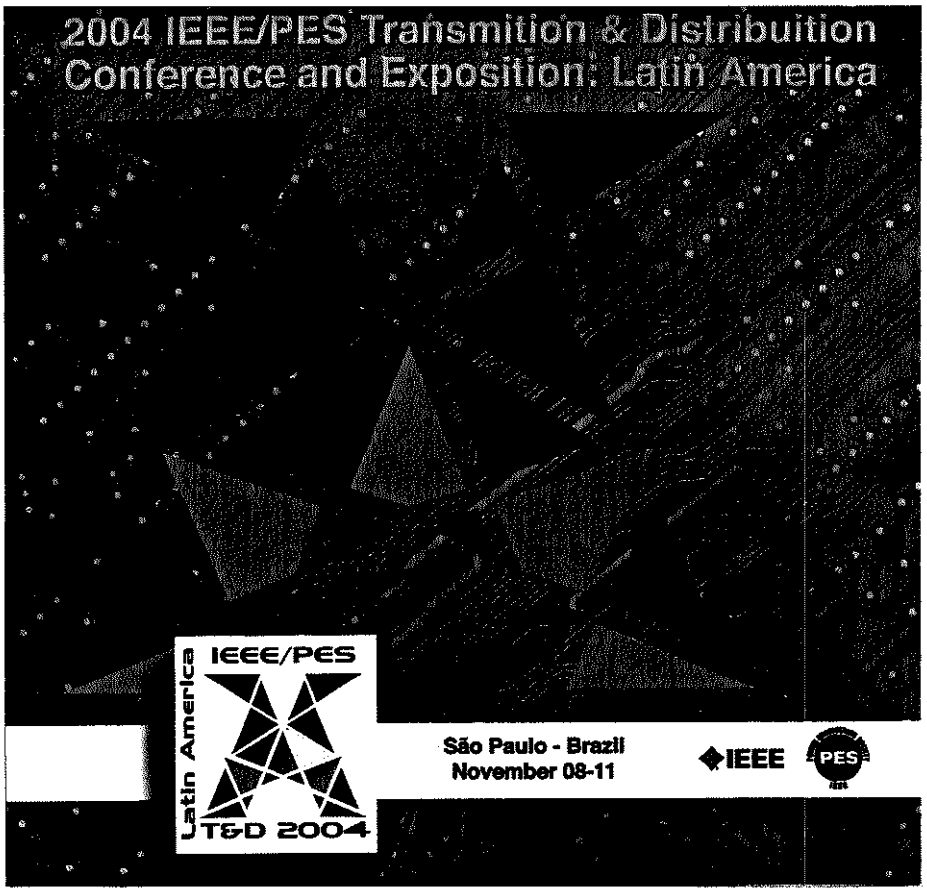

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A PRIMARY AND BACKUP COOPERATIVE PROTECTION SYSTEM BASED ON WIDE AREA AGENTS

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***Abstract*--This paper presents a study of wide area agents based on communication for primary and backup coordinated protection. Agents are used to give each protection component control capacity as well as the ability to communicate with other agents. We feel that this method naturally points towards a new philosophy for primary and backup protection. Simulations are used to illustrate concepts, using a simulation engine named EPOCHS that combines the EMTDC/PSCAD power simulator with the NS2 network communications simulator. Results illustrate the improved performance of our protection scheme. In this new protection system, agents were embedded in each of the conventional protection components to construct an IED relay (Intelligent Electronic Device). The agent searches for relevant information by communicating with other agents. Agent communications can take place at the same substation or at remote substations. This information can be used to detect primary and remote faults, relay misoperation, breaker failures, and to compensate such problems with much better performance than that can be done in traditional schemes. Preliminary results give us hope that the proposed protection scheme may be able to contribute towards the mitigation of wide-area disturbances and the power blackouts that frequently follow them.**

***Index Terms* — Power System Protection and Communication, Cooperative Systems**

I. INTRODUCTION

During the last decade, a new policy has arisen for the Brazilian power system utilities. The old monolithic system was dismantled into a decentralized model. As a result, these power systems are now being operated closer and closer to their limits. Problems such as transmission congestion, power fluctuations and smaller generation reserves are new drawbacks in this scenario. Faster, more reliable, and better coordinated protection and stability control are even more critical under this new environment than they have been in the past. New methods are needed to overcome this chalenge.

Traditional protection relays are based on standalone units. These relays take decision based on their local inputs and data from remote units are rarely used on their internal logic. Communication plays a little role on these systems but relay engineers are beginning to study and access the benefits of wide area communication. One of the technologies that has called attention is the success of Internet. The Internet has shown the capabilities and advantages of IP based networks. With this in mind, the power industry started to consider this kind of communication as a reliable way for improving the protection of the electric power grid. Faster responses, better coordination and increased correctness are all expected features from communication.

