Improving Circuit Breaker Maintenance Management Tasks by Applying Mobile Agent Software Technology

M. Kezunovic, *Fellow, IEEE,* X. Xu, *Student Member, IEEE,* D. Wong, *Member, IEEE*

***Abstract*--Circuit breakers are crucial components for power system operation. The currently adapted time-directed maintenance strategy and the emerging new condition-based strategy require a flexible information processing technique and software architecture. In this paper, mobile agent software has been applied in implementing circuit breaker maintenance and repair tasks. Several potential application scenarios have been described and the relevant software features have been discussed. The benefits of using the mobile agent techniques are discussed at the end.**

Index Terms-- **Circuit breaker, maintenance, monitoring, mobile agent, power systems, substations, distributed processing**

I. Introduction

CIRCUIT breakers play a crucial role in switching for the reasons of both the routine network operation and protection of other devices in power systems. To ensure circuit breakers are in healthy condition, periodical inspection and preventive maintenance are typically performed. The maintenance schedules and routines usually follow the recommendation of circuit breaker vendors, although the recommended schedules may be conservative.

New maintenance techniques and methodologies are emerging, while the circuit breakers keep improving in their designs and functions [1][2][3]. As an example, some new circuit breakers have embedded monitoring instruments available to measure the coil current profiles and the operation timing [4]. The recorded information can be used to monitor the condition of breakers during each operation. In this case, it may be more appropriate to replace the time-directed maintenance by condition-directed maintenance practice [5]. When applied properly, both the size of the maintenance crew and maintenance cost may be reduced greatly with this approach. Since the number of circuit breakers in a power system is usually very big, a small maintenance cost saving per each circuit breaker can accumulate to a considerable benefit for the whole system. A more systematic solution is Reliability Centered Maintenance (RCM)[6][7], which can be used to select the most appropriate maintenance strategy.

During the maintenance or repair work, the maintenance crew will need to access information distributed across the utility and stored using different data formats. By equipping the crew with new information access methods to replace the old paper-based information exchange and logging method, the efficiency may be improved since less time will be spent on preparation, reporting and logging. An information access method that is capable of handling heterogeneous information sources will be helpful to achieve the above goal. Also, the new information access method should be secure and able to work on unreliable public networks.

The mobile agent software provides a flexible framework for mobile agent applications [8][9]. An agent application program can travel through the internet/intranet to the computers where the mobile agent server or transporter is running. The mobile agent software also supports Distributed Events, Agent Collaboration and Service Bridge. Compared with client server systems, an agent can process the data locally and thus reduce the network traffic. Besides, the Java platform encapsulates the network layer from the agent, which makes the programming easier. The mobile agent software may fit very well in the circuit breaker maintenance scenario.

In this paper, we considered how mobile agent software might be applied in circuit breaker maintenance and monitoring from the viewpoint of the maintenance crew. Section II discusses several problems in circuit breaker maintenance, followed by Section III where a brief introduction to the mobile agent software is given. Several application scenarios implemented with the mobile agent platform are discussed in Section IV. Conclusions are given at the end.

II. Circuit Breaker Maintenance Tasks

The circuit breakers consist of the interrupter assembly (contacts, arc interrupters and arc chutes), operating mechanism, operation rod, control panel, sealing system, and breaking medium (SF6, oil, vacuum and air). To ensure the performance of a circuit breaker, all the components should be kept in good condition, therefore time-directed preventive maintenance has been widely adopted. The preventive maintenance tasks include periodic inspection, test, and replacement of worn or defective components and lubrication

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M. Kezunovic is with Texas A&M University, College Station, TX 77843
X. Xu is with Texas A&M University, College Station, TX 77843
D. Wong is with Mitsubishi Electric Research Laboratories, MA 02139

of the mechanical parts. The maintenance intervals are usually determined using experiences or following the recommended schedules provided by the vendor or standard [10].

