicate which switches and automatic protective relays have operated in response to the fault. These telemetry messages are normally regarded as 'post fault symptoms', and they are vital information to the control engineer when diagnosing faults.

The task of fault diagnosis would be easier if the relevant switches and protective relays operated correctly. However, fault diagnosis could become quite complex due to factors such as an item of equipment failing to operate when required, or operating when not required. There are other factors, the telemetry messages received are not always in relation to the time the fault occurred, and there is often simply a lack of detailed information regarding the low voltage networks. In some extreme cases (e.g. blizzards, storms etc.) where several faults occur simultaneously, telemetry messages could arrive at the rate of 2,000 per hour or higher (Brailsford and Cross, 1989). The use of computer-aided systems in fault diagnosis of electricity distribution networks is becoming more and more important to increase effectiveness and efficiency. This paper reports on an experimental research work carried out at Power Systems and Electronics Research Group, University of the West of England, UK. The aim of the project is to develop a multi-agent system for fault diagnosis of electricity distribution networks (Yang, 2001).

1.2 Traditional AI approaches

Since the birth of artificial intelligence (AI) based on symbol manipulation impressive progress has been made in human understanding of the basic issues related to knowledge representation. This has motivated active researchers to apply AI techniques to fault diagnosis of power systems. Many methods have been developed to assist the control engineer in diagnosing faults using expert systems (Fukui and Kawakami, 1986), (Montakhab and Adams, 1998), (Cockburn, 1992), (Wang and Dillon, 1992) and neural networks (Mohamed and Mazumder, 1999), (Swarup and Chandrasekharaiah, 1994), (Yang et al., 1994). The most common method is an expert system (ES) approach. The ES approach is appropriate for this task because diagnosis requires the experiential knowledge of an expert, and logic reasoning is the primary task. A good review of the expert systems based approach to fault diagnosis of power systems can be found in (Sekine et al., 1992). Although good results have been obtained, as they are highly centralised, these systems suffer from some drawbacks as follows:

i. The complexity of an expert system increases rapidly as the size of its knowledge base increases, maintenance of such a large knowledge base often proves to be difficult and the design of these systems often requires considerable efforts because of the complex knowledge acquisition process.

ii. Touching any part of a centralised system often endangers the entire structure, making it difficult to modify and debug.

iii. Large knowledge bases execute less efficiently, because more time is spent in search.

iv. A single point of failure often makes the overall problem useless.

v. A centralised system is expensive.

1.3 Benefits of multi-agent approach

Historically, multi-agent systems technology was invented as a sub-field of distributed artificial intelligence, which itself is a sub-area of artificial intelligence. Today, the term 'multi-agent systems' is used to refer to all types of systems composed of multiple (semi) autonomous components (Jennings et al., 1998). This approach represents a new and promising solution to problems outlined above.

In multi-agent systems, individual problem-solving entities are called agents; agents are grouped together to form communities which co-operate to achieve the goals of individuals and of the system as a whole. It is assumed that each agent is capable of a range of useful problem-solving activities in its own right, has its own aims and objectives and can communicate with others (Jennings et al., 1993). As distributed systems, multi-agent architectures have the capacity to offer several desirable properties over centralised systems (Stone and Veloso, 2000):

Speed-up and Efficiency - Agents can operate asynchronously and in parallel, and this can result in increased overall speed.

Robustness and Reliability - Each agent is more reliable because of its reduced complexity. The failure of one or more agents does not necessarily make the overall system useless, because the control and responsibilities are shared among different agents.

Scalability and Flexibility - The system can be adopted to an increased problem size by adding new agents, and this does not necessarily affect the operationality of the other agents.

Costs - Since it could be composed of simple subsystems of low unit cost, it may be much more cost-effective than a centralised system.

Development and Reusability - Individual agents can be developed separately, either from scratch, or on the basis of already available hardware and/or software facilities. The overall system can be tested more easily, and it may be possible to reconfigure and reuse agents in different application scenarios.

2. MAFS - A MULTI-AGENT FAULT DIAGNOSIS SYSTEM

In this section we describe the multi-agent approach underlying the MAFS system.

2.1 MAFS Architecture

In the architecture shown in Figure 1, fault diagnosis of power systems is devolved to five agents, a Power System Agent (PSA), a High Voltage Diagnosis Agent (HVDA), a Substation Diagnosis Agent (SDA), a Low Voltage Diagnosis Agent (LVDA) and a Global Decision Agent (GDA). The arrows indicate the inter-agent communication.

2.2 Role of each agent

PSA - The function of this agent is to report fault symptoms associated with a fault to HVDA, SDA and LVDA as required.

HVDA - The function of this agent is to diagnose the location and type (permanent or transient) of faults on high voltage circuits (132 kV and 33kV).

SDA - The function of this agent is to diagnose the location and type of faults on substations of the distribution network (132/33kV and 33/11kV).

LVDA - The function of this agent is to diagnose the location and type of faults on the low voltage networks (11kV and below).

GDA - The function of this agent is to make a final diagnosis based on the local hypotheses from HVDA, SDA and LVDA.

2.3 Diagnosis procedure

Stage 1 HVDA, SDA and LVDA ask PSA about local telemetry messages.

Stage 2 On the receipts of telemetry messages from PSA, HVDA, SDA and LVDA initiate diagnostic processes. Each of them produces corresponding hypotheses based on locally observed information.

Stage 3 The GDA considers all the received hypotheses from the HVDA, SDA and LVDA and, if required, makes the necessary comparison between them until it identifies the cause of problem.

2.4 Protocol language

The notion of a multi-agent system presumes that the individual agents can exchange meaningful information in order to achieve individual goals and a shared global goal. A protocol language defines the structure of the message so that it is understandable to all agents.

The Knowledge Query and Manipulation Language (KQML) is a protocol language that is designed to support interactions among distributed intelligent agents (Finin et al., 1997). It provides a standard message format for knowledge sharing between agents. The basic syntax of a KQML message has the following structure:

```
(KQML - performative
        :sender   <word>
        :receiver   <word>
        :language   <word>
        :content   <expression>
        …
)
```

As can be seen from the above, the syntax of KQML is Lisp-like; however, the arguments identified by keywords preceded by a colon, may be given in any order. The term 'performative' comes from *speech act theory*, which views human natural languages actions such as requests, or suggestions, or replies (Cohen and Perrault, 1979), e.g., *ask*, *tell*, *send*, *receive* and *reply* etc. The *:content* field stores the message to be sent and the *:language* field states the language in which the message is expressed.

When using KQML, a software agent composes messages in its own representation language, wrapped in a KQML message, and relies on a separate router process to deliver KQML messages across the network to the agent with whom it wishes to communicate (Figure 2).

2.5 Communication mechanism

While KQML defines the structure of messages exchanged by agents, the question now is how a message from one agent to another agent can be delivered. In other words, a communication mechanism is needed to carry the message across the network to its final destination.

In MAFS, inter-agent communication is achieved using *sockets* - program-defined end-points for network communication between processes. The Windows Sockets (abbreviated "WinSock") specification defines a network programming interface for Microsoft Windows which is based on the "socket" paradigm popularised in BSD Unix. It encompasses both familiar Berkeley socket style routines and a set of Windows specific extensions. The underlying transport protocol used here is TCP/IP. Two types of sockets are possible: stream sockets, which provide bidirectional, reliable, sequenced and unduplicated flow of data; and datagram sockets which do not guarantee that data is reliable, sequenced or unduplicated. MAFS uses the more reliable stream sockets. The sequence of actions for setting up a communication channel via a pair of stream sockets is as follows:

1. Each process opens a socket (using the socket ( ) function).
2. Sockets are named (using the bind ( ) function).
3. Sockets are associated with each other (using connect ( ), listen ( ) and accept ( ) functions).
4. Stream of data can now be exchanged using write ( ) and read ( ) functions.
5. Finally the sockets can be closed using close ( ) or shutdown ( ) function.

2.6 Implementation

MAFS is implemented using different programming tools. PSA is implemented using Turbo C++. The HVDA, SDA, LVDA and GDA are implemented using an expert system shell called GoldWorks (GW) (Gold Hill, 1998), which is based on the Common Lisp language.

GW is a real-time environment which provides a powerful rule-based inference engine and is easily integrated with external code. The knowledge base of the above diagnostic agents consists of two major parts: the database and the rule base. The database stores the location, connectivity and characteristics of a collection of network components i.e. lines, buses, transformers, circuit breakers, relays and customers. All components of the network are represented using an object oriented data structures. Components with common attributes are grouped into a class, which is represented by the frame structures in GW. The rule base consists of both shallow and deep knowledge of the domain studied. By definition, shallow knowledge refers to the expert's experiential knowledge i.e. knowledge based on practical experience. Deep knowledge refers to the structural and functional knowledge of a domain, which captures the underlying principles of the domain explicitly. The shallow knowledge ensures diagnostic efficiencies and the deep knowledge ensures diagnostic effects.

The development of MAFS has been done on multiple PCs, running Windows 95 or Windows NT. The inter-agent communication is achieved through WinSock, which is implemented in Visual C++.

3 CASE STUDY

At 16.00 hours a lightning strike hit phase A of the above 11kV line causing a phase to ground fault on phase A (Fig. 3). Consequently the instantaneous overcurrent relay of CB18 operated, but due to mechanical problem CB18 failed to operate. As a result, standby earth fault relay of transformers T9 and T10 operated and CB13 and CB15 opened to isolate the faulty section from the rest of distribution network. The first "no supply" call from post code PC1 was received after 12 minutes.

Stage 1

HVDA asks PSA about local telemetries, and the PSA informs the HVDA that there are no telemetry messages.

SDA asks PSA about local telemetries, and the PSA informs the SDA that at 16.00 hours, standby earth fault relays of transformers T9 and T10 operated and circuit breakers CB13 and CB15 opened.

LVDA asks PSA about local telemetries, and the PSA informs the LVDA that at 16.00 hours, instantaneous overcurrent relay of circuit breaker CB18 operated and the load flows through 11kV circuits CCT1 & CCT2 were reduced to zero.

Stage 2

HVDA initiates local diagnosis. Because there are no local telemetry messages, the HVDA makes the hypothesis that there are no local faults.

SDA initiates local diagnosis. Since the circuit breakers CB13 & CB15 opened as a result of operation of the standby earth fault relays, which provide earth fault protection for busbar BB1, the SDA makes the hypothesis that there may be an earth fault on busbar BB1, as standby earth fault relays have operated and circuit breakers CB13 and CB15 have opened.

LVDA initiates local diagnosis. By using the information related to the interrupted customers (post code, time of call), the LVDA infers that the fault is related to one of the 11kV circuits CCT1 and CCT2 and one of the secondary transformers T1, T2 and T5. The LVDA asks the user whether there are any pre-known damaged plants. The answer is negative. The LVDA also wants to know if there is a sudden load reduction in CCT1 and CCT2. The answer is that they both have a 100 percent change of load. The LVDA also asks the user whether there are lightning strike reports at 16.00 hours. The answer is positive. The x and y co-ordinates of the lightning point is 200 and 373. The LVDA takes this piece of information to calculate the distance between the lightning point and above suspected circuits. If the distance is less than 3 km, then there is possibility that the line has been damaged. In this case, the distance between lightning point and CCT2 is 500m, so it is highly possible that the lightning has damaged CCT2. In addition, telemetry messages show that the relay of circuit breaker has operated, but circuit breaker CB18 itself has not. In the end, the LVDA makes a hypothesis that circuit CCT2 may have been damaged by lightning strike and circuit breaker CB18 has maloperated and circuits CCT1 and CCT2 are off supply.

In this case, four more phone calls from post code PC2 and PC3 were received following the first one. As LVDA has already diagnosed the fault, the LVDA takes no further action.

Stage 3

GDA compares the local reports from HVDA, SDA and LVDA. Both of the SDA and the LVDA report possible local fault in its own region. In order to draw any conclusion, the GDA needs to identify whether there are any possible connections between them. In this case, the GDA tries to relate possible fault identified by the SDA to the malfunction and the fault reported by the LVDA. In the end, the GDA concludes that the actual fault is the one identified by the LVDA.

4 CONCLUSION AND FUTURE WORK

Experiments have shown that a multi-agent approach can serve as a good formalism for fault diagnosis of electricity distribution networks, and with a good potential for real-time application in terms of speed, reliability, robustness and costs. Moreover, the system's modular structure of autonomous agents makes it easily modified. As the network changes, new agents can be added in with minimum disruption to other agents.

At the present, the MAFS is restricted to diagnosing the faults on distribution networks only. In the next phase of the project, it will be extended to cover the problems of the transmission and distribution systems both. Power system instability is one major cause of power failure in transmission systems, which caused August 2003's massive blackout in the US (Edwards, 2003). In just one minute on a hot afternoon, power plants separated by hundreds of miles in the north-east of the US and in Canada were suddenly disconnected automatically from the vast power network that covers those countries. As power was restored over the next few days, investigators tried to understand what had happened. But to discover exactly how the problem could spread quickly and pinpoint its main cause seemed to be a difficult task. In a few minutes, the power failed in Cleveland, Ohio. Within the next 15 minutes, the lights went out in New York and across nine states in the US. It seems that developing an intelligent agent capable of analysis of oscillations in the network could provide an indication of problems well before the blackout.

5. ACKNOWLEDGEMENTS

This research work was set firmly in context by discussions with and visits to Western Power Distribution, a local power distributor. The authors wish to express their thanks to Mr. Neil Griffiths from Western Power Distribution, for his assistance in preparation of case studies presented in this paper.

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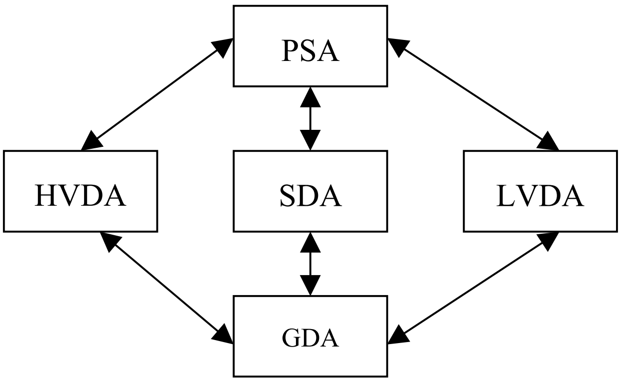

Figure 1

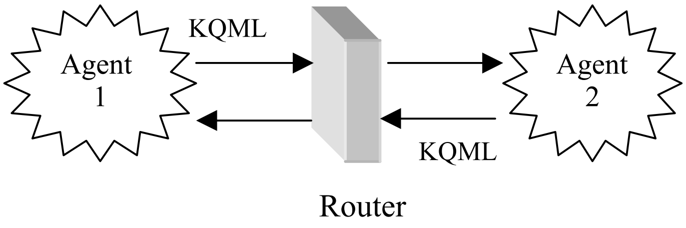

Figure 2

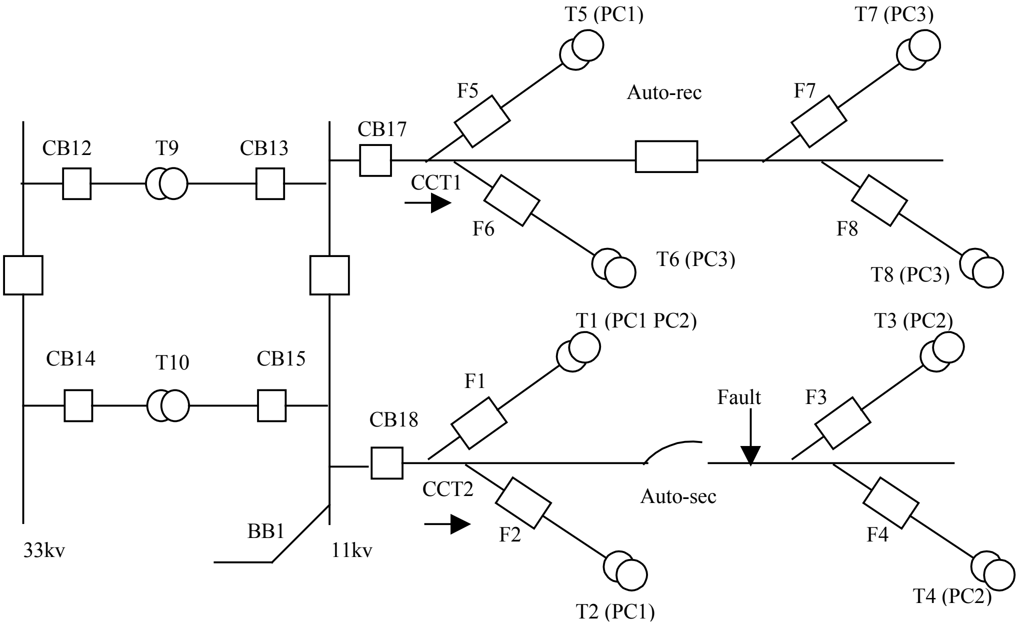

Figure 3