Despite the great interest in the electric power community involving communication scenarios and protection, no software has offered the possiblity to simulate IP networks for protection purposes. For this reason, a platform named EPOCHS (Electric Power and Communication Synchronizing Simulator) was built. EPOCHS combines simulators from different domains (power systems and communication networks) in order to evaluate protection schemes based on communication.

This paper presents the study of wide area agents based on communication for primary and backup coordinated protection. An IEEE base power system was used in conjunction with fiber-optic ethernet network. The simulations presented show the performance of these agents. Aspects pertaining to power systems and communication networks are analysed. Caracteristics such as traffic congestion, and link losses are considered, as well as agent, and breaker failures. In all cases, the communication approach proves to be superior to the legacy system.

II. AGENTS FOR PROTECTION AND CONTROL OF POWER SYSTEMS

The electric power grid has traditionally been made up of a large number of protection and control devices that act on local information to respond to problems. This method works well in some cases, but is inefficient in many others. Agents have begun to be recognized as a natural solution to this problem in the electric power research community. Their autonomous nature, ability to share information and coordinate actions, and the potential to be easily replaced from remote facilities make them potentially valuable [1].

The protection and control scenarios that interest us use geographically distributed agents located in a number of Intelligent Electronic Devices (IEDs) as shown in Fig. 1. An IED is a hardware environment that has the necessary computational, communication, and other I/O capabilities needed to support a software agent. An IED can be loaded with agents that can perform control and/or protection functionality. These agent-based IEDs work in an autonomous

manner where they interact both with their environment and with each other. An example of this might be digital relays where each one has its own thread of local control, but they perceive a more global scope of the system and act in response to their non-local environment by communicating with other agents either via Local Area Networks (LANs) or via Wide Area Networks (WANs).

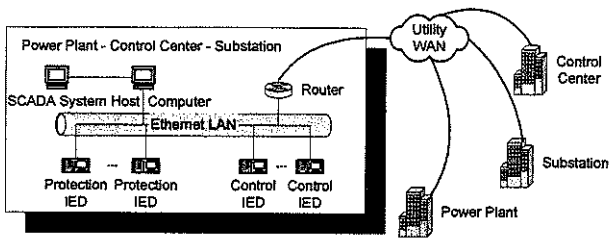

Fig. 1 Placements of the Agent-based IEDs within the Utility Intranet Infrastructure

The agent-based IED's structure is depicted in Fig. 2. Agents within an IED perceive their environment through local sensors and act upon it through the IED's actuators. Examples of sensor inputs might include local measurements of the current, voltage, and breaker status. Actuator outputs might include breaker trip signals, adjusting transformer tap settings, and switching signals in capacitor banks. Agents might even interface with systems such as Supervisory Control and Data Acquisition (SCADA) systems. The host computer shown in Fig. 1 could act as a bridge between the old and new systems in this type of situation. As shown in Fig. 2, agents have the ability to communicate through a LAN in order to interact with other agents directly located on that same LAN, or can pass information along to the Utility WAN, i.e. the Utility Intranet, ultimately communicating with more remote IEDs.

A. The Structure of a Utility Communication Network

Networked computing systems are becoming increasingly prevalent in many areas and we believe that this growth will occur within electric utility systems as well. Technology is constantly changing, but we can make some guesses about what utility communication systems will look like. First, the network systems will almost certainly be built from standard commercial off-the-shelf components. To do otherwise would be expensive both in terms of initial cost outlay and system maintenance. This means that these networks will be based on Internet standards even if the systems remained independent of the global network conglomeration. We can already see hints that such changes are coming in recent standardization efforts such as the Utility Communications Architecture (UCA). We believe fiber-optic Ethernet networks in conjunction with IP-based communication protocols will be heavily used in utility communication for these reasons.

III. EPOCHS

A. Overview

EPOCHS is a distributed simulation platform that links commercial and high quality simulators through the use of a Runtime Infrastructure (RTI) to allow modelers to investigate electric power scenarios that involve network communication. EPOCHS seamlessly links its three simulation systems from a modeler's perspective, enabling them to investigate power protection and control scenarios that combine communication with real-time sensing of the state of a power grid and real-time response [2].

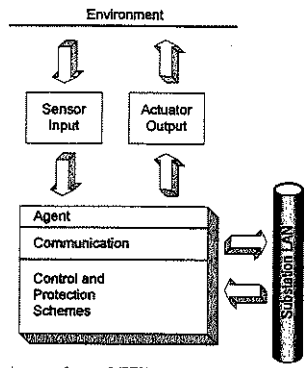

Fig. 2 Structure of an Agent-based IED

EPOCHS is particularly valuable for evaluating the communications requirements of new protection and control schemes and the impact of common Internet behavior, such as traffic congestion, on power system operation [3-5].

