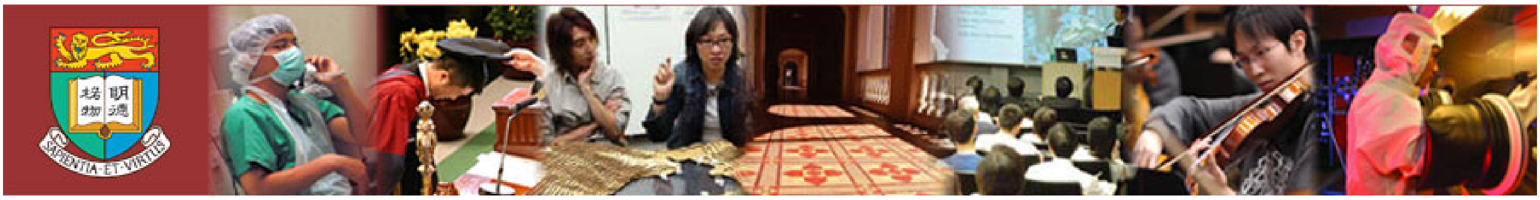

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Author(s)	**Liu, H; Chen, X; Yu, K; Hou, Y**
Citation	**Smart Grid, IEEE Transactions on, 2012, v. 3, p. 1119-1129**
Issued Date	**2012**
URL	**http://hdl.handle.net/10722/164129**
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The Control and Analysis of Self-Healing Urban Power Grid

Haoming Liu, *Member, IEEE*, Xingying Chen, *Member, IEEE*, Kun Yu, and Yunhe Hou, *Member, IEEE*

***Abstract*—In this paper, the concept and system structure of the self-healing urban power grid (UPG) are presented. The proposed method has five operating states and four subcontrols, which are emergency control, restorative control, corrective control and preventive control. The entire self-healing UPG is controlled by the multiagent system (MAS). The agent system has three layers, each of which comprises several agents. This paper discusses the design and function of each agent, as well as the agents' structures and their communication methods. A practical test case based on the urban power grid in Jiangning County in China is employed to demonstrate the ability of the proposed agent-based system to perform self-healing functionality. Research findings indicate that the self-healing control system proposed in this paper can intelligently adjust the operating state to eliminate all the potential threats, and thus achieving the desired operation objectives.**

***Index Terms*—Corrective control, emergency control, multiagent system, preventive control, restorative control, self-healing control, urban power grid.**

I. Introduction

WITH the rapid economy growth, demands for electricity have been increasing dramatic, especially in developing countries. Due to the lack of new investments in generation and transmission networks, many urban power grids (UPGs) operate closer and closer to their limits. In addition, the increase in the penetration of distribution energy resources (DERs), especially renewable energy, such as solar and wind generating sources, in UPG makes the operations of UPGs more complex. Recently, many power system blackouts have taken place successively in big cities of various countries. These facts strongly remind an urgent need to design an intelligent control system to allow UPG to be self-healed when facing power system disturbances.

In recent years, the concept of smart grid was proposed [1]–[4]. The National Energy Technology Laboratory (NETL) in the United States has presented seven principal characteristics of a smart grid. A smart grid should be able to heal itself after a power system event; it should enable active customer participation, resist attacks, provide power quality for the 21st century needs, accommodate all generation and storage options, enable markets, and optimize asset utilization and operate efficiently [1]. Among them, self-heal is the key characteristic. Some literatures also called a smart grid as a self-healing grid [5]–[7].

European Technology Platform SmartGrids defined the word "self-healing" as not only automated network restoration strategies that take into account the impact of high penetration of distributed generation and demand side participation, but also high level decentralized preventive control methodologies that will address options for the management of unplanned outages [8]. "Self-healing" was also interpreted as an engineering design that enables the problematic elements of a system to be isolated and, ideally, restored to normal operation with little or no human intervention [6]. A framework for a self-healing power grid was presented in EPRI's Fast Simulation and Modeling (FSM) project [7]. This concept is based on a distributed autonomous architecture and a set of coordinated closed loop controls. The Strategic Power Infrastructure Defense (SPID) system was proposed in [9], [10]. In SPID, preventive and restorative self-healing controls are defined as the self-healing strategy. A load shedding strategy based on islanding and rate of frequency decline was proposed in [11] to deal with catastrophic events in power systems. Other areas of relevant research could be pursued in [12], [13]. The common ground in these papers shows that self-healing is one of the advanced control techniques. Self-healing characteristic can provides a greater degree of automation to implement strategic improvements in power system security, reliability and availability.

In this paper, the novel concept and detailed system structure of self-healing control of UPG are proposed. It is comprised of four subcontrols, which includes emergency control, restorative control, corrective control and preventive control. The multiagent system (MAS) technology is employed to design the entire self-healing system. For this system, three layers, the inner structure and the communication method are proposed. The paper is arranged as following: Section II presents the structure of the proposed self-healing control; Section III discusses the MAS implementation; case simulations are implemented in Section IV; conclusions are drawn in Section V.

II. Self-Healing Control of UPG

The modern self-healing UPG should perform continuous, online self-assessment to detect existing or emerging problems, and initiate immediate corresponding responses to avoid power grids in the high-risk condition. It needs fundamental supports from a variety of up-to-date hardware infrastructure, advanced measurements and communication techniques, new power relay protection scheme, and so on. The most important one is the coordination and control strategies, which are relatively weak in the current urban electric power management system.

Manuscript received February 20, 2011; revised July 02, 2011; accepted August 19, 2011. Date of publication July 24, 2012; date of current version August 20, 2012. This work was supported by National Natural Science Foundation of China under Grant 51077043 and Research Grant Council, Hong Kong SAR, under Grant 7124/10E and 7124/11E. Paper no. TSG-00053-2011.

H. Liu, X. Chen and K. Yu are with the College of Energy and Electrical Engineering, Hohai University, Nanjing 210098, China (e-mail: liuhaom@hhu.edu.cn; xychen@hhu.edu.cn; kun.yu@vip.sina.com).

Y. Hou is with the Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong, China (e-mail: yhhou@eee.hku.hk).

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Digital Object Identifier 10.1109/TSG.2011.2167525

A. Characteristic Analysis on Modern UPG

Due to more and more connections of DERs, the modern UPG is much different from the traditional system. There exist two main kinds of power suppliers, one is the key regional substation, the other is the DERs. That is the reason we name it UPG rather than urban distribution grid. The typical topology of UPG in China can be described as 220 kV substation locates in the center of the city, the voltage is dropped to 110 kV, 35 kV, or 10 kV by different scale step-down transformers, and the grid is mainly in radial topology from the outgoing line of 220 kV substation, many kinds of DERs are connected in 110 kV, 35 kV, and 10 kV distribution systems directly.

In summary, the modern UPG at least has the following major features.

a) The electrical distance between the loads and the key substation or DERs is short, and the line type is similar to the transmission line, that is, the ratio of R/X is relative small, and long/short lines and cables are coexisting.
b) The capacity of DERs is relatively small, and the failure of any DER would hardly cause frequency instability.
c) Due to the large proportional asynchronous motor of the total load, the voltage stability sensitive to the load should be taken into account.
d) Since many DERs are connected in the grid, the load can get the electric power from more sources rather than only from the upstream substation, which means the power supply path is more flexible, and there exists weak-loop topology.
e) There are more equipments in different types, so that the fault occurs more frequently, that might cause a great influence and be more difficult to deal with.
f) With latest technologies, such as phasor measurement units (PMUs), it becomes possible to get synchronized and precision measurements every few milliseconds.

B. Conceptual Structure of Self-Healing Control

In essence, self-healing control is the immune technique of the modern grid; its autonomous actions will perform continuous, online self-assessments to predict potential problems, detect existing or emerging problems, and initiate immediate corrective responses, and will result in minimal or no interruption of service to consumers.

In order to realize the self-healing characteristic in UPG, the conceptual structure is designed in Fig. 1, which consists of five operating states and four subcontrols.

1) The Five Operating States: The UPG is always in either normal state or abnormal state, the difference between them is certain. If there is no fault, lost load, isolated island of electricity, overload or under/overvoltage, and every equipment is in good health, the grid is in normal state. By the time, all the operating constraints are matched. We consider it as five different states based on the operating condition, and present a set of novel definitions respectively.

a) Emergency state. In this state, there exists fault, severe low voltage, critical overload, or overload duration exceeding the limit, when the protective relay equipment must operate immediately in order to avoid the collapse of the whole system.

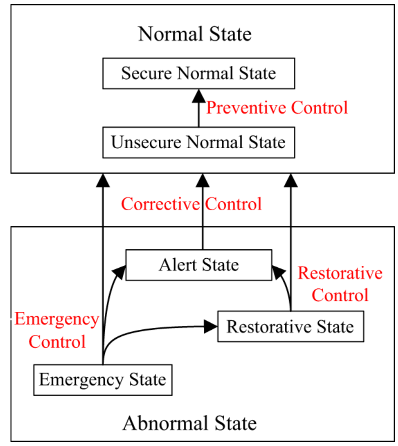

Fig. 1. The relationship among subcontrols and operating states.

b) Restorative state. After the emergency control action was taken in emergency state, the operating parameters almost meet the limits, although there might be the loss load, or the isolated micropower grid. At the moment, the situation is abnormal but it will not deterioration further.
c) Alert state. There exists overload, or abnormal equipment, or overvoltage but the duration is acceptable, or the tendency to be voltage unstable while the system is still stable.
d) Unsecure normal state. For a normal state, if there is any hidden danger of security in secondary electric system, or the electromagnetic loop network, or it does not match the "N-1" criterion, which means it would not match all the constraints after a rational contingency. In this state, the grid might be easy to be transferred to the abnormal state.
e) Secure normal state. If there is no hidden danger of security in secondary electric system, no electromagnetic loop network, and it matches the "N-1" criteria, the UPG is in the ideal secure normal state.

2) The Four Subcontrols: Based on the framework of the five operating states, the self-healing control of UPG can be defined as an autonomous strategy, that can obtain all the real-time operating parameters, and determine a set of operations intelligently and optimally, such as the open/close actions of all kinds of switches, or adjustment on any automatic equipment, to transfer the current state to the better one, so as to help the grid to handle the emergency, restore the power supply, match all the constraints with good economic performance, and have good suitability to the uncertain disturbance, then finally realize the self-healing UPG.

Corresponding to the five states, four subcontrols are introduced here to achieve the state-shift.

a) Emergency control. Once the UPG is in emergency state, some measures should be taken immediately in order to prevent the system collapse, such as DERs tripping, fault clearing, load shedding, active grid splitting, and so on. All the fast actions driven by unpredictable events are open-loop, and always transfer the situation to restorative state, alert state or normal state effectively.
b) Restorative control. When the grid is in restorative state, the lost loads in nonfault areas, which have been disconnected after an emergency control, should be restored as

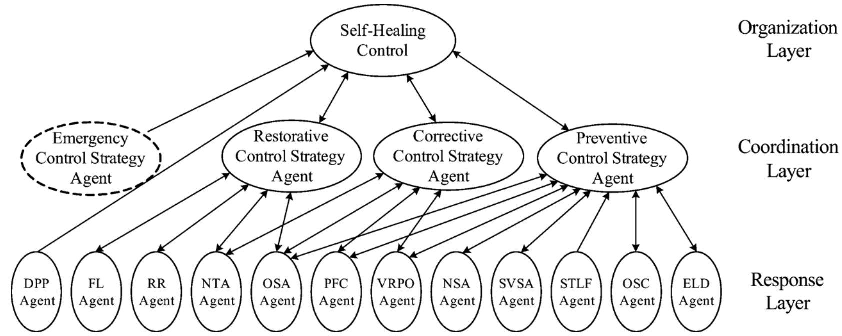

Fig. 2. Structure of self-healing control of UPG based on MAS.

much and quickly as possible, so the fault should be located exactly, and the electric power supply path need to be chosen rationally. The control action would drive the situation to alert state or normal state.

After restoration, not only the loop power supply of multiterminals is permitted, but the slight overload or low voltage is allowed to exist in a short period [14], which would be eliminated in the further control.

c) Corrective control. When the grid is in alert state, some measures, such as tap adjustment of transformer, the switches of capacitor or FACTS, and other actions, should be taken to resolve the anomalous conditions of equipments, or relieve overload and voltage violation in order to avoid further insecurity or voltage instability, these measures could drive the situation to normal state.

d) Preventive control. Even if the grid is in normal state, it might not meet the "N-1" criteria, and then some decisions should be made without direct impact on system users to minimize the system vulnerability with respect to future severe disturbances that would drive it to instability; these measures will always drive the situation from unsecure to secure normal state. The measures include updating the setting value of relay protection, checking and repairing secondary system, changing the tap of transformer, switching on/off the capacitors or FACTS, alternating the supplying path, and so on.

The above five states and four subcontrols set up the framework of self-healing control of UPG. The five states form a sequence from the worst to the best. Contingency or disturbance always transfers the better state to the worse, which would activate corresponding subcontrol to drive the system from the worse state to the better one, and the change might occur from a state to a nonneighboring state.

III. MAS Implementation

The self-healing control system designed in this paper must have the high requirements in both time and space to ensure its effective operation in an open and real time environment. The architecture of self-healing control has to be modular, flexible and scalable to meet the challenges introduced by unforeseen disturbances.

Agent has some basic attributes, such as autonomy, social ability, reactivity and proactiveness. The characteristics of the MAS are almost completely consistent with the needs of the self-healing control system, such as distributivity, wide-area coordination, initiative, and intelligence [15]. The MAS technique is introduced here to construct the self-healing control system of UPG.

A. System Structure and Function

The structure of the self-healing control system based on MAS is shown in Fig. 2. It is composed of three layers, namely the response layer, the coordination layer and the organization layer.

1) Response Layer: The layer is composed of some fundamental function module agents that can realize some basic control functions following the related coordination agent.

- Data preprocessing (DPP) agent. Acquire, validate, store, and retrieve data in a timely manner, and carry out state estimation instead of just providing raw data, and then deposit them into sharing database. Data may include static, dynamic, real-time, and forecasting information.
- Fault location (FL) agent. Locate the positions of faults according to the change of the switches state. A novel matrix algorithm is applied here, that can deal with the complex grid with multisources [16].
- Restoration reconfiguration (RR) agent. Restore the power supply to the lost loads in the nonfault area as much as possible via changing the on/off status of switches. The objective adopted here is to maximize the total load restored [17].
- Network topology analysis (NTA) agent. Obtain the topology structure of the UPG and deal with the real-time changes of switch states [18].
- Operation sequence arrangement (OSA) agent. Arrange the optimal operation sequence of all the actions that need to be taken. The optimal sequence must take into account the transient impulse current caused by all the actions, in order to make the harmful influence minimized.
- Power flow calculation (PFC) agent. Calculate the power flow based on the given parameters.
- Voltage and reactive power optimization (VRPO) agent. Eliminate the violation of the voltage or reactive power via switching on/off capacitors or FACTS devices, and adjusting tap ratios of OLTC, so as to reduce the power loss, improve the voltage condition and enhance the security. The hybrid algorithm of ordinal optimization and Tabu search is implemented [19].

- "N-1" security analysis (NSA) agent. Evaluate the current operating condition or a forecasting operating condition against a contingency. The sensitivity ranking algorithm is adopted to select the key contingencies for evaluating [20].
- Static voltage stability analysis (SVSA) agent. Calculate static voltage stability margin based on continuous power flow method, and identify critical lines or weak nodes, whose voltages often fluctuate out of the range, and might lead to a broader scale of voltage instability [21].
- Short-term load forecasting (STLF) agent. Predict the load ahead of a certain period. The load forecasting method based on gene expression programming is selected here [22].
- Online setting calculation (OSC) agent. Calculate the setting value of all kinds relay protection after some alterations of the grid structure or other parameters. It is also called adaptive protection, the relay settings are recomputed intentionally to maintain protection system operation when system conditions have changed [10].
- Electromagnetic loop decoupling (ELD) agent. Decouple the existing electromagnetic loop to reduce short-circuit capacity and improve the security of the UPG [23].

2) Coordination Layer: Four agents corresponding to the four subcontrols form the coordination layer. Each one can be realized based on some fundamental function modules in response layer.

Emergency Control Agent: In general, if the UPG enters the emergency state due to some serious unpredictable disturbances, emergency control will be applied to drive the grid back to some better state immediately. The purpose is to minimize the durational and geographical extent of the interruption, possibly by disconnecting some loads to the benefit of the overall grid integrity, which may lead to system islanding [14], [24].

There have been a lot of literatures on emergency control and different control strategies; almost all these papers focus on event-driven vs. response-driven, autonomous vs. nonautonomous, centralized vs. distributed, etc. Compared with the transmission system, event-driven, nonautonomous, and distributed operation is preferred in UPG due to the relative fixed operating situation, less operating parameters, and radial topology. Since there are only discrete switching type of actions under emergency state, and no communication or coordination is needed in advance from the self-healing control agent, the emergency control strategy can be activated instantaneously. Of course, the implementation results would be returned in time.

Restorative Control Agent: The main goal of restorative control is to achieve the secure and reliable restoration of power supply to the lost loads as much and quickly as possible, considering the physical limitations of all the operating parameters. Mathematically, it is a multiobjective combinatorial optimization problem with all kinds of constraints, these objectives might be to maximize the quantity of load restoration within nonfault area, to minimize the total losses of the distribution network, to minimize the number of switching operations, and so on [17], [25]. The capacity of branch and transformer, the node voltage limitation, and the operating number limitation of switches should be considered as the constraints. For simplicity, the detailed models are omitted.

The restorative control agent is responsible for coordinating the related agents in the response layer to complete the restoration of power supply. Once the event-driven triggering signal arrives, the restorative control agent reads the data from the sharing database, and informs the NTA agent to analysis the current topology structure. Immediately, it actives not only FL agent to locate the fault, but also RR agent and OSA agent to maximize the loads served of nonfault area and determine the optimal sequence of the operations which should be operated.

It should be pointed out in restoration reconfiguration, due to the high DERs penetration, power supply in loop mode, as well as slight violation of node voltage or the branch power, is permitted temporarily.

Corrective Control Agent: When the UPG is in alert state, the corrective control agent organizes certain agents to complete the function of corrective control, activates the voltage reactive optimization agent to eliminate the voltage and power flow violation, and determining the operation sequence for implementing.

Once the timing triggering signal arrives, the corrective control agent reads the data from the sharing database, and informs the NTA agent to analysis the current topology structure. Then the PFC agent is invoked to calculate the current power flow distribution before activating the VRPO agent. If all the violations have been removed, the OSA agent runs to determine the optimal sequence of all the operations, otherwise, an alert message would be returned.

Because the main power grid is able to provide infinite active power supply, the objective of corrective control measures, such as adjustment on transformer tap changer, capacitors switches and FACTS parameters, is mainly to correct the voltage or reactive power flow violations, rather than active power violation.

Preventive Control Agent: It coordinates certain agents to complete the function of preventive control, including online setting calculation of relay protection, electromagnetic loop decoupling, "N-1" security analysis and static voltage stability analysis in a forecasting load level.

Once the timing triggering signal arrives, the preventive control agent reads the data from the sharing database, and informs the STLF and NTA agents to forecast the load level and analyze the current topology structure respectively. Then PFC agent is invoked to calculate the future power flow distribution before activating the NSA and VRPO agents. If all the violations have been removed, the SVSA agent checks the voltage stability margin, and if the margin is abundant, the OSA agent would be activated; otherwise, an alert message would be returned. After that, the OSC agent would be activated to check and revise the setting value of relay protection adaptively. Then, the UPG would match the "N-1" criteria, and the voltage margin is sufficient in a certain future. In other words, the preventive control can make the UPG stronger given any predictable disturbance.

The preventive control would take the measures that could prevent the system from getting into instability in a supposed contingency, thus a certain time ahead load forecasting should be considered, such as 1 h. The short-term load forecasting should be performed regularly to form an integrated and accuracy set of operating data, which should be transferred to the DPP agent in time. Based on the data, analysis on "N-1" security and static voltage stability would be implemented respectively, and the VRPO agent is activated if necessary.

The entire "N-1" analysis is especially time consuming due to the huge quantity of elements such as lines, transformers, switches, capacitors, and so on. The strategy employed here is to select the key elements that would cause a severe effect on the grid if unplanned single outage of these elements occurs, or the elements with poor reliability, that is, they frequently lose function in the past. The key branch set determination module provides a list of the potentially severe contingencies to be analyzed. A predefined list of contingencies could dynamically be modified based on the current operating conditions, and the list is ranked according to the severity.

To be selective and reliable, the relay protection should be adaptive to the changing of grid configurations [26]. The changes may not frequently occur, but the risk associated with their impacts on the UPG may be catastrophic if the relay settings remain constant. Therefore, it is important to choose some typical and severe system configurations to calculate the fault current, and conduct the setting value calculation. Several setting value groups would be calculated and saved in the protective relay in advance, and the right group of relay setting would be activated according to the practical condition.

It should be pointed out that voltage and reactive power optimization might be recurred in both corrective control and preventive control, while the requirements and restrictions are not the same. In preventive control, the upper and lower limitations of voltage might be stricter, and the time consuming restriction might be relaxed since the preventive control can be carried out off-line.

3) Organization Layer: Self-healing control agent obtains the practical data, such as operating parameters and the status of all the switches, from data preprocessing agent, determine the true state of the UPG, and then optionally triggers the corresponding agent in the coordination layer.

The framework discussed above focuses on the control system excluding the on-spot devices, thus it can be installed and operate in a centralized location. The devices are the rock-bottom controllers, which should be installed in a distributed manner [27], [28].

B. Inner Structure of Each Agent

The internal structure of each agent is illustrated in Fig. 3, which is mainly composed of the communication module, the analysis module, the algorithm module, the memory module, and the read/write control module. Among them, the communication module is responsible for communicating with other agents, requesting or accepting the messages to/from other agents to perform the cooperating task, which would be completed by the analysis module with the effective algorithm provided from the algorithm module, and the results and other messages are stored into the memory module, or sharing database block via the read/write control module.

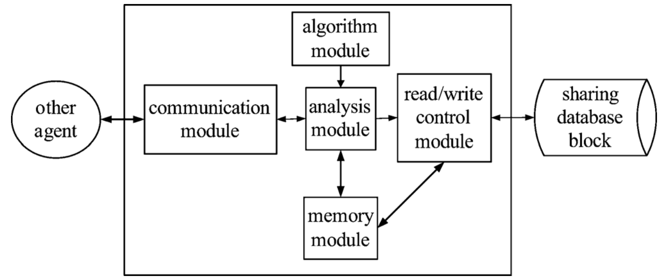

Fig. 3. Inner structure of each agent.

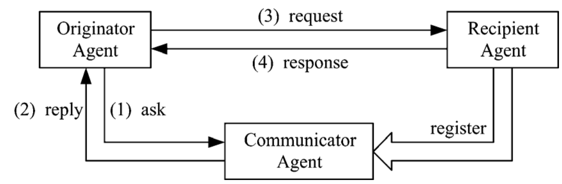

Fig. 4. The collaboration based on the "request and response" protocol.

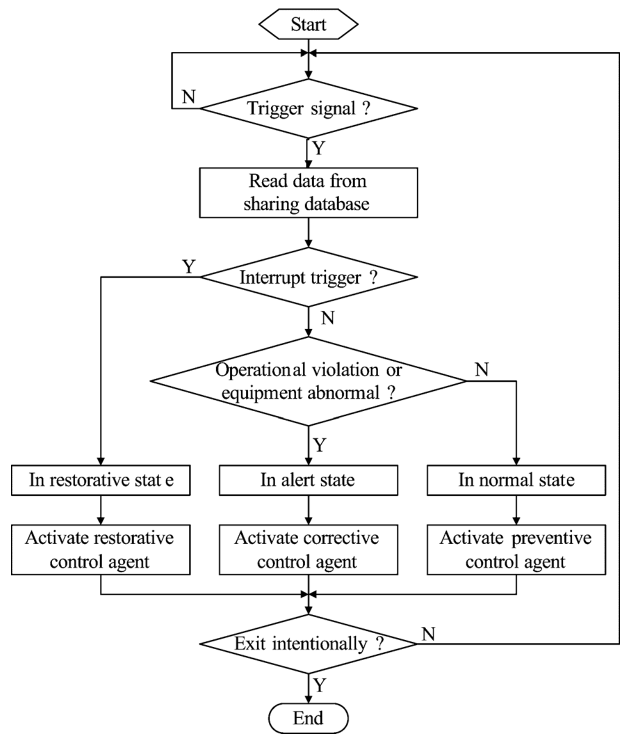

Fig. 5. The flowchart of decision steps of the self-healing control.

C. The Communication and Cooperation Method

The point-to-point of request-respond communication protocol is applied to achieve communication between agents. The principle of point-to-point protocol is shown in Fig. 4. In this protocol, all agents may enter or exit freely. Any agent must register itself to communicator agent when it enters the control system, and check out once exit.

Knowledge Query and Manipulation Language (KQML) is used as a communication language between agents. Once an agent has some request, it will send a packaged message in KQML to the communicator agent. The communicator agent identifies the requested task and determines the recipient agent, then builds a special channel to connect the originator and recipient agents. After receiving the message, the recipient agent

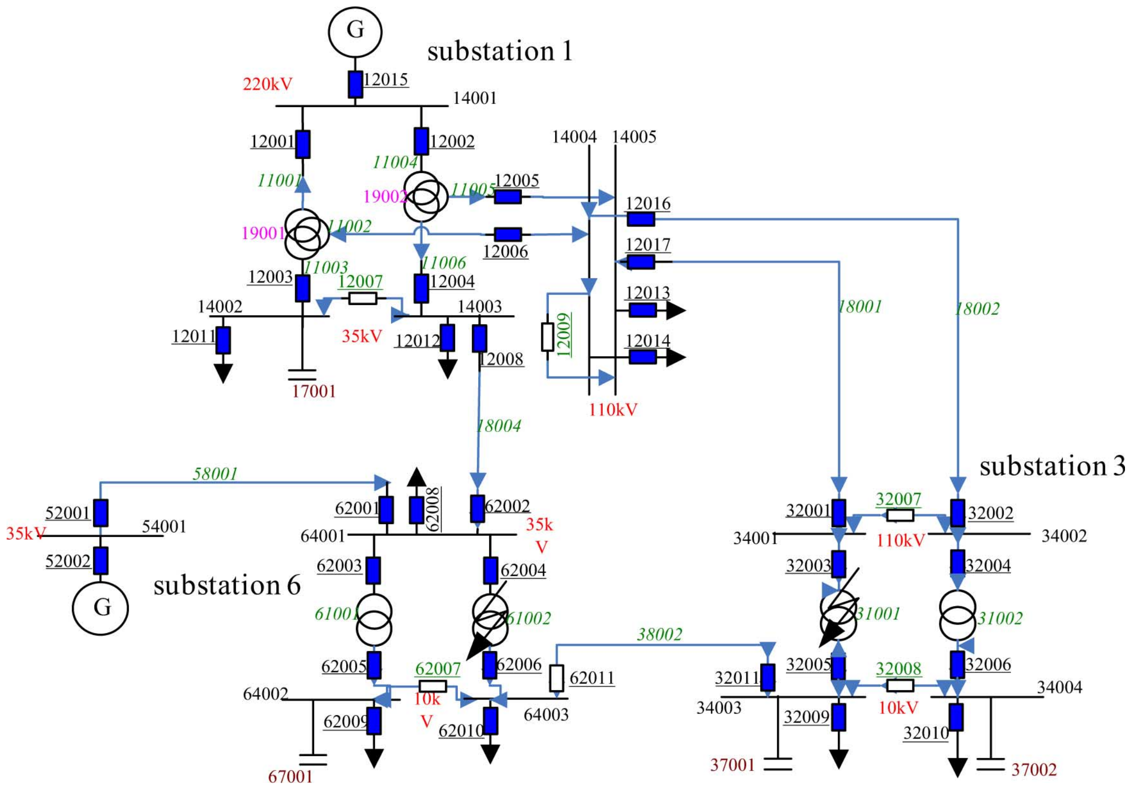

Fig. 6. The first test case.

unpackages the message, and then returns a confirmation signal to the originator agent.

The originator will send the message repeatedly until the confirmation signal arrives, and the maximum number of sending times might be set. After the maximum times efforts, the originator would give up and return the failure message to the upper level agent.

D. Overall Decision Steps

Once a severe disturbance occurs, which drives the system to the emergency state, and the automatic devices operate immediately, which always results in the interruption of power supply to some loads. According to the current status of the UPG, one control would be triggered to drive the grid to a higher state. If there is any lost load or isolated micro power grid, the restorative control is activated in time to serve the load of the nonfault area. Else if there is only some parameters violation or abnormal equipment exists, corrective control or preventive control will be activated selectively.

The trigger signals to activate corresponding control have two kinds, one is interrupt trigger or event trigger, the other is timing trigger, and the former has the priority. It indicates clearly that the rank of restorative control is higher than that of corrective control or preventive control, and the restorative control starts by interrupt trigger while the corrective control and preventive starts by timing trigger. During the process of restoration control, any timing signals for corrective control or preventive control would be ignored until the restorative control has finished and implementation signal has been returned or time has expired. After restoration, self-healing control agent will amend the next start-up timing of trigger signal appropriately. The overall decision-making process of self-healing control is shown in Fig. 5.

IV. Case Study

In order to verify the feasibility and effectiveness of the proposed control system, two cases are implemented. The first one is a small test case, and the second is a practical case.

A. The First Test Case

As in Fig. 6, the grid is comprised of 3 substations, 5 branches, 13 buses, and 6 transformers; two power resources are a 220 kV substation and a 35 kV distributed generator. There are 4 levels of voltage involved including 10 kV, 35 kV, 110 kV, and 220 kV.

Set the internal triggering time as 15 min, that is to say, corrective control or preventive control would be activated every 15 min. Suppose two permanent faults occur in transformer 31001 (fault 1) and transformer 61002 (fault 2) simultaneously at 0 s, relay protection devices would take actions as emergency action effectively at 0.06 s to isolate the two breakdown transformers via opening the switches 32003 and 32005, 62004 and 62006. After that, the self-healing control coordinates and manages all the restorative control, corrective control and preventive control, and activates right control sequentially to drive the system to more healthy status following the predetermined strategy. The three processes are addressed as three cases respectively.

1) Restorative Control After Interrupt Trigger at 0.06 s: After 0.06 s, the grid is split into three parts. The first one contains substation 1, part loads of substation 3 and substation

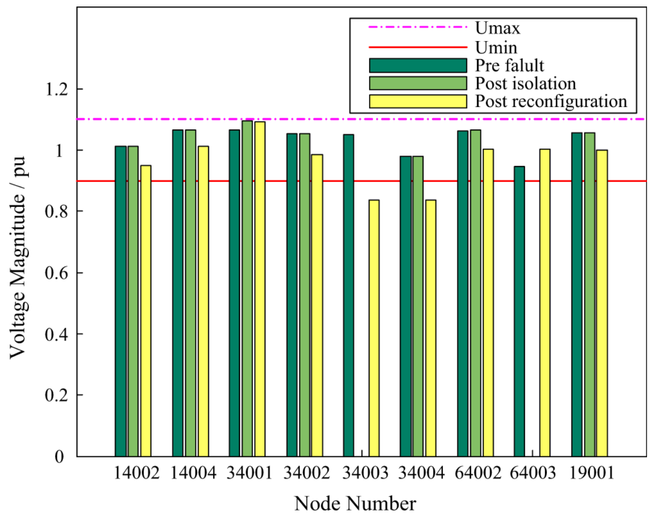

Fig. 7. The comparison of voltage magnitude before/after restorative control.

TABLE I
RESULTS OF FAULT LOCATION AND RESTORATION RECONFIGURATION

	Fault 1	Fault 2
Fault section	[32003, 32005]	[62004, 62006]
Switches to be closed	32008	62007

TABLE II
THE OPERATION SEQUENCE

Number	Switches number	Actions
1	32008	close
2	62007	close

6 with the distribution generator, the second one is node 34003 of substation 3 and its lost load, and the third one is node 64003 of substation 6 and its lost load.

After receiving the return signal from emergency control, the self-healing control agent read the latest data from the sharing database, and considers that the grid is in the restorative state via state judgement block, then sends out an interrupt trigger signal to activate the restorative control agent.

Once the restorative control agent receives the request signal, it coordinates related agents to recover the lost loads, then returns the mission success message to self-healing control agent, and finally shows the relevant information to operator through the human-machine interface. Part of the restoration results are shown in Tables I and II and Fig. 7.

Tables I and II show that the lost loads at node 34003 and node 64003 could be restored via switching on branch 32008 and 62007, and the two operations should be in sequence so as to lower the transient surge current. Fig. 7 indicates that the voltage magnitudes of nodes 34003 and 34004 after restorative control, i.e., they are almost 0.84 p.u., cannot meet the lower voltage limitation due to the heavy power flow passing through. Such few slight violations are permitted temporarily in the case of special situation, and would be eliminated via further corrective control.

2) Corrective Control After Timing Trigger: Once the return success message from restorative control agent arrives at self-healing control agent, the self-healing control agent would analyze the situation and find severe lower voltage violation that

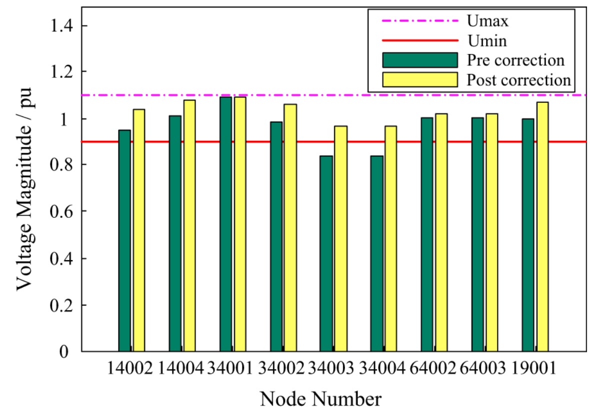

Fig. 8. The comparison of voltage magnitude before/after corrective control.

TABLE III
OPERATION SEQUENCE OF CAPACITORS SWITCHING IN CORRECTIVE CONTROL

Operating order	Capacitor	Node	Actions	Group number
1	17001	14002	increase	3
2	37001	34003	increase	3
3	37002	34004	increase	2
4	67001	64002	increase	4

TABLE IV
OPERATING ORDER OF OLTC TAP ADJUSTMENT IN CORRECTIVE CONTROL

Operating order	Transformer branch	Actions	Change number
1	11001	up	2
2	31002	up	1
3	61001	down	3

still exists, and the triggering time would be determined and sent out to activate the corrective control agent in time.

After receiving the request, the corrective control agent takes the responsibility of organizing the related agents to complete the corrective control, the measures include tap adjustment of on load tap changer (OLTC) and open/close swtiches of capacitors. If all voltage violations are eliminated, it returns the success message to the self-healing control agent, and shows the relevant information to operator through the human-machine interface. A part of simulation results are shown in Tables III and IV and Fig. 8.

Fig. 8 shows that the corrective control not only modifies the voltage magnitudes of node 34003 and 34004, but also optimizes the voltage magnitudes of other nodes. Generally speaking, the voltage level of the overall system has been improved.

3) Preventive Control After Timing Trigger: If there is no accident occurs, timing trigger would be send out every 15 min, and the situation would be analyzed to determine the state of the UPG. If there is no violation on voltage and power flow, the preventive control agent would be activated.

After receiving the request signal, the preventive control agent takes the responsibility of organizing related agents to complete the preventive control. Preventive control involves a number of functional modules, and has to perform numerous optimal calculations. Here, only “N-1” security analysis is addressed. After the key branch set is selected, some branches are considered as essential such as branch 61001, 31002. For example, suppose transformer 61001 is down in a forecasted load level, switch 62011 should be closed in time to serve the

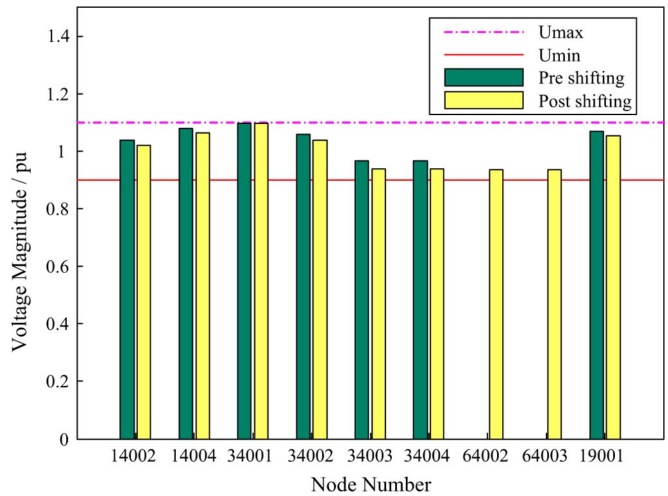

Fig. 9. The comparison of voltage magnitudes before/after load shifting in branch 61001 "N-1" contingency.

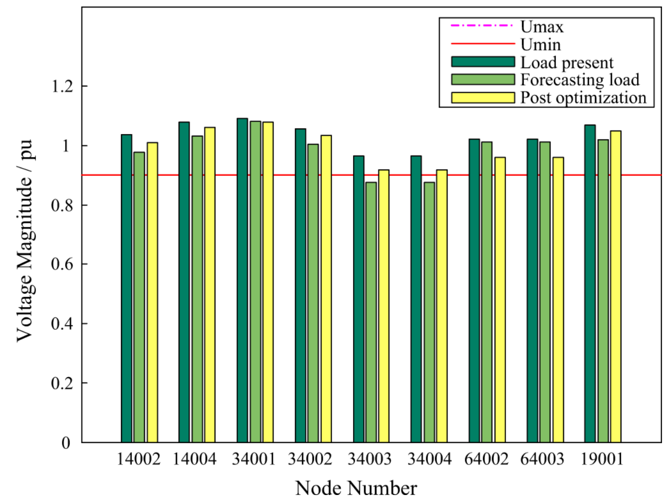

Fig. 10. The comparison of voltage magnitudes before/after preventive control in a forecasting load level.

TABLE V
OPERATION SEQUENCE OF CAPACITORS SWITCHING IN A FORECASTED LOAD LEVEL

Operating order	Capacitor	Node	Actions	Group number
1	37001	34003	increase	1
2	67001	64002	reduce	4

TABLE VI
OPERATION SEQUENCE OF OLTC TAP ADJUSTMENT IN A FORECASTED LOAD LEVEL

Operating order	Transformer Branch	Actions	Change number
1	11001	reduce	1
2	61001	reduce	2

load at node 64002 and 64003, which results in some violations. Then the voltage and reactive power optimization agent would be activated.

The comparison of voltage magnitudes before and after load shifting in branch 61001 "N-1" contingency at current load level is shown in Fig. 9. And the comparison of voltage magnitude before and after voltage and reactive power optimization at a forecasting load level is shown in Fig. 10. Results of operation sequence of capacitors switching and OLTC tap adjustment at a forecasted load level are shown in Tables V and VI respectively.

Fig. 9 shows that the preventive control could not only realize the load shifting, but also optimize the overall voltage distribution. Fig. 10 shows the voltage violation at node 34003 and 34004 at a forecasted load level could be eliminated via optimization scheme of preventive control.

What is different from corrective control is that all the operations, ranked via operation sequence arrangement agent of preventive control, would not be performed immediately, they would be returned to self-healing control agent and operator as the reference. The reason is all the operations are only optimal choice rather than the critical measure to maintain the stability of UPG, so they do not need to be implemented at once.

B. The Second Practical Case

The software package of the self-healing control system was developed in Visual C++ and Oracle environment, and it has been running in one computer server in the dispatching center of Jiangning urban power grid in China. The pilot network is shown as in Fig. 11.

TABLE VII
CLASS AGENTSPIRIT

AgentSpirit		
*m_strName	:CString	
*m_bStarted	:BOOL	
*m_Msg	:AgentMessage	
<<Implement>>	SetName(String name)	:void
	GetName( )	:CString
<<Constructor>>	AgentSpirit( )	
<<Constructor>>	AgentSpirit(CString name)	
	Process( )	:void
	Reset( )	:void
	Initialize( )	:void
	Stop( )	:void
	Run( )	:void
	OnAgentEvent(AgentEvent*e)	:void
	PostAgentEvent(AgentEvent*e)	:void
	InitInstance( )	:void
	ExitInstance( )	:void

A self-defined base class AgentSpirit, which is derived from the existing class of CcmdTarget in MFC, is used in VC++ programming to achieve all the communication functions, such as message encapsulation, message trigger and message reply, etc. AgentSpirit is the base class, which has common attributes of all agents, and it provides common API for all agents, see Table VII.

Function OnAgentEvent() is defined in AgentSpirit to receive messages. Since a class object called AgentEvent is the message carrier, it must be triggered so that the message could be sent out every time. AgentMessage is to package and parse the messages, that is considered as a parameter in the AgentEvent object, then the message body could be delivered after the class object AgentEvent is triggered. The AgentEvent and AgentMessage are shown in Tables VIII and IX respectively.

In the presented framework, two kinds of data should be dealt with. One is shared and permanent, the other is dynamic with restrict time limit for real time task. The first kind of data could be stored into Oracle, the second kind of data must be processed via real-time database, that is created artificially.

A practical event has occurred on May 24, 2010, and all the data and operating behaviors have been recorded and saved into

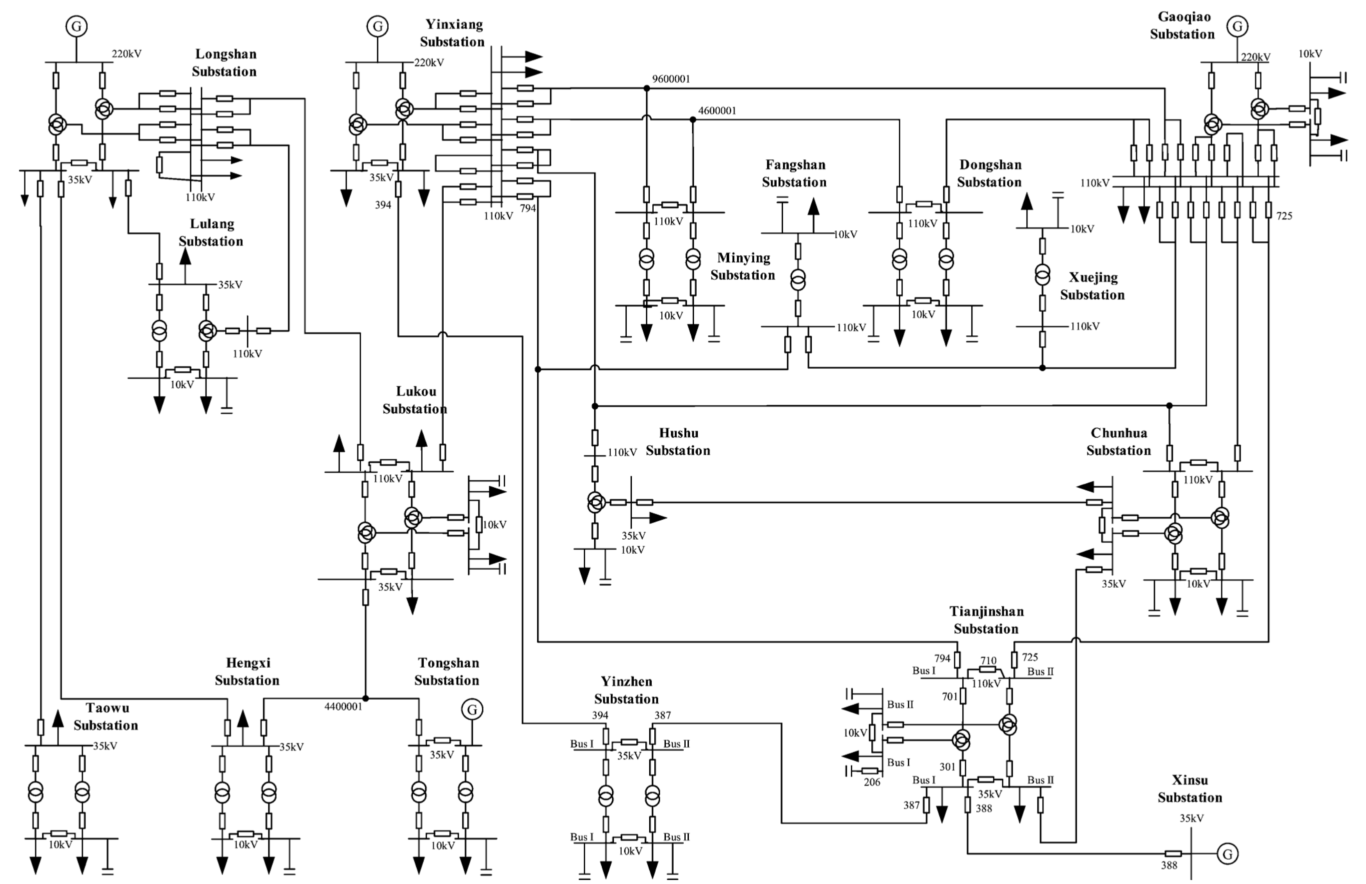

Fig. 11. The urban power grid in Jiangning county.

TABLE VIII
CLASS AGENTEVENT

AgentEvent		
m_argObject		:AgentSpirit*
	GetObject( )	:AgentSpirit*
<<Constructor>>	AgentEvent(Agent source)	
<<Constructor>>	AgentEvent(Agent source, Object arg)	

TABLE IX
CLASS AGENTMESSAGE

AgentMessage	
*m_strPerformative	:CString
*m_strSender	:CString
*m_strReveiver	:CString
*m_strInReplyTo	:CString
*m_strReplyWith	:CString
*m_strLanguage	:CString
*m_strOntology	:CString
*m_strContent	:CString
<< Constructor >>	AgentMessage()

the Oracle database. The Xinsu generating station is under operational maintenance, when there is a permanent single phase ground fault in line GaoTian 725 (the line 725 between Gaoqiao and Tianjinshan substation), and the fault resistance is zero. The succeeding events are shown in Table X.

All the succeeding events can be illustrated as follows. After the fault occurs in line GaoTian 725, the autonomous emergency control runs immediately, and the fault is isolated via tripping off the switches 725 in both Gaoqiao and Tianjinshan substations respectively. Then the restorative control closes the switch 710 to pick up the lost load at Tianjinshan substation, that causes the overcurrent in line 794. The corrective control is activated to transfer the lost load from line YinTian 794 to line YinTian 387 via switches 387 closure and 701 open, in order to eliminate the overcurrent. After that, the preventive control is activated to increase the stability margin, the operations are to increase the OLTC of Yinzhen substation and switch on the capacitors at switch 206, so as to increase the var power injection and the node voltage.

After that, due to the change of the UPG's structure, all the relative relay setting should be computed to assure all the equipments are reliable, selective, speeding, and sensitive. The relay setting values of overcurrent protection of relay 394 at Yinxiang substation need to be changed from group 1 to group 2, the detail setting values are shown in Table XI.

From Table XI, it can be found that the protective relay is activated and isolates the fault immediately after the ground fault occurred, the time lag is mainly caused by the operating time of relay setting and the time consumption of self-healing control system.

After the line GaoTian 725 has been cut off, the UPG is in the restorative state. The result of restorative control is to close Tianjinshan switch 710. Due to the Xinsu generating station is under operational maintenance, all loads in Tianjinshan substation are supplied from Yinxiang substation, that make the line 794 overloading, then the corrective control is activated and transfers a part of the load to Yinzhen substation via closing switch 387, and then adjusts the tap-changer to increase the voltage at Yinzhen substation to avoid the undervoltage. At last,

TABLE X
THE RECORDED EVENTS AND OPERATING DATA

Events in order	Bus voltage (kV)						Line current (A)			
	Tianjinshan				Yinzhen		GaoTian	YinTian	YinZhen	TianYin
	110		35	10	10					
	Bus 1	Bus 2	Bus 1	Bus 1	Bus 1	Bus 2	725	794	394	387
Original situation	112.0	109.5	34.65	10.04	10.10	10.09	231.0	370.5	293.1	0.0
Fault occurs in Line GaoTian 725	112.0	--	34.65	10.04	10.10	10.09	5128	370.5	293.1	0.0
Gaoqiao switch 725 opens in 36.2ms	112.0	0.0	34.65	10.04	10.10	10.09	0.0	370.5	293.1	0.0
Tianjinshan switch 725 opens in 1.3s	112.0	0.0	34.65	10.04	10.10	10.09	0.0	370.5	293.1	0.0
Tianjinshan switch 710 closes in 0.2s	110.6	110.6	34.19	9.88	10.10	10.09	0.0	601.4	293.1	0.0
Yinzhen switch 387 closes in 3.6s	110.7	110.7	34.25	9.91	9.96	9.96	0.0	473.8	665.9	372.8
Tianjinshan switch 701 opens in 0.3s	111.6	111.6	34.08	9.86	9.74	9.74	0.0	456.2	1602	1309
OLTC of Yinzhen substation increases in 0.1s	111.6	111.6	34.08	9.86	10.01	10.01	0.0	456.2	1602	1309
Tianjinshan switch 206 closes in 0.2s	111.6	111.6	34.37	9.88	10.02	10.02	0.0	456.2	1320	827

TABLE XI
THE SETTING OF OVERCURRENT RELAY 394 AT YINXIANG SUBSTATION

Setting name	Setting value	
	Group 1	Group 2
Stage I (A)	3600	3600
Operating time of stage I (s)	0	0
Stage II (A)	2400	2200
Operating time of stage II (s)	0.3	0.6
Stage III (A)	1500	1800
Operating time of stage III(s)	1.5	1.8

the corresponding setting value of protective relay 394 is alerted as the result of preventive control.

V. CONCLUSIONS

The self-healing grid has become the latest trends of power system development. In this paper the self-healing control of UPG is decomposed into four subcontrols to reduce the overall vulnerability of the UPG with respect to unforeseen events and internal failures. The multiagent technology is introduced to realize a complete self-healing control system. Simulation results illustrate that under emerged or potential threats, the UPG with the proposed self-healing control system can intelligently adjust the power network operating state to eliminate these threats, and thus achieve the desired operation objectives.

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Haoming Liu (M'07) received the B.Eng., M.Eng., and Ph.D. degrees from Nanjing University of Science and Technology, Nanjing, China, in 1998, 2001 and 2003, respectively.

Since 2006 he has been Associate Professor of Electrical Engineering at Hohai University, Nanjing. His areas of interest are in smart grid, and power system stability and control.

Xingying Chen (M'07) received the B.Eng. and Ph.D. degrees from Southeast University, China, in 1984 and 2002, respectively, and M.Eng degree from Hohai University, China, in 1995, all in electrical engineering.

She joined the faculty of Hohai University, China, in 1984, and has been professor there since 2002. Her current interest is power system stability, control, automation, and restructuring.

Kun Yu received the B.Eng. and M.Eng. degrees from Hohai University, China, in 2000 and 2003 respectively.

Since 2003 he has been a Lecturer in Hohai University. His current interest is distribution power system economic operation, automation, and control.

Yunhe Hou (M'06) received the B.E. and Ph.D. degrees from Huazhong University of Science and Technology, China, in 1999 and 2005, respectively.

He worked as a Postdoctoral Research Fellow at Tsinghua University, China, from September 2005 to August 2007. In 2008, he worked as a Postdoctoral Researcher at Iowa State University, and then as a Research Scientist with University College Dublin, National University of Ireland, Dublin, in 2009. In 2010, he was a Visiting Scientist with the Laboratory of Information and Decision Systems (LIDS) of Massachusetts Institute of Technology (MIT), Cambridge. He has been a Research Assistant Professor (since 2009) and an Assistant Professor (since 2011) with Department of Electrical and Electronic Engineering, the University of Hong Kong.