Studies on Multi-Agent Based Partial Discharge Online Monitoring System for High Voltage Apparatus

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Abstract: In the contribution, the authors applied the Multi-Agent methodology to the partial discharge (PD) online diagnosis for high voltage apparatus, and a PD diagnosis Multi-Agent system for high voltage apparaus was implemented. Based on the investigation of problems existing in partial discharge detection and evaluation, such as preprocessing, features extraction, trend and fingerprint analysis, corresponding methods and schemes were described. The framework of the Multi-Agent system and detailed design of each agent were also depicted. And furthermore, a complete system implemented by Zeus are established for performing evaluation in field application.

Key-Words: High voltage, Partial discharge, Multi-Agent, Monitoring, .Net Framework, Zeus

1 Introduction

Partial discharge occurring in insualtion system of high voltage apparatus is not only a symptom of deterioration in its insulation but also a cause of its further deterioration. Therefore online monitoring system for partial discharge plays a significant role in condition monitoring for high voltage apparatus. Features extracted from the partial discharge signals can determine the level and type of partial discharge pulses and proper diagnosis can be made for the precaution of latent failure. However, problems still exist in both aspects of signal processing and system framework establishment. Due to the difficulties in the capturing and preprocessing of PD signals, making meaningful interpretation for the detected results is still a devilish problem to solve. As condition monitoring requires different measurements to make accurate decision, the framework of the system must be more flexible to integrate comprehensive monitoring means which can be easily installed or updated as required [1].

One solution to developing diagnosis system utilizes Multi-Agent technique [2]. In recent years, Multi-Agent becomes a hotspot in the research field of artificial intelligence. Multi-Agent can permit developers to extend components to construct various types of agents with different capabilities and patterns of interaction. Compared with other frameworks, Multi-Agent is flexible in structure and extensible in function [3]. Moreover, this architecture meets the current demand of auto diagnosis and conditional monitoring and has a board future in field application.

This paper puts forward an online partial discharge monitoring system based on Multi-Agent architecture designed for high voltage appartus and introduces the advantages in data interpretation and framework extensibility.

2 Research approach of Multi-Agent methodology

Traditional ways of designing methodology do not fit the Multi-Agent paradigm. The methodology should be indenpendent of a particular multiagent system architecture, agent architecture, programming language or message-passing system. During the last few years, great progress has made in both fields of Multi Agents design methodology (MaSE, GAIA, OAA) and development toolkit (JADE, JAFMAS, Zeus).

MaSE follows the steps of capturing goals, applying use cases, refining roles, creating agent classes, constructing conversations, assembling agent classes and system design[4].

GAIA methodology divides the designing into the following steps: collection of requirements, analysis, architectural design, detailed design and implementation, which and design of multiagent systems. GAIA also provides clear guidelines for the analysis and design of complex and open software systems[5].

OAA presents the mechanisms including: approach to cooperate between agents, facilitators to coordinate the satification of goals, facilities for sharing data, which facilities the use of cooperate task completion[6].

JADE is a software development framework fully implemented in the Java language, which offers to developer a number of features: distributed agent platform, FIPA-compliant agent platform, Efficient transport of agent commnunication language(ACL) messages[7].

JAFMAS (Java-based Agent Framework for Multi-Agent Systems) primarily focus on providing communication and message exchanging support for agent system developers in the form of conversation. By conversation, agents exchange messages, change state and perform local actions[8].

Zeus defines a Multi-Agent system design approach and supports it with a visual environment for capturing user specification of agents that are used to generate Java source code of agents[9].

In this paper, authors achieved the Multi-Agent architecture under the environment of Zeus.

3 Function design of PD monitoring system

Before the implemention of Multi-Agent system, detailed function desgin must be performed as carefully as possible. The design of Multi-Agent architecture ususlly follows the general operations as listed:

3.1 Requirements analysis

Firstly, the system should be well designed for PD signals preprocessing. It is difficult to recognize normal PD signals from significant noises and interferences in the field application. So the system must be capable of eliminating these noises autonomously before feature extraction.

Secondly, interpretation of the diagnosis must be meaningful for the operators. As the relationship between the data and condition of the apparatus is not always well understood, technology of artificial intelligence is required.

Thirdly, in order to achieve an accurate conclusion, various sources of data should be centralized to process. The system in the essay is able to integrate various monitoring technologies such as electrical loading and acoustic detection.