The maintenance practices can be divided into three categories: corrective maintenance, preventive maintenance, and predictive maintenance [6]. The different strategies are summarized in Table I. Each maintenance strategy has its own advantages and disadvantages, and thus most suitable application scenarios. A systematic solution is to utilize the Reliability Centered Maintenance (RCM) methodology. It performs analysis of the failure modes and the cause-effect impacts on the devices as it tries to find which strategy is the most cost-effective and appropriate for an application. The result of utilizing the RCM techniques and tools will be an optimal maintenance schedule for a specific application scenario.

TABLE I
MAINTENANCE STRATEGIES

Strategy	Description
Run-to-failure maintenance (Corrective, repair only)	The repair and restoration of equipment or components that have failed or are malfunctioning and are not performing their intended function
Time-directed maintenance (Preventive)	The periodic and planned maintenance actions taken to maintain a piece of equipment within the expected operating condition. It extends the equipment life and is performed prior to equipment failure to prevent it. This includes technical specification surveillance, in-service inspection, and other regulatory forms of preventive maintenance
Condition-directed maintenance (Predictive)	The continuous or periodic monitoring and diagnosis in order to forecast component degradation so that as-needed planned maintenance can be performed prior to equipment failure. Not all equipment conditions and failure modes can be monitored; therefore, predictive maintenance must be selectively applied.

The location of the information needed to perform maintenance can be the enterprise maintenance system, the substation data concentrators and the maintenance crew's computer.

The information about the spare parts, test procedures, historical maintenance records, and instruction manuals, etc. is typically accessible in the enterprise maintenance system. Also, the enterprise maintenance will usually utilize a RCM or conventional maintenance scheduling system to generate work orders. The work orders indicate when and where to perform what kind of maintenance on what devices.

The information about the substations equipment may be retrieved from the substation computers or concentrators. With the introduction of continuous monitoring of circuit breakers, the real-time data becomes available for accessing in the substation concentrators. The continuous monitoring instrument may measure the coil current profiles and switching timing during the normal operation. The condition of a circuit breaker can be assessed using some signal processing and artificial intelligence techniques. In this way, the time-directed preventive maintenance may be replaced by condition-directed predictive maintenance. The real-time data in the substation concentrators is also a useful complement to the historical information stored in the enterprise maintenance system. The data may be utilized to automatically update or populate the enterprise maintenance database.

The maintenance crew may have the inspection or test report stored on a mobile computer. Also, the crew may need to update the status of the work order stored on the computer as well.

Since the maintenance information is distributed among different systems, a software technique that has the flexibility of interfacing with multiple heterogeneous information systems is desired. The software should have the following characteristics to meet the maintenance information exchange requirements:

- Security support (encrypted data transmission, user authentication and authorization)
- Efficient network bandwidth usage
- Robust and fault-tolerant communication over unreliable environment and portable personal communication devices
- Ability to integrate with heterogeneous systems
- Automatic software update to ease the user burden

III. MOBILE AGENT SOFTWARE

There are different definitions of what is a software agent. We define an agent as a proactive software component, which is capable of acting reasonably to accomplish tasks on behalf of the user. An agent should be autonomous and have sound intelligence. A good software agent should be able to adapt to the changing environment; it may also be helpful to have the ability to exchange knowledge with other agents. Agent-based programming offers greater flexibility and adaptability than component-based programming [11]. Compared with object-oriented software engineering, agent-oriented software engineering uses a set of high-level, flexible abstractions to represent systems. Agents communicate with each other by passing messages or by synchronization. Depending on their functions, we can classify agents into several categories: personal agents, mobile agents, collaborative agents, etc. [11].

Mobile agents are small software entities that can travel around the network, performing their functions on behalf of users [8][9]. As the next generation middleware infrastructure for developing distributed applications, it meets all the requirements mentioned above. Since the mobile agents travel to the locations of the data sources and process the data locally, the network bandwidth consumption has been minimized. The built-in support for security, event notification, and agent collaboration can greatly improve the programming efficiency.

As shown in Fig. 1, the mobile agents can travel to devices that have mobile agent servers or lightweight transporters running. The mobile agent server can run on any platform where the Java runtime environment is available, and the devices without Java Virtual Machine (JVM) are supported through a communication node. The communication node can use any proprietary protocol to talk with the mobile devices.

As long as the communication node has the mobile agent server running and exposes the communication functions to the agent through some programming interface, the agent can communicate with the mobile devices. Since the Java environment cannot cover the whole range of devices, the mobile agents need to know the programming interface in order to communicate with certain mobile devices.

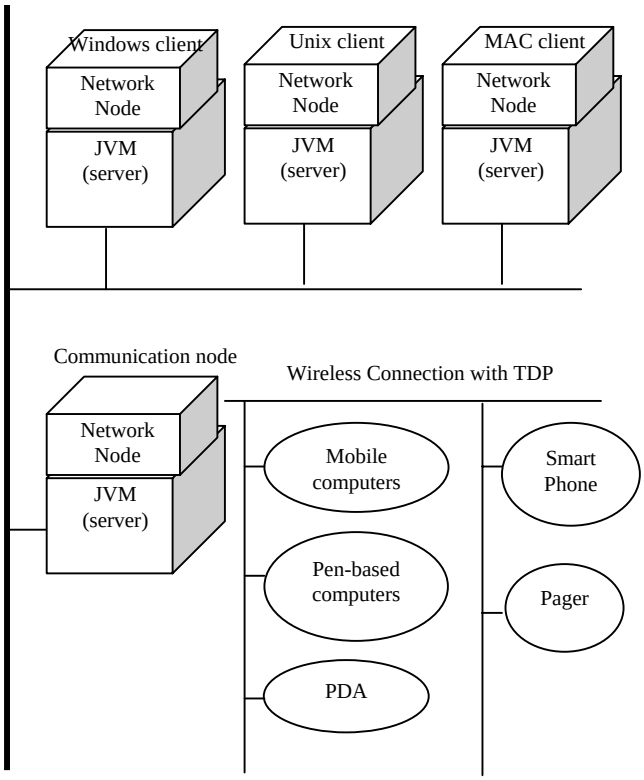

Fig. 1. A typical network setup of a mobile agent system

Since the mobile agent software is built on Java platform, other functions supported by Java platform are also available for the mobile agents. Among them, the Java Database Connectivity (JDBC) interface to access database, the Remote Method Invocation (RMI) for distributed objects, and the Extensible Markup Language (XML) support are most notable.

IV. Application Scenarios

To reflect the distributed characteristic of the data sources, three computers are used to represent the enterprise maintenance system, the substation concentrator and the maintenance crew respectively as shown in Fig. 2.

The enterprise maintenance system may contain the maintenance history database, the RCM system, warehouse inventory system, and other information. The substation concentrator is in charge of collecting data from the sensors installed on the circuit breakers. Some analysis software will be running and a status report describing the circuit breaker operation can be generated. The maintenance crew uses a mobile computer to access the information and prepares report utilizing software mobile agents. The number of possible application scenarios is great. Only a few of them are given here to illustrate the benefits of utilizing the mobile agent software in the circuit breaker maintenance practice.

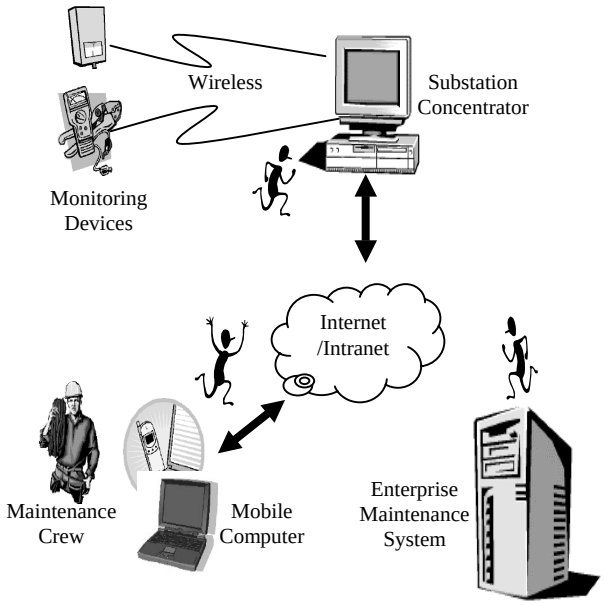

Fig. 2. Application scenario

A. Information Storage and Retrieval

The mobile agent can help storing and retrieving all the information needed to perform maintenance or repair work.

Mobile agent software supports accessing the data saved into heterogeneous systems. The information related to maintenance may be saved at heterogeneous databases and files. The heterogeneity may be reflected platform wise (differences in protocol, differences in format), concept wise (differences in schema and vocabulary, relative incompleteness), or both. Also, an information source may use a slow network connection, which means great network delays. And a source may only be operating part-time. Mobile agent software provides a framework to work in heterogeneous environments. At first, the Java platform is highly portable, which makes the mobile agent server run on a plethora of platforms. Java also has standard Application Programming Interface (API) to access data source in relational database and Extensible Markup Language (XML) files. Second, the mobile agent server will save the status of mobile agents, therefore providing reliable transmits on slow or part-time connected networks.

Agents can do sophisticated search and improve efficiency and scalability. The mobile agents travel to the location where the data is stored to do the processing and return with the final results only. In this way, the bandwidth consumption is minimized. Also, the mobile agents have abilities beyond using only the SQL or XML API. It can utilize some heuristic knowledge to do more complicated search. What an agent can do is limited by its intelligence. For example, in a database table, a field is named “phone” instead of “telephone”. When an agent tries to search a field named “telephone”, it will fail. But if the agent knows the relationship between “phone” and “telephone” and it finds the “phone” field from the database

metadata, it will try to use the “phone” field. Of course, the semantic may be different, but it is better to return some results to the user rather than just reporting “nothing found”.

Agents can help to make the location and format of the information transparent to users. In general, to utilize an information source, the users are required to know the types and location of the information. “Intelligent” agents should be able to comprehend the user’s requirement and automatically find the appropriate information and services. In a simple implementation, every agent has a knowledge base about the location of certain information and format, so the crew no longer needs to remember those trivial things. He/she can ask the agent to actually do something instead of how to do something. The knowledge about the information locations can be acquired via a central agency or mutual knowledge exchange among agents. Currently, we store all the information about locations at a centralized place and the agent can populate its location knowledge base at first. After that, the agent could use its own knowledge base to retrieve the information. When the location or format of an information source is changed, the central database will be updated. The agent will fail when it uses its own old copy of the knowledge base. In that case, the agent will consult the central agency again to update its knowledge base.

B. Creating Circuit Breaker Failure Reports

No maintenance activities can ensure no failure will happen. When a circuit breaker failure does happen, some immediate action and follow-up investigation are required [12]. As an example, to file an IEEE Std-1325 compliant power circuit breaker failure report, the user needs to collect the circuit breaker information (manufacturer, type, voltage, etc.), the operating environment data, the description of the trouble, the effect of the failure, the single line substation diagram, the operation and timing sequence, line condition, oscillogram, etc. To gather all the information and compile a report may be time consuming and error prone, since the information may be distributed among different data sources and in versatile formats. Therefore an automated method is preferred.

A mobile agent makes an itinerary according to its knowledge about the location of information sources and will travel to each source and collect the information. The agent may also choose to delegate tasks to a bunch of second level agents and edit the last returned result from other agents. The second method may be faster when there are many sources for the software agent to visit. The interface to create a failure report is shown in Fig. 3. The software agent that helps the user to create the report will create and send out additional mobile agents to the distributed information sources for collecting the data. The collaboration mechanism provided by the mobile agent software has been utilized to exchange information among agents. The agent may also utilize some heuristic rules to help determine the possible causes of the failure.

The generated report is in Extensible Markup Language (XML) format and contains only the necessary information about the failure report [13]. After giving the corresponding Extensible Stylesheet Language (XSL) style sheets to define the appearance, the reports of different formats (e.g. HTML or PDF) can be automatically generated using XSL Transformation (XSLT) tools from a single data set. Using XML to represent the report separates the content from the presentation, which makes the data more accessible and exchangeable. In fact, XML has been selected as the proposed standard to exchange real-time system information among control centers [14]. By saving only the content, the storage space is also optimized.

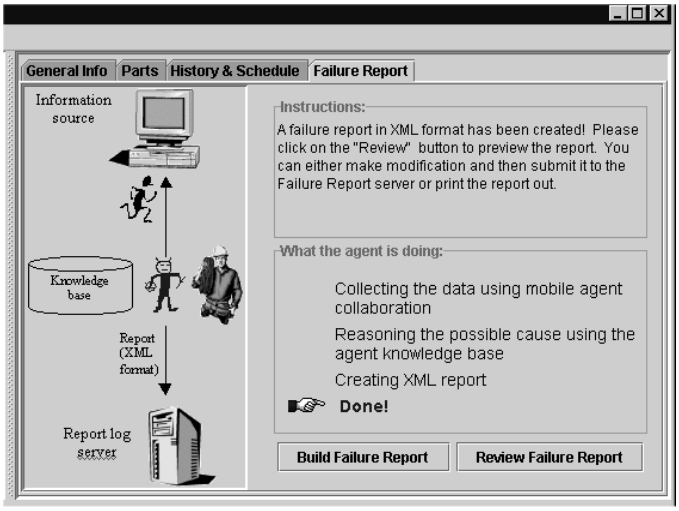

Fig. 3. Creating failure report

C. Circuit breaker monitoring

The distributed event mechanism is helpful in monitoring the status and events of circuit breakers. As shown in Fig. 4, the user can select the event of interest to monitor. Once the monitoring starts, the selected events will be registered with the mobile agent server running on the corresponding substation concentrator. The concentrator can get the real-time information about the circuit breakers by communicating with sensors, and it can notify the user when the selected type of event happens.

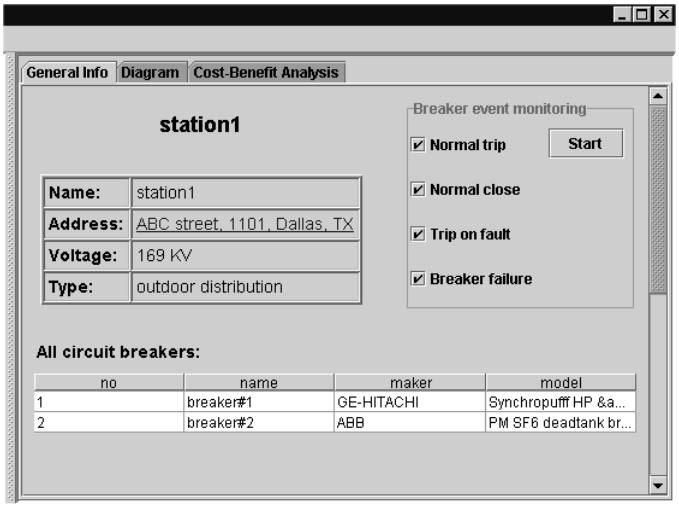

Fig. 4. Circuit breaker monitoring

D. Security Consideration

Two apparent security problems arise when applying mobile agents. First, the mobile agents need to be authenticated and authorized at the servers. Second, to ensure the integrity of the data, it must be transmitted in secure communication channels.

Every mobile agent must be authenticated at first to identify whom it represents. *SecureAgent* supports user authentication by using the username/password pairs. Once identified, mobile agents can be checked against the security policy to see whether they are authorized to do certain things at a server. The Administrator tool, shown in Figure 5, provides a user-friendly interface for the server security and service management.

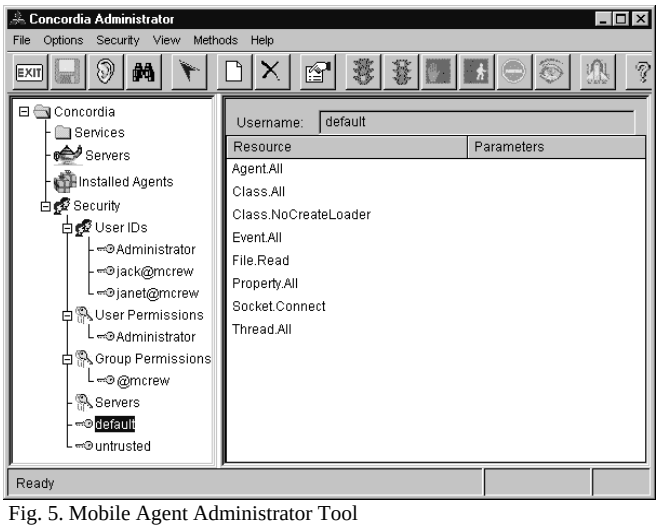

Fig. 5. Mobile Agent Administrator Tool

The mobile agent server can control agent's access to resources depending on both the user identification and server permits. A user can be created for each maintenance crew. Alternatively, a maintenance crew group can be used to represent all the crews. In Figure 5, a *mcrew* group has been created, which has two members: *jack* and *janet*. The *mcrew* group has the permissions to access maintenance-related services.

The user interface to assign different types of permissions to users or groups is shown in Figure 6. The permissions are divided into different groups for agent, class, event, file, etc. For example, the permission in the agent group decides if an agent with the user/group's identity can arrive or be launched to/from this server. The file group permission determines whether a user or group can access the local files.

Secure communication channels among the mobile agent servers may become important, especially when the data passes through the public network or wireless channels. The mobile agent software provides options to encrypt the data when it is in transit, and thus prevents others tampering with the data. A digital envelope will be used to protect *Sealed Agents* when travelling.

All the above security measures are supported by the mobile agent software directly and thus greatly simplify the programming work. There are some other security-related features provided. As an example, the mobile agents can work with firewalls, which is important when accessing the company Intranet from the outside public Internet is needed.

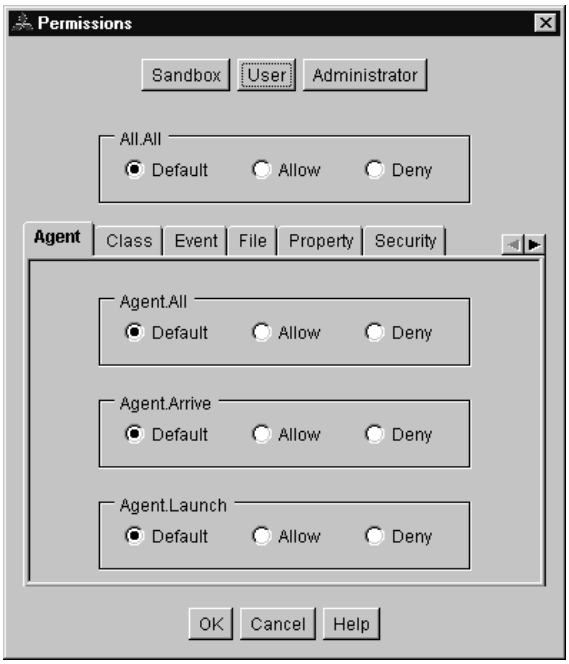

Fig. 6. Set user permissions

E. Logging and Experience Sharing

Software agents may help in logging and sharing maintenance experience. In the maintenance and repairing industry, experiences are often extremely important. Having an effective way to accumulate and distribute the experiences will help avoiding common mistakes and improving work efficiency. Currently, most of the experiences are still passed and shared by word of mouth, therefore some good experiences may be lost with years and personnel changes. The quality of this kind of experience sharing depends on the willingness of the people to share experience and their expression abilities. It is also difficult to search a solution for a given problem, since it is hard to know who has the corresponding experience. Agents may help in recording the maintenance process and converting it into some standard format (e.g. XML with standardized schema). The recorded experience can be saved in a case-based reasoning system for future retrieving.

F. Cost-benefit analysis

Agents can assist users in performing some standard analysis. For example, to determine whether in-service monitoring of a circuit breaker is satisfied, a cost-benefit analysis based on the risks and investment return may be processed automatically. In [5], a decision making sequence has been recommended, which consists of three stages. Some historical data will help the user to give a more appropriate score for assessing each failure mode.

G. Other

Some other applications of agent technique have been proposed. For example, agents can improve the usability of

some software by providing a friendly user interface with ability of speech recognition and synthesis.

V. Summary Of the Implementation Benefits

Utilizing mobile agent techniques, the convenience and speed of accessing and generating maintenance data will be improved. With increasing complexity of circuit breaker equipment, more information is needed to perform the maintenance work, so an efficient data communication exchange becomes very important. Mobile agents can process information locally with less network bandwidth consumption. Also its ability to provide reliable transmission on disconnected or low quality networks is an important merit.

Mobile agent computing easily facilitates the integration and automation of the maintenance process, starting from the generation of work orders to the completion of the maintenance report. The entire process may involve multiple entities and steps. Thus, an automated procedure is highly desirable. With the ability to collaborate and update agent itineraries adaptively, the mobile agent software provides an ideal framework for modeling and supporting the maintenance workflow.

Furthermore, mobile agent computing also provides the means by which real-time and off-line data can easily be integrated into a single distributed maintenance management system. Using real-time monitoring data, the maintenance system can evaluate the condition of devices, which makes predictive maintenance possible. The integration of real-time data may be utilized to improve the maintenance management decisions. The platform independence feature of mobile agents provides interface and support for great variety of devices.

VI. Conclusions

In this paper, mobile agent software has been applied in circuit breaker maintenance. Several representative application scenarios have been described. Mobile agent software may be suitable for applying in circuit breaker maintenance practice due to its support for heterogeneous systems, security, distributed events, low-bandwidth usage, etc. Using the mobile agent software, the development work can be greatly simplified. Also, agent-based software architecture makes the application more flexible and upgradable.

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VIII. Biographies

Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. Degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. Dr. Kezunovic's industrial experience is with Westinghouse Electric Corporation in the USA, and the Energoinvest Company in Sarajevo. He also worked at the University of Sarajevo. He was a Visiting Associate Professor at Washington State University in 1986-1987. He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of IEEE.

Xiangjun Xu (S'99) received his B.E and M.E. degrees from Southeast University and Shanghai Jiaotong University, all in electrical engineering, in 1992 and 1995 respectively. After that, he worked as a teacher/researcher in Shanghai Jiaotong University. Since Sep. 1998, he has been with Texas A&M University pursuing his Ph.D. degree. His research interests are computer application on power systems, signal processing, artificial intelligence, fault analysis.

David Wong (M'92) is an expert in mobile agent technology and the primary evangelist for Mitsubishi's mobile agents initiative. His background also includes substantial work in transactional message queuing systems and distributed transaction processing. Prior to joining MERL in 1994, David worked on the advanced development and performance analysis of transaction processing systems at Compaq. He has also taught and conducted research at Brown University and the University of Connecticut. David holds a B.S. degree in chemical engineering from Brown University and a Ph.D. degree in computer science from the University of Connecticut.