B. Architecture

The EPOCHS system is shown in Fig. 3. It is composed of 5 main components:

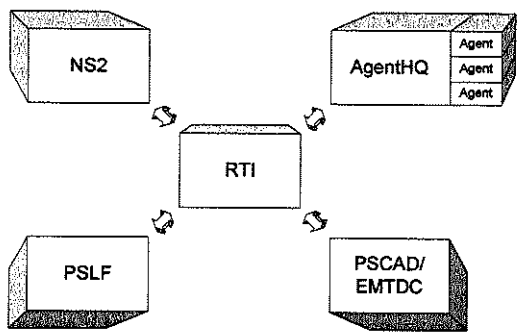

Fig. 3 Relationship Between EPOCHS's Five Components

- PSCAD/EMTDC: It is used for electromagnetic transient simulation. EMTDC is a well-known electric power simulator produced by the Manitoba HVDC Research Centre [6].
- PSLF: It is an electromechanical transient simulation software used for stability studies. It is produced by General Electric [7].
- NS2: It is a communication network simulator that was created through a joint effort between the University of California at Berkeley, Lawrence Berkeley Labs, the University of Southern California, and Xerox PARC [8].

- AgentHQ: It is a module that we developed to present a unified environment to our agents and acts as a proxy for those agents when interacting with other EPOCHS components. Through it, the agents can get and set power system values and send and receive messages to one another.
- Runtime Infrastructure (RTI): It acts as the "glue" between all other components. It is responsible for simulation synchronization and for routing communication between EPOCHS components.

It must be pointed out that in this paper PSLF is not used, and all electric simulations were performed by PSCAD/EMTDC.

C. Component Interaction

The synchronization between the various simulation components follows a simple algorithm. All systems are halted at time 0. At the beginning of any time step, the RTI waits for synchronization messages from both the power system simulator and NS2. Then, the RTI yields control to the AgentHQ. The AgentHQ passes the control on to the agents one by one until all have had a chance to execute. During this cycle, the agents are capable of sending communication messages and getting/setting power system variables. Once all agents are done, the AgentHQ returns control back to the RTI. Finally, the RTI notifies both NS2 and the power system simulator that the current time step is done. At this point, the two simulation engines run for an additional time step. Special attention must be paid to NS2. Messages may be received in between two synchronization points within NS2. If a message arrives, NS2 will immediately pass it along to the RTI bound for the AgentHQ. The AgentHQ will, in turn, pass the message on to the appropriate agent. The agent can process the message and send another in response. If the message requires power system state to be read or changed then that agent keeps the message in a queue until the next synchronization point occurs.

IV. The Strategy Employed by the Agent-Based Protection System

In the current implementation, agents are responsible for the transmission line protection. These agents receive information such as local voltages and currents from the local IED or acquire information by communicating with remote agents. Three types of agents were implemented: primary agents, backup agents, and load agents. Primary agents are responsible for the first zone protection, covering 100% of the transmission line. Backup agents are responsible for the third zone protection which covers the first zone plus all the transmission lines connected to the remote end of the first zone. Load agents are responsible only for sending their current state, usually their current phasors, to the backup agents. An agent can either receive the list of agents, which are in its protection zone and with which it will communicate, at initialization or it might learn this information through some type of network topology discovery algorithm.

Primary and backup agents follow the differential philosophy to detect a fault. At every time-step, they read in their local current phasors and send this information to its agent counterpart. Once an agent receives the phasors from its protection zone remote end/ends, it calculates the differential current and decides whether a fault occurs or not. After detecting a fault, the agents take action based on the preset rules depicted in Table 1. As shown, if a primary agent detects a fault (rule 1), it sets its internal variable FaultStauts to DETECTED, send an INTERTRIP to all agents in its primary agents list and starts a timer. As we can see, no action is taken to open the associated breaker. At first this might be strange, but since a communication network is available, we will wait for a message confirmation to perform this operation. If an INTERTRIP or BACKUP_TRIP is received, the primary agent will open its breaker (rule 6). On the other hand, if a INTERTRIP_RESPONSE = NEGATIVE is received (rule 8), it means the primary agent counterpart hasn't detected the fault, which might signalize an agent misoperation. In this case it disables its internal timer and it waits for another message. If a BACKUP_TRIP message is received, it follows rule 6, and opens the breaker. Finally, if after detecting a fault no message is received withing 15 ms, the primary agent assumes that a communication problem might be occuring and triggers its breaker (rule 5). In all cases, after opening a breaker, the primary agent starts a second timer. This timer will then check if the breaker was really opened. If after 50 ms there is still current flowing into the primary protection zone, the agent sends a NEIGHBOUR_TRIP to all primary agents located at the same bus, in order to them to open their breakers (rule 2). A primary agent can receive a INTERTRIP, a BACKUP_TRIP or a NEIGHBOUR_TRIP without having detected a fault either. In a first case, if a primary agent receives the first two types of messages, it will assume that it is defective, and will open its breaker without detecting a fault by itself (rule 7). In a second case, if a primary agent receives a NEIