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Multiagents-based wide area protection with best-effort adaptive strategy

Zhu Yongli [a,*], Song Shaoqun [b], Wang Dewen [a]

[a] North China Electric Power University, Baoding, China
[b] Fuzhou Electric Power Industry Bureau, Fujian Province, China

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ABSTRACT

Abstract—Multi-trips of circuit breakers often occur within a short period in a severe blackout, and the tripping usually relates to relays' mal-operations. In fact, when two ore more electric primary devices are isolated by circuit breakers, the settings of most relays to protect their power system are getting infeasible and uncoordinated. Adaptive settings are needed to prevent them from wrong operation. This paper presents an adaptive protection scheme based on wide area information with best-effort protection strategy, and the outline of multiagents and WAN Based Adaptive Protection System (MAWAPS). In the scheme, the best-effort adaptive strategy is used to guarantee the adaptive settings to operate safely and effectively in most situations. The IP/SDH-based wide area network (WAN) is used to realize real-time wide area information exchange in the proposed protection scheme. Adaptive setting algorithms for the second stage zero-sequence current and phase overcurrent relays are proposed, which can provide larger line coverage than traditional relays. Moreover, multiagent techniques and IEC 61850 are employed to realize the fast communication between different agents, and MMS plays a prominent role in real-time remote communication. A simulating system has been developed according to the above ideas and approaches, and the experimental results show that the proposed adaptive protection scheme is feasible from the view of protective performance including the executing time.

1. Introduction

In a traditional protection scheme, a relay is usually given just one operative setting to respond to faults in its protected primary device under all conditions of its power system, which can hardly meet the relay's requirements on selectivity, speed, sensitivity and reliability. Therefore, the adaptive protection was proposed in 1980s, and one of its important meanings is to adjust relative relays' settings to promptly respond to any change of the operating conditions of their power system [1,2]. Research results shows that adaptive distance protection can effectively extend the protecting range of zone II distance relays [3], so it can reduce the trip probability of zone III distance relays. Therefore, the adaptive protection is contributable to reduce the blackout area and improve the speed to isolate faults in its protected power system. Researchers on power system security have realized the importance of the adaptive protection or other special protection system in preventing a power system from a large-scale blackout [4,5].

Due to lacking of adequately reliable, affordable and fast communication infrastructure, much previous research on power system relaying was relating to the protection of a single primary device, and the relaying scheme had to be based on the local operating information of the system. With the advance of the technology of communication and wide area computer networks [6], it is feasible to integrate wide area information into the protection of the whole system [7]. However, only very few protection schemes of such kind have been proposed so far [8]. Although many problems [9] are needed to be solved to realize the adaptive protection, the adaptive strategy based on the wide area information, speedy data communication between relays, the information processing and fast computation of relay settings in the dispatching center are the most important and urgent things at present. The fast communication depends largely on communication physical links, data coding and decoding approaches. Here we should point out that the popular Web technology and its relative http protocol cannot be used in the adaptive protection because data are transmitted in text format and unreliable communication manner by Web. Fortunately, manufacturing message specification (MMS) has been established for fast digital exchange in process control and other manufacturing industry for about two decades, and its coding and decoding is efficient by using binary system. Due to this advantage, IEC 61850 maps its data and services to MMS for transmission. Many unified object-oriented information models and communication services are defined in IEC 61850, which is helpful to realize the interoperability of the intelligent electronic devices (IEDs) from different manufacturers. Furthermore, dedicated

* Corresponding author. Tel.: +86 312 7525251; fax: +86 312 7525255.
E-mail addresses: yonglipw@heinfo.net (Y. Zhu), sqsong1979@hotmail.com (S. Song).

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optical fiber SDH (Synchronous Digital Hierarchy) networks have already been built in most power transmission systems in China, and each of them can link all IEDs or their proxy computers in substations with a host computer in their dispatching center in a rapid and reliable way.

A multiagent system (MAS) can make the wide area protection system intelligent and to be realized and maintained separately and easily. Each substation IED can be an agent, and the information stored in one agent can be shared by other agents. Some contributable attempts have been made to improve the performance of relays in a power system through MASs [10,11], but they are limited to the protection of single primary devices. Because the MAS techniques and real-time wide area communication are complicated and still in researching stage, it is a challenging work to develop the proposed Multi-Agents and WAN based Adaptive Protection System (MAWAPS).

2. IP/SDH-based WAN for adaptive protection

As shown in Fig. 1, the proposed IP/SDH-based wide area network (WAN) for adaptive protection of a power system imitates the configuration of the Internet. Although a router is a commonly used device to link the Ethernet interface with the E1 interface of the SDH, it takes longer time delay to forward data. Also, many routers make the computer network complicated in its management. Therefore, in the proposed scheme, IEDs in substations are connected with the EMS computers through rather bridges (Ethernet /E1 converters) than routers and bridges. In fact, the WAN structure in Fig. 1 can be used for not only adaptive protection, but also tele-control in a power system. The advantages of connecting IEDs directly into the IP/SDH WAN are: (1) only digital communication is used in the whole process, and the modulating and demodulating processes are removed; and (2) IP/SDH is a looped circuit, so its communication reliability is much higher than that of a traditional tele-control system.

As the data throughput of an optical backbone SDH network reaches 622 Mbps or more, the accessing data throughput of an optical terminal can be 100 Mbps at present. Because the amount of real-time data to transmit in a substation is small, the time for the data being transmitted to the dispatching center is less than 0.01 s (s) in most cases [12]. Even though there are sharp state changes at several substations after an event occurs in the system, the total time for a EMS computer in the dispatching center to acquire sharply varied data of its power system could be smaller than 0.2 s.

The networked adaptive protection mainly depends on the real-time status of all breakers in the protected power system, and the operating time difference between a main relay and its backup relay is about 0.5 s. Therefore, if the total time of receiving the status changing message plus calculating and issuing the new settings is within 0.5 s, adaptation is feasible for backup relays. In fact, the time interval of one breaker's trip after another is larger than 0.5 s in most cases, so the adaptive protection is usually workable for primary relays. However, sometimes the interval may be too small for a computer to finish the calculation of the adaptive settings of primary relays, or the communication network is congested, in this situation, the traditional relay settings should be used. Therefore, a best-effort adaptive strategy for power system protection is proposed in this paper.

3. Construction of MAS-based adaptive protection

3.1. Brief introduction on MAS

A multiagent system (MAS) is applicable for solving on-line distributing problems in a computer network [13]. In a MAS, many intelligent agents interact with each other, and can cooperate to reach their mutual goal or to solve their own problems via exchanging their own information and knowledge. MAS researchers have developed communications languages, interaction protocols, and agent architectures that facilitate the development of MASs. Because an agent not only has reasoning ability like an expert system, but also possesses very fast responding ability to events around its environment, it is feasible to apply MAS theory to the adaptive wide area protection system, which may reduce the occurring probability of chain trips of breakers in its protected power system.

3.2. Structure of MAWAPS

According to the structural and geographical feature of a power system, the proposed MAWAPS is constructed as Fig. 2.

The task and definition of agents in MAWAPS are listed in Table 1.

3.3. The advantages of MAS for adaptive protection

During the computation of adaptive relay settings, many factors such as the connection scheme and status of electrical primary devices, and the speed and selectivity of relay operation must be taken into account. It is impossible to set up only a numerical algorithm to determine the settings of all relays in a power system and take the above factors into account. Therefore, intelligent inference based on relating knowledge and experience must be used. One of available and tentative methods is to build an expert system. However, an expert system has some defects such as poor responsibility to the dynamic environment, difficult realization and hard maintainability because the proposed system and its knowledge base are too large.

A MAS is composed of several separated and intelligent agents that are smaller programs and easier to be built and maintained, and each agent can respond to its environment changes in an adaptive speed. Furthermore, an agent can exchange knowledge and information with other agents to improve its problem solving abil-

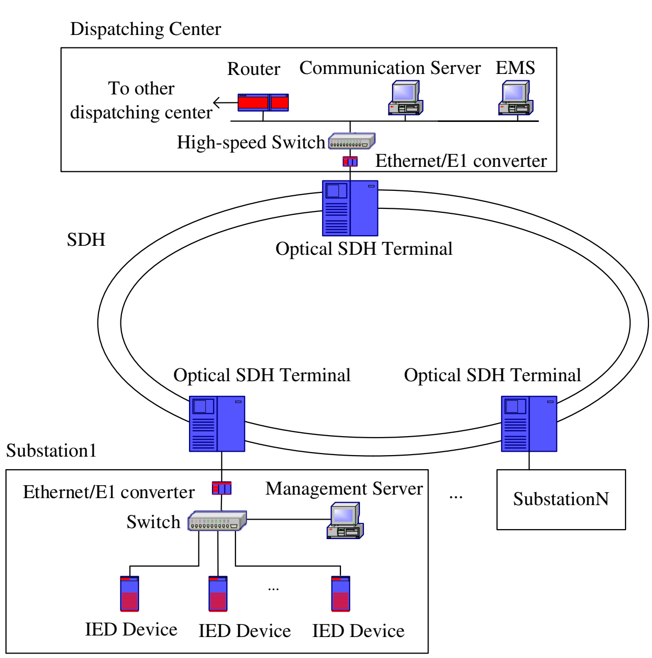

Fig. 1. IP/SDH-based WAN for adaptive protection of a power system.

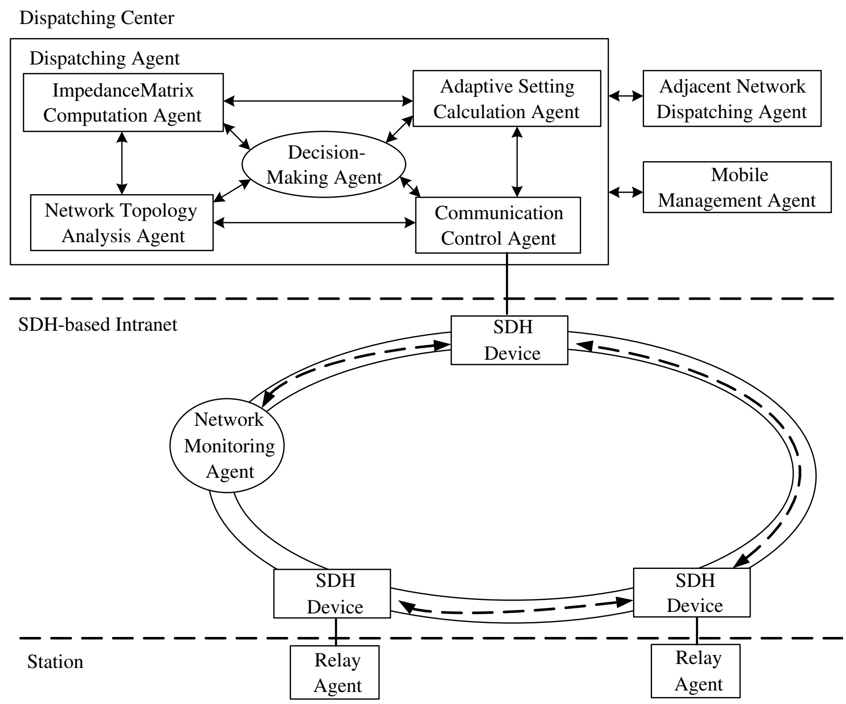

Fig. 2. The structure of the proposed MAWAPS.

Table 1
The task assignment of agents in MAWAPS.

Agent name	Agent task
Communication control agent	Use communication thread pool to handle communication messages according to their priorities. A resource-reserved method is used to guarantee important messages to be handed in time
Network topology analysis agent	Use graph theory and AI searching techniques to analyze and update the network topology when a switching-event is detected
Impedance matrix computation agent	Modify network impedance matrix by parallel computing according to updated network topology, and send its equivalent matrix to the impedance matrix computation agents of adjacent networks
Adaptive setting calculation agent	Calculate adaptive settings by parallel computing according to the updated network impedance matrix
Relay agent	Send real-time data of IED and Compare sensing data with a relay's setting, and decide to act or not
Mobile management agent	Manage the mobile agents in the system, and maintain their communication
Network monitoring agent	Monitor the status of the communication network and evaluate its present loading capacity

ity. Although building a MAS is more difficult than developing an expert system of the same size at present, the development is getting easier as more and more MAS tools are available in the business market. Therefore, the task of determining adaptive relay settings can be decomposed and performed by the agents represented in Fig. 2. Because each agent can only store the closely relative knowledge to its task, the knowledge base is small and the knowledge matching is faster. In this way the problem solving performance of the whole system can be improved, and the selectivity and sensitivity of relays can be coordinated by the negotiation of relative relay agents. Moreover, because the interrelation between the agents is incompact, the whole system can be easily built and upgraded.

3.4. Communication mechanism

IEDs or their proxy computer in a substation, and the EMS computer in the dispatching center are usually produced by different manufacturers, and run under different operating systems, so the communication between a Relay Agent and the Dispatching Agent is a challenging problem. KQML primitives based on XML can be used to solve the problem. However, there are a large number of additional descriptive symbols to represent a little piece of communicative information in a XML document, so this communication method is inefficient. Fortunately, MMS is an efficient and widely used real-time data exchange protocol between two computers for industrial process monitoring and control. The basic and commonly used communicative primitives between two agents in KQML are 'ask' and 'tell', while there are corresponding 'read' and 'write' operations in MMS. In fact, MMS has many other kinds of communicative services, such as Get Name List, to obtain a group of objects containing monitoring data from a remote terminal or a server. Moreover, the data are transmitted in efficient binary codes rather than in the text mode of XML-based KQML by MMS. Furthermore, the popular IEC 61850 for data communication in a substation network is based on MMS, and it uses several directory services to retrieve some data from a server conveniently. Therefore, MMS is a more suitable means for real-time data communication in the proposed MAWAPS.

4. Best-effort adaptive protection strategy

The proper action of a relay is prominent to the security of its power system. A fault might occur when MAWAPS is computing the adaptive settings of the relays, in this situation post-fault adaptive relay settings cannot be used, while the traditional settings of the relays near the faulty point have to be used until new adaptive settings are calculated and distributed to relating relays. To solve this problem, MAWAPS adopts a reliable control strategy called 'best-effort adaptive strategy with permission check'. The strategy works as follows.

After Dispatching Agent has detected a switching event in its power network through the proposed WAN or has received a changed equivalent impedance matrix of border nodes of a neighboring power network, it arouses Adaptive Setting Calculation Agent to compute new settings and tells all Relay Agents to stop using existing adaptive settings. Meanwhile, Network Topology Analysis Agent traces the network topology change rapidly [14]. Then Impedance Matrix Computation Agent modifies the node impedance matrix and the equivalent border node impedance matrix of its power network by parallel computing and sends the latter matrix to the Dispatching Agents of its adjacent power networks [15]. Next short circuit currents can be easily calculated based on the node impedance matrix and the equivalent matrices of the neighboring networks. Determining relay settings needs to calculate the functional dependency set (FDS) of each relay, the minimum break point set (MBPS) and the relative sequence matrix (RSM) of a looped power system [16]. Although the above initial computations need much computing time, their subsequent calculations can be based on the initial ones and could be very fast. After a new switching event, Adaptive Setting Calculation Agent needs only to modify the FDS of the relays that have primary/backup relationship with the relays installed at the switching branch. Then the new MBPS and RSM can be determined. After the new settings have been calculated, Communication Control Agent distributes them to corresponding Relay Agents via the high-speed WAN. By means of parallel computing techniques, it is very possible for MAWAPS to control the total time of above computations within an acceptable range.

Because there is collaborative relation between primary relays and backup relays, the new adaptive settings must go into effect together after an event. To reach this objective, Dispatching Agent tells Communication Agent to broadcast the alarm signal of 'Adaptive Settings Being Invalid' to all Relay Agents as soon as Adaptive Setting Calculation Agent is aroused by a new event. After receiving the command, all Relay Agents automatically use their traditional settings instead of their adaptive settings. After Dispatching Agent finishes the calculating and distributing of the new adaptive settings of all relays, it broadcasts the signal of 'Adaptive Settings Being Valid' to all Relay Agents.

If Network Monitoring Agent finds out or forecasts that the communication network is congested, it sends an alarm signal to Decision-Making Agent. If Network Topology Analysis Agent, Impedance Matrix Computation Agent and Adaptive Setting Calculation Agent can't finish their tasks within reasonable time limit, they also send similar alarm signals to Decision-Making Agent. Once Decision-Making Agent receives these alarm signals, it broadcasts the command of giving up adaptive settings and using traditional ones to all the other Relay Agents. If a Relay Agent has not yet received new adaptive settings for a long time, it chooses the traditional settings and sends a corresponding signal to Dispatching Agent. If Dispatching Agent cannot receive the real-time data from a substation Relay Agents within a pre-given time, it broadcasts to all Relay Agents the command of giving up adaptive settings and sends an alarm to the operators of the dispatching center. Therefore the employment of adaptive settings is conditional and their use permissions must be checked before their being effective.

5. Adaptive multi-stage current line protection

5.1. Construction of networked adaptive current relays

The objective of the networked adaptive protection is to improve the operating performances of protective relays. Adaptive settings are only corresponding to the prevailing system condition, and many factors, such as line's being out of service, need not to be taken into account, so the protection coordination can be easily attained. Research results show that adaptive distance protection can effectively extend the protecting range of zone II relays [3]. Furthermore, the networked adaptive protection can greatly improve the operating selectivity of relating relays after an unpredicted multi-trip event in a power system, so it is helpful to avoid large-scale blackouts.

To effectively realize the adaptive protection proposed in Sections 3 and 4, it is necessary to find adaptive setting algorithms. Because adaptive setting algorithms for backup distance relays and instantaneous relays have been presented in paper [3,17], respectively, attention is paid only to adaptive setting algorithms for backup current relays in this paper. Moreover, the formula to calculate the adaptive setting of the first stage current relay is similar to the one to compute its traditional setting, except the reliable coefficient in the latter could be a little bit smaller than that in the former. Therefore, only adaptive algorithms for backup current line relays are discussed below.

5.2. Adaptive setting algorithms for backup line current relays

The network shown in Fig. 3 is used to illustrate the proposed adaptive algorithms for backup current line relays.

Let's consider the adaptive settings of the second stage zero-sequence current relays installed at 1BR first. The zero-sequence current relay of the second stage is used to safeguard its whole protected line and part of downward neighboring lines, and should never go beyond the protection range of the first stage relay of any downward neighboring line. Therefore, the adaptive setting of the zero-sequence current relay of the second stage at 1BR in Fig. 3 can be determined by the following formula:

$$I''_{dz.A.0} = 3\left\{I^{(1)}_{A.B.0} - K''_{K.AD}\left(I^{(1)}_{A.Bi.0.\max}\right)\right\} \tag{1}$$

$I^{(1)}_{A.B.0}$ – zero-sequence current sensed by this relay when a single-phase earth fault occurs at B; $K''_{K.AD}$ – reliable coefficient, which could be a little bit larger than that in traditional setting formula, is set to be 95%; $I^{(1)}_{A.Bi.0.\max}$ – the maximum zero-sequence current sensed by this relay when a single-phase earth fault occurs at the tail end of the protection range of the first stage relay at the initial end of each downward neighboring line. For example, the zero-sequence current flowing through 1BR may be this wanted value when a fault appears at protection tail end of the first stage relay at 3BR in Fig. 3. In this formula, $I^{(1)}_{A.Bi.0.\max}$ is used to guarantee the protection range of this relay does not exceed the range of the first stage relay of any downward neighboring line.

Similarly, the adaptive setting of the second stage phase overcurrent relay at 1BR can be set as follows:

$$I''_{dz.A.CUR} = \left\{I^{(3)}_{A.B.} - K''_{K.AD}\left(I^{(3)}_{A.B} - I^{(3)}_{A.Bi.\max}\right)\right\} \tag{2}$$

$I^{(3)}_{A.B}$ – current sensed by this relay when a three-phase fault occurs at B; $I^{(3)}_{A.Bi.\max}$ – the maximum current sensed by this relay when a three-phase fault occurs at the tail end of the protection range of the first stage relay at the initial end of each downward neighboring line.

5.3. Testing of the proposed protective algorithm

To compare the protective performance of the proposed adaptive current protection against that of the traditional one, the depicted system in Fig. 3 is selected as the testing object. The parameters of the system is given in Table 2.

Let's do the comparison by using the relays that are installed at the 1BR of Line AB. When any kind of fault occurs at any line in

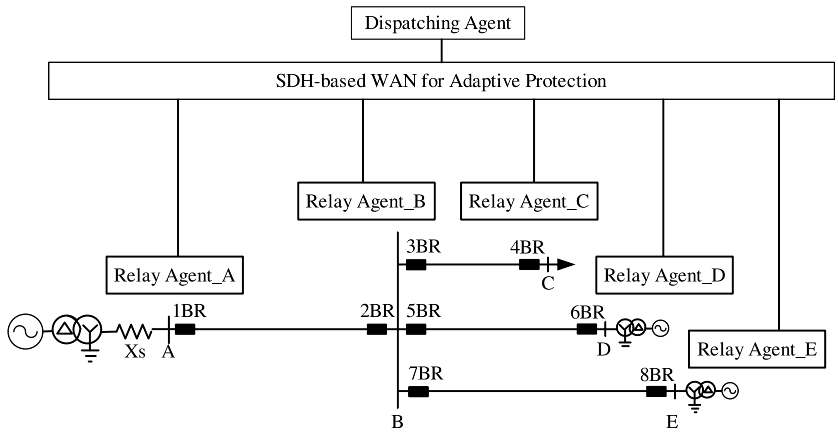

Fig. 3. The illustrative diagram for adaptive current relay setting.

Table 2
The parameters of illustrative system in Fig. 3.

Parameter	Positive sequence impedance (pu)	Zero sequence impedance (pu)
$X_{GA.min}$, $X_{GD.min}$, $X_{GE.min}$	0.052	0.067
$X_{GA.max}$, $X_{GD.max}$, $X_{GE.max}$	0.104	0.134
X_s	0.075	0.225
X_{ab}	0.058	0.175
X_{bc}	0.053	0.160
X_{bd}	0.072	0.215
X_{be}	0.092	0.275

Fig. 3, the smaller the positive sequence impedance between generator A and the fault point, the larger the short circuit positive/zero-sequence current flowing through 1BR. Therefore, with regard to both the zero-sequence current relay and the phase current relays at 1BR, the system is in the maximal operation mode when the impedances of the generators are $X_{GA\ min}$, $X_{GD.max}$ and $X_{GE.max}$, respectively, while the system is in the minimal operation mode when the impedances of the generators are $X_{GA\ max}$, $X_{GD.min}$ and $X_{GE.min}$, respectively. Network Topology Analysis agent shown in Fig. 2 is responsible for determining the current topology and operation manner according to the status of the output circuit breakers of generators in the system.

The traditional settings of a zero-sequence current relay and a phase overcurrent relay of the second stage at 1BR are calculated under the maximal operation mode, and their operating sensitivities are verified under the minimal operation mode. To compare the performance improvement of the adaptive current relays with the traditional ones, the protection ranges for the adjacent lines of Line AB by the above two relays under the above two operation modes are listed in Table 3.

Table 3
The protection ranges (%) for adjacent lines of AB.

Relay	Line	Maximal operation mode		Minimal operation mode	
		Traditional	Adaptive	Traditional	Adaptive
Zero-sequence current relay	BC	58.42	67.79	25.65	50.27
	BD	62.76	73.76	30.79	62.0
	BE	49.58	57.65	24.18	46.38
Phase overcurrent relay	BC	25.9	38.18	4.91	36.22
	BD	30.41	44.83	6.23	42.85
	BE	22.3	32.87	4.43	32.66

According to the results in Table 3, we know that the proposed adaptive current protection extends the protection range of the second stage current relays of the above two kinds obviously. In this way, the operating probability of the third stage current relays is reduced, which means that the blackout area can be lessened.

6. Simulation and testing of MAWAPS

6.1. System configuration for simulation of MAWAPS

Fig. 4 shows the hardware configuration to simulate the proposed MAWAPS. A PC cluster (6 Intel Pentium IV 2.40 Ghz PCs) is used to simulate the EMS system in the dispatching center of a power system. The cluster is integrated by Myrinet for parallel processing.

In the figure, Workstation 1 to Workstation N (Intel Pentium IV 1.70 Ghz PC) act as the proxy computers in Substation 1 to Substation N, respectively, and the adjacent network simulator (Intel Pentium IV 1.70 Ghz PC) serves as the EMS computer of an adjacent network. A 100M-Ethernet switch is used to connect the workstations and the simulator with the server of the PC cluster.

All software agents for simulating MAWAPS have been developed by the authors according to the hardware configuration in Fig. 4. In the figure, each workstation at a substation contains its corresponding Relay Agent; the server and the cluster of PCs in the dispatching center possess all software agents to determine adaptive relay settings of a power system.

To calculate adaptive relay settings of the simulated power system in time after a switching event, a parallel algorithm on node impedance matrix computation and modification, which is proposed by the authors in Reference [15], is adopted. When the node

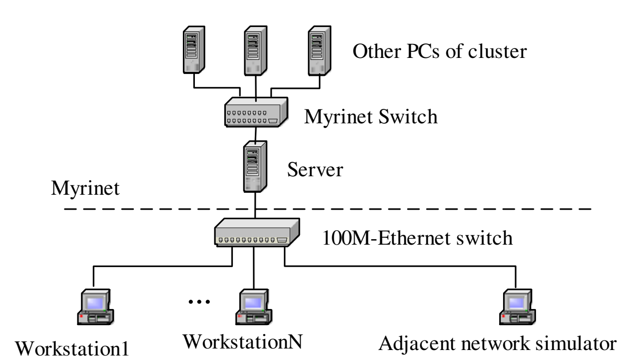

Fig. 4. The configuration of the simulating system of MAWAPS.

Table 4
Executing time of agents for computing adaptive settings (s).

Computing sequence	Network topology analysis	Node impedance matrix computation	Adaptive settings determination	Total time
First time	0.265	0.369	0.325	0.959
Subsequent time	0.079	0.153	0.128	0.360

impedance matrix of the power system is known, all short circuit currents need in formula (1) and (2) for adaptive relay settings can be easily calculated.

IEC 61850 is used in the information organization of each agent, and IEC 61850 and MMS are jointly used in the real-time message exchange between the above agents stored in different computers. The simulating system MAWAPS can be run continuously. Manual switching events, short circuit faults and their trip events in the simulated power system can be set through an one-line diagram on the computer screens. Fast modification of node impedance matrix of an interconnected power network is pivotal to realize the real-time adaptive relay setting.

6.2. Testing results of simulated MAWAPS

To test the feasibility of the proposed adaptive protection approaches, an actual provincial power network in China is used as the simulating object. There are 98 nodes, 286 relays, and 146 lines in the network. Among the lines, there are 15 groups of mutually coupled lines. The results show that the protective performance of almost all current relays except for some first stage relays of short lines has been improved by the proposed WAN-based adaptive protection method, and the increase in the protection range of the second stage current relays adaptive protection is similar to that in Table 3.

The running speed of the simulated MAWAPS has also been tested. Experimental results on the provincial power system mentioned above show that it needs 0.959 s to calculate its adaptive current line relays' settings at first time, while it needs only 0.36 s to compute them after a switching event, which could be either a normal operation or a fault-resultant trip, in the power system. Table 4 shows the detailed executing time of all main agents to compute the settings at first turn and a later turn responding to an event.

The results show that the relating agents of MAWAPS can rapidly compute the adaptive settings based on preceding results, and implementation of the proposed adaptive protection in a provincial power system is feasible according to the executing time. Furthermore, because much time is spent in data communication between different PCs under the above cluster environment [15], the total computing time may be less than 0.2 s if a cluster of parallel computers of memory shared symmetric multiprocessors (SMP) are employed. In this way, plus the time for an EMS computer in the dispatching center to acquire the topological changes in the relative substations, the backup relays can adaptively operate with about 0.4 s delay to respond to any kind of topological change event in the power system.

7. Conclusions

Chain trips of breakers in many large blackouts often relate relays' mal-operations. Adaptive protection is a means to prevent the relays from wrong operation. This paper presents an adaptive protection scheme based on a wide area network and MAS techniques with best-effort protection strategy. Adaptive setting algorithms for the second stage zero-sequence current and phase over-current relays are proposed, which can provide larger line coverage than traditional relays. Moreover, MAS techniques and IEC 61850 are employed to realize the communication between different agents, and MMS plays a prominent role in real-time remote communication. A simulating system of the proposed MAWAPS has been developed, and the experimental results show that the proposed adaptive protection scheme is feasible from the view of protective performance including the executing time.

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