Finally, with the development of monitoring technologies, how to integrate these new technologies into the system in operation easily must be considered.

Considering issues above, a monitoring system must achieve these functions:

1) Autonomously data capturing and processing
2) Ability for interpretation and fault diagnosis
3) Corroboration by weighing and balancing different source of data
4) Flexibility and extensibility for new technologies.

The last point mentioned above decides the running life of the system, which offers an easily plug and play way to the new detecting technologies. Designed according to this rule, modules of the system is able to run in independency and achieve the final objective through mutual interaction.

3.2 Task decomposition

Process of partial discharge diagnosis usually contains four stages: Preprocessing, Feature extraction, Interpretation and Corroboration, as shown in Fig.1.

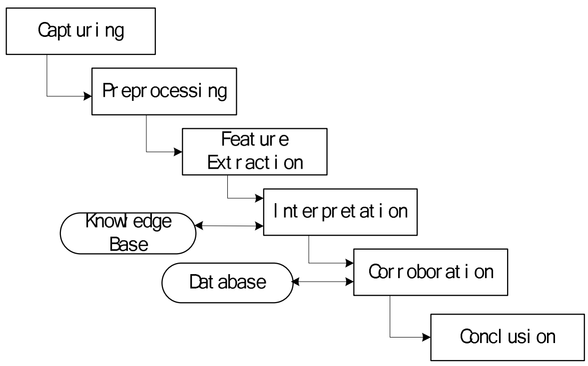

Fig.1 Flow chart of PD diagnosis

Establishment of knowledge base is also critical to decompose tasks properly. Abundant knowledge of apparatus's insulation is essential to diagnosis. Knowledge mainly comes from:

1) International and national standard;
2) Operating rules and instructions from State Grid;
3) Consultations and experiences from experts;
4) Scientific literature.

Based on these knowledge and experience, each stage is transferred to some specified tasks and sub-tasks to simplify the implementation in computer. As shown in Fig.2, the root task Diagnosis is divided into several sub tasks.

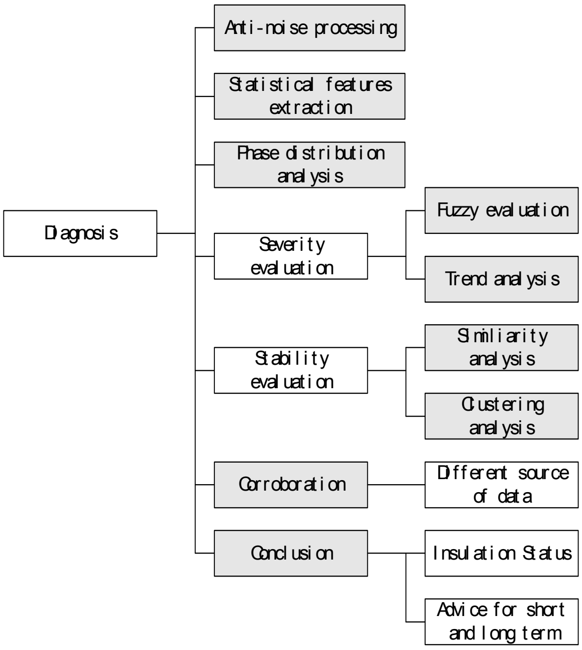

Fig.2 Task hierarchy and agents in Multi-Agent System

Agents are designed to fulfill these tasks. And these agents are grouped by their function to six layers: device layer, preprocessing layer, feature extraction layer, interpretation layer, Corroboration layer and information layer (Fig.3).

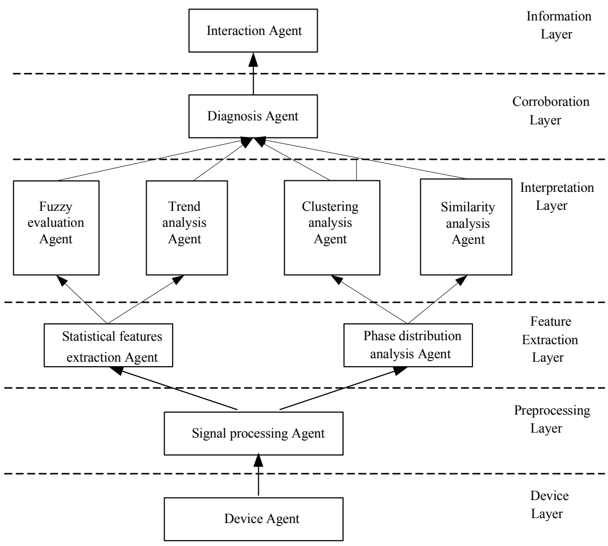

Fig.3 Multi-Agent system for monitoring PD

3.3 Design of individual layers

3.3.1 Device Layer

The device layer obtains data from sensors and instruments installed on or nearby the high voltage apparatus. The acquired data includes PD signal and field environment. PD signal is acquired by coupling capacitor, coil transformer or acoustic sensor, while the field environment can be described by temperature and humidity. Usually, devices installed onsite is unattended, so the system should have reliable self test mechanisms to ensure its operating steadily.

The scheme of device layer implemented by the authors is described as Fig.4.

The analog signals obtained by the high frequency current transducer (HFCT) are processed by the band pass filter and transmit to the program controlled amplifying circuit. Then the amplified analog signals are digitalized and sampled and digitally filtered by DSP[10]. The processed signals are finally transferred to the subordinate computer through HPI for the further analysis.

The subordinate computer(Fig.5) realized by embedded system is aimed to be compact, fast and extendable. The authors selected the ARM920T embedded processor as hardware core and Windows CE.NET operating system as software base. The system is composed of controlling module for coordinating data acquisition with DSP, communication module for data transferring with supervisory computer, database module for temporary features storage and watchdog module for system status guarding.

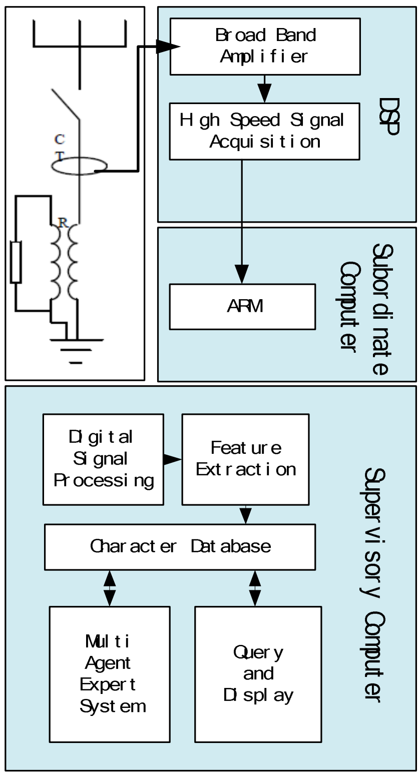

Fig.4 Scheme of online system for monitoring PD in high voltage apparatus

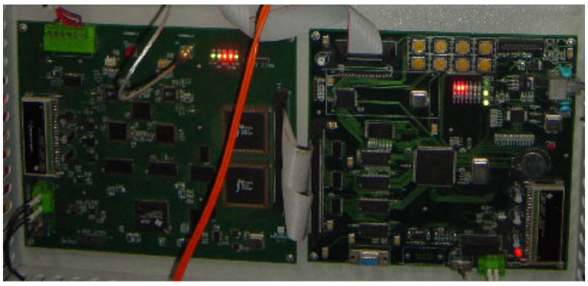

Fig.5 Pictures of DSP and ARM control unit board

The supervisory computer is operated on the hardware of IBM Xeon Server with a fast processor and a large amount data storage and on the software of Windows Server operating system with .NET Framework and SqlServer. The multi agent software environment are mostly based on it.

3.3.2 Preprocessing Layer

The preprocessing layer is mainly used to eliminate the noise in the original acquired data. The pulse of PD is of short duration in time domain and embedded large quantities of high frequency noise components, and the wave transmited through the winding, distorted to reflection and resonance.

The source of the noise is listed as below[11]:

1) The power system's noise through the apparatus outlets, which may excited by the internal discharge of other equipments in power system, such as discharge of the busbar, switching of the breaker and so on.

2) The high frequency noise such as coupling by capacitor and inductor form the generator's rotator DC excitaion. These noise may originated by the thyristor of excitation system.

3) The external noise from the environment out side, such as broadcasting interference of AM radio and high frequency signals from mobile phone.

4) The noise in diagnosis system itself, such as noise of circuit or switch power supply.

Noises and interferences in the field application can be divided into three types: white noise, discrete spectral interference, impulse interference. These noises vary so much in both time domain and frequency domain that they cannot be eliminated simply by a single method. Therefore, different measures should be taken in order to eliminating different kind of noises. At present, the wavelet [12] and multi-wavelet [13] filtering technology are widely regarded as the most effective method in white-noise elimination. Fast Fourier Transformation(FFT) filtering [14] and adaptive filtering [15] offers an ideal result in discrete spectral interference elimination. Neutral network filtering [16,17,18] is hopefully effective to random impulses.

The authors select Bandpass Filter, FFT Filter, Wavelet Filter, Neural Network Filter to eliminate the noise. As shown in Fig.6, signals captured by devices are filtered by means above to restrict disturbances to the further stage.

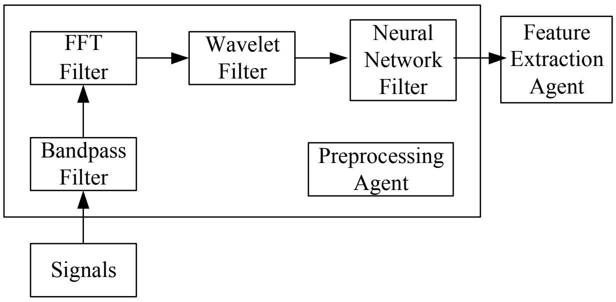

Fig.6 procedure of agents in preprocessing layer

1) Bandpass Filtering:

FIR (Finite impulse response) algorithm is an effective method for bandpass filtering which can be carried out by DSP. With Embedded MATLAB toolbox supplied with MATLAB environment, DSP C code can be generated automatically. In our realization, authors design a 300 order filter with bandwidth from 500K to 10M Hz. Its magnitude and phase response are shown in Fig. 7

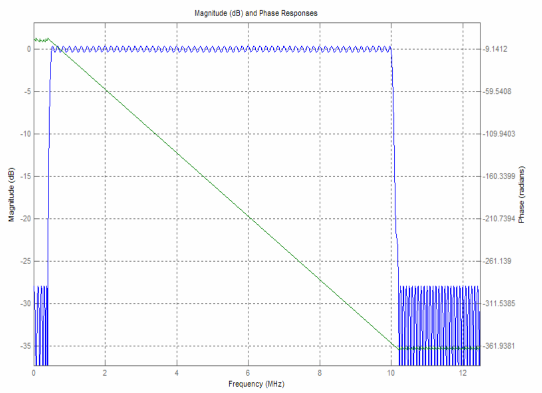

Fig.7 The magnitude and phase response of designed filter

2) FFT Filtering:

Discrete spectral interference maybe another type of noise carried by captured signals, which mainly come from radio broadcasting in the field application.

FFT filtering converts the signals in time domain into frequency domain firstly. And it searches the discrete spectral components above threshold calculated adaptively and cuts off them with certain algorithm. Finally, inverted FFT are applied to reconstruct the signals in domain.

Before the system is installed, it is recommended to collect the background signals to estimate the frequencies of discrete spectral interference.

3) Wavelet Filtering

White noise such as thermal noise or shot noise from amplifier, sampling circuit and ambient surroundings, for its broad spectral bandwidth, cannot be elimated by the traditional filtering based on frequency domain analysis. In recent study, wavelet and multi-wavelet filtering methodology are proved to be an effective way to supress the white noise, which can process partial discharge waveforms in varous mode by means of preserving more partial discharge pulse features when denosing.

The procedure of wavelet filtering in this thesis involes four steps, decomposition, calulating threshold, modifiying the detail coefficients and reconstruction.

The authors select db8 wavelet and the threshold described as equation(1)[19].

$$\lambda_j = m_j / 0.675 \cdot \sqrt{2 \cdot \log(n_j)} \tag{1}$$

λ_j is the threshold at level j, m_j is the median value of the coefficients at level j, and n_j is the length of coefficients at level j.

4) Neural Network Filtering

The principle of denoising by Neural Network Filtering is based on the recognition of both partial discharge pulse waveforms and interference waveforms, which are picked up from the field application. However, neural network algorithm usually has a disadvantage of low convergence and easily sticking in the local minimum. So in order to avoid this, Particle Swarm Optimization algorithm is adopted in our implementation[20].

By means of filtering mentioned above, the signal-noise ratio of partial discharge signals can be improved obviously. The comparisons both in time domain and frequency domain between the raw data and the filtered data are shown as Fig.8 and Fig.9. The raw data is captured from field application with kinds of serious interferences. From the view of time domain (as Fig.8), some pulses with large amplitude are recognized as random noises and eliminated by the methodology of Neural Network Filtering. Meanwhile, from the view of frequency domain(as Fig.9), discrete spectral interferences like single pulses above 10uV are constrained. Signals must be preprocessed before being transmitted to subsequence layer in the field application.

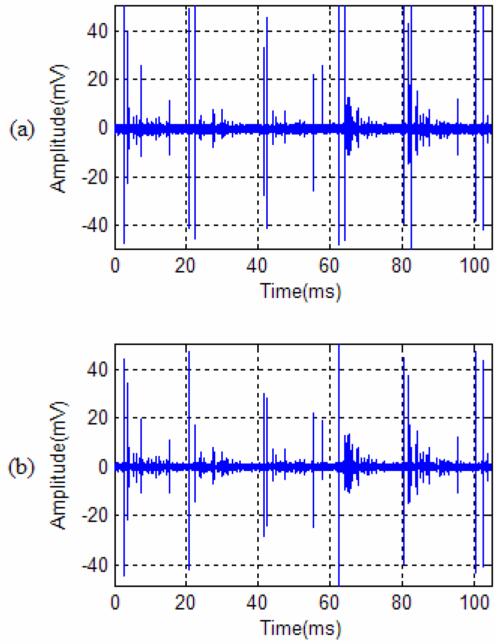

Fig.8 (a) is raw signal and (b) is filtered signal from field application in time domain.

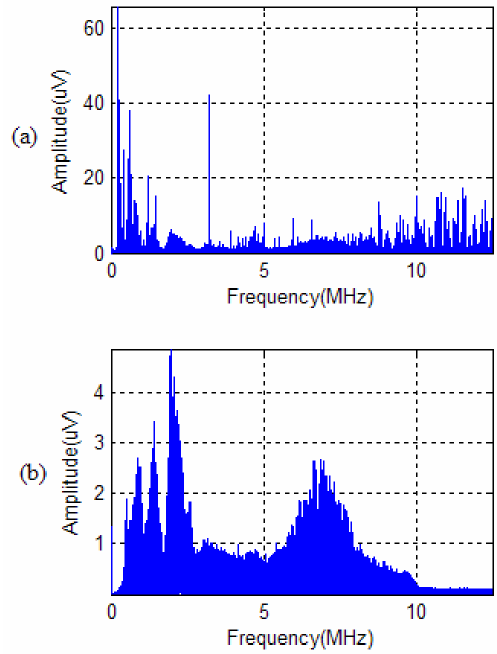

Fig.9 (a) is raw signal and (b) is filtered signal from field application in frequency domain.

3.3.3 Feature Extraction Layer

The feature extraction layer is mainly used to extract the features of detected PD signals. The features of PD signals can be divided into statistic features and phase-based features. The statistic features are extracted from the signals in the time domain directly while the phase-based features are acquired from the signals in the phase domain. The system in the essay extracted 10 statistic features, they are:

1) voltage level of discrete spectral signals
2) threshold for extracting pulses
3) maximum discharge magnitude
4) mean discharge magnitude
5) maximum magnitude regardless of maximum 5% of discharge
6) average level regardless of maximum 5% of discharge
7) average discharge current
8) quadratic rate
9) number of discharges
10) mean number of discharges.

And another 26 statistical fingerprint features extracted by the system. Totally 78 features are extracted after twice phase shift (with 120 degree and 240 degree separately), which are as same as those detected by PD Detector TE571[21].Therefore, two discrete agent modules are configured in this layer, one for statistic features extracting and the other for fingerprint features extracting, as shown in Fig. 3.

3.3.4 Interpretation Layer

The interpretation layer is used to transfer abstract PD features to meaningful information.

The interpretation of the PD signals is a complex problem which requires the combination of the expertise of power equipments and different kinds of intelligent diagnosis techniques. The past research shows that at present, it is impossible to accomplish the automatic PD diagnosis by a unitary method. Different techniques are required to establish a mixed diagnosing system and the main advantage of the Multi-agent structure is to support different interpretation. The statistical features are usually used to describe the trend of the partial discharge, evaluate the severity of the partial discharge while phase-based features are regarded as the fingerprint in identifying the type of partial discharge. In the essay, the fingerprint features of partial discharge are used in correlation analysis and clustering analysis so as to deducing the stability of the type of the partial discharge. The interpretation of PD signal in the essay is realized by four agents, which are Fuzzy evaluation agent, trend analysis agent, similarity analysis agent, clustering analysis agent.

3.3.5 Corroboration Layer

The corroboration layer is used to integrate the results in different interpretation layer and achieve an overall conclusion.

This layer utilizes the confidence to determine the overall confidence and diagnosis result. Furthermore, it will integrate the results obtained by other monitoring technologies and evaluate the diagnosing results to judge whether it is the problem of the equipment or the monitoring system. Informations like device temperature, environment humidity and electrical loading are also of great referential value.

The layer is configured with one diagnosing agent. As seen in Fig. 3, the data will be sent to the analysis system by the data monitor. Then, each interpretation will send the obtained results to the corroboration agent. At last, the corroboration agent will achieve the final conclusion with its own knowledge and other information it can get. Because the existence of this specific interpretation layer, by easily adding agent module and reconfiguring the corroboration agent module, we can adopt the most advanced technology as soon as possible and updates the current technology in use.

3.3.6 Information Layer

The information layer is mainly used to interact with the corresponding operators and provide useful information about the system. Moreover, the operator can change the operating mechanism through this layer. In the essay, the interaction layer provides the final diagnosing conclusion and corresponding maintaining suggestion to the corresponding operators. The diagnosing conclusion includes four grades as Table 1, which are normal, attention-needed, alarming and severe. The conclusion should also contain relevant confidence factors which identifies the reliability of the conclusion. The bigger the factor is, the more reliable the result is. The information layer only contains an assistant engineering agent as shown in Fig.3. The information layer also plays an important role the extensibility of the system. The system can be applied to monitor multiple equipments by the suitable adjustment of overall Multi-Agent structure.

Grade	Interpretation
Normal	The apparatus is in good insulation
Attention-needed	Regular inspection is needed.
Alarming	PD is quite active. The apparatus needs to be monitored, or retested by other means soon.
Serve	The apparatus must be tested offline as soon as possible.

Table 1 Diagnosis conclusions

4 Development Environments and Realization

For keep correspondence with the Windows CE.NET operation system installed on the subordiante computer, the whole Multi-Agent monitoring system is developed on the operating system of Windows Server 2003 with the support of SQL Server, MATLAB and other accessorial applications.

4.1 Introduction to Zeus framework

Zeus is a Multi-Agent framework for developers to fulfill a appliation rapidly. The core principle for agents to cooperate is demonstrated as Fig.10.

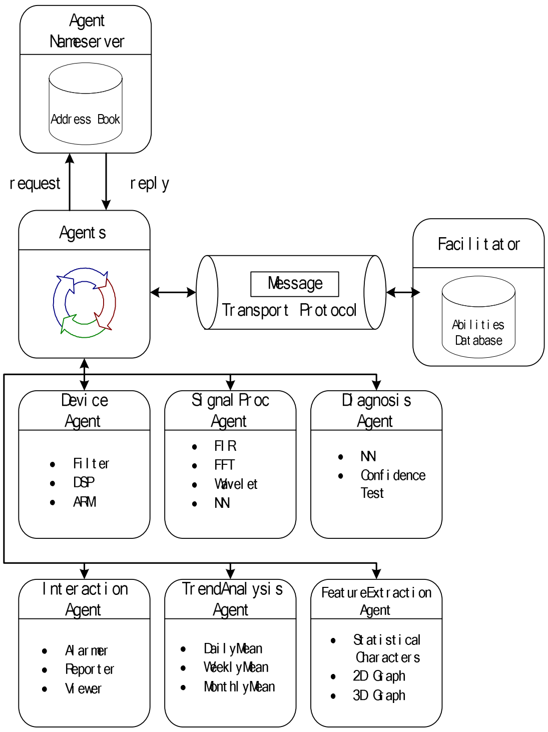

Fig.10 Diagram of co-operation between agents in Zeus

of and features facilities to implement Multi-Agents architecture. The diagram is shown in Fig.10. The central agents perform a complex task of collabrating with other agents. To do so it uses Faciliator to discover the agents with the required abilities, and Agent Name Server to determine the addresses of these agents. The inter-agent communication language is used to communicate with the Agent Name Server, Facilitator and other agents. The communication requires a shared representation and understanding of common domain ontology.

The phases for developers to apply Zeus desgin approach to create a working application usually include: Domain Study to identify potential agents and create an ontology of the concepts in the domain, Agent Definition (Fig.11) to identify the significant attributes of the agent, Agent Organisation (Fig. 12) to identify the acquaintances of each agent, Agent Co-ordination to identify co-ordination protocols, Task Definition to define the task in terms of their preconditions, effects, cost, duration, and constraints, Code Generation to automatically generate source code implementations for each agent, Code Compilation to make the final execuable program[22].

The whole Zeus framework and its generation code must be complied and executed under the Java Virtual Machine(JVM) for better transplatable.

Fig.11 Agent Definition to define the attributes for agents

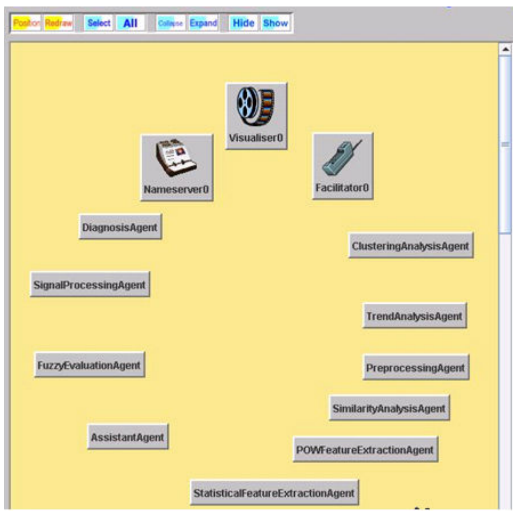

Fig.12 Agents Organisation realized in Zeus for the monitoring system

4.2 Realization under the .NET Framework

The tasks that agent defined are actually fulfilled by external programs coded under the .NET Framework, and Zeus multi-agent expert toolkit as its communication platform, thus improving its performance on data capacity and knowledge learning ability which leads to higher accuracy of the detection results compared to traditional partial discharge monitoring system.

The communication between Java based Zeus agent and .NET framework based external program are through TCP/IP protocol for better compatible and transplantable.

4. 3 Matlab interface for .NET Framework

There are three ways that Matlab coding script can be assemblied into program based on .NET Framework[23]:

1) MATLAB Engine. In this way, program can invoke all facilities supported by MATLAB, including evaluating and printing commands. While program is running, a background MATLAB environment starts to exchange command and data. So, MATLAB environment must be completely installed on the target computer and the program cannot be distributed without limits.

2) .NET Interface is an extension to MATLAB Complier. Programmers can access them from any CLS(Common Language Specification). Compared with COM Interface, it is provided a constraint of strong type check which can avoid errors while developing.

3) COM (Component Object Model) Interface, which is an alternative way to access facilities of MATLAB. COM is an early version of software architecture for encapsulating objects designed by Microsoft Corporation. It cooperates well with programs complied by VB, VC.

COM and .NET Interface have advantages of fast execuation and compact installation. The MATLAB code is completely complied to binary code for speeding the execuation. Additionally, it can be executed under the minimal installation of MATLAB with some dynamic link libraries (DLLs).

The authors implement the combination in the MATLAB Engine way. Without being supported by .NET Framework directly, it must be encapsulated the MATLAB Engine to C++ Compiled Dynamic link library and invoked under the System.Complier.InteropServices namespace.

4.4 Storage and Database Design

The raw data received from suborinate computer is packed with an additive header describing acquisition information and is to separate folders named by acquisited time for conveniently retrieving. The raw data is usually too large that compression of Zip technique is taken to reduce the size of storage.

The extracted features and diagnostic results are imported to database for further query and analysis. The scheme of database relationship is shown as Fig.13. The data table DailyMean is the mean value of features for one day while the data table WeeklyMean and MonthlyMean are mean value of 7 days and 30 days, which indicates slow varying trend of features. For convience, the authors design a stored procedure for calculating the mean value of characters automatically while inserting and deleting records in database. The history of serious result are stored into Alarm table for operators to review.

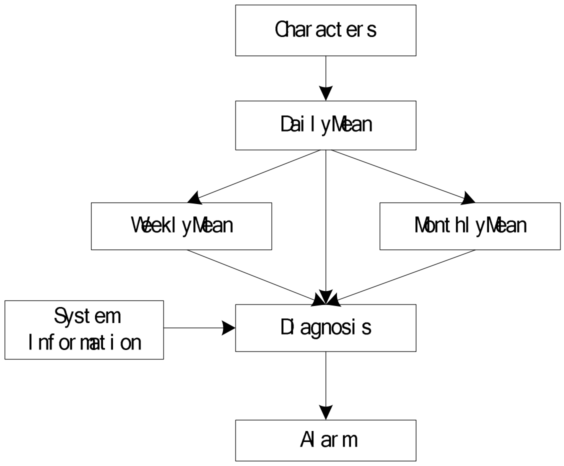

Fig.13 Scheme of diagnosis database tables.

5 Field Application

The system designed for generator has been installed in one power plant of Hebei Province, China since 2005. It has been proved effective in helping the operators to identify the type of PD, thus confirm the type of the electrical fault. The analysis of the PD trend refers to the trend of the aging process in the insulation layer, as shown in Fig.14 and Fig.15. Through these results, we can see that the trend of the feature extracted from the signals are smooth and steady. Though partial discharges occurs at times, the quantity and amplitude are too small to cause serious falut. Finally the diagnosis agent can draw a conclusion that the insulation of the generator is in good condition and give a evaluation of Normal grade[24].

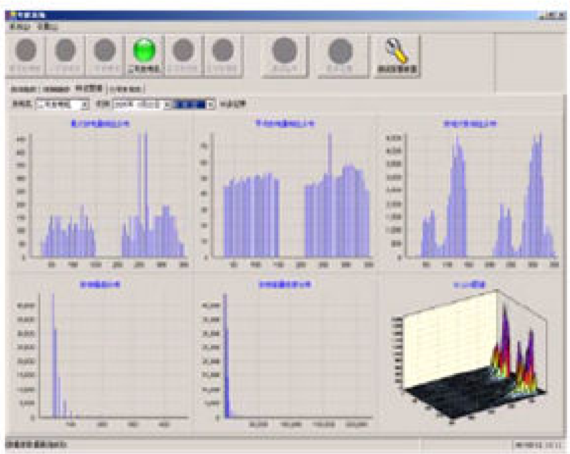

Fig.14 Results from phase distribution agent

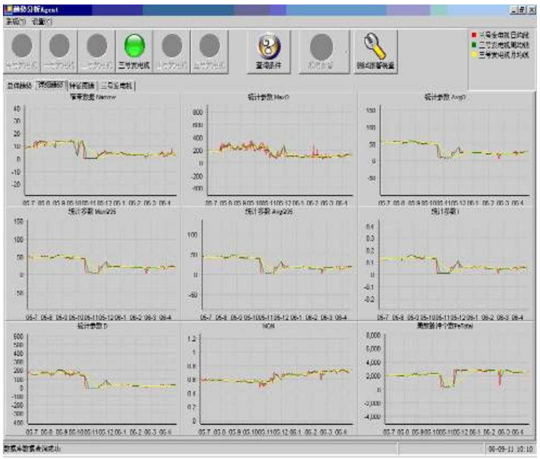

Fig.15 Results from trend analysis agent

6 Conclusion

The essay introduces a kind of online partial discharge monitoring system based on the Multi-Agent technology. Compared with other PD monitoring system, the system in the essay obsesses the following features:

1. Distributed Calculation. The system can deal with large amount of sampled data concurrently through the narrow-band communication channel.

2. Autonomy. Agents cooperate with each other in the background without human's intervention.

3. Flexible Structure and Easy Maintenance. All the agent modules in the system can be assembled and updated independently to ensure the application of the most advanced technology.

4. Reliable and fault tolerance. Due to the incompact architecture of agents, system can function properly within limits.

The onsite application of the system and the results of signal analysis shows that the design and implementation of the system meets the actual requirement. The conclusion of the multi agent system demonstrates that the system can deliver a reliable monitoring result and provide corresponding maintaining suggestion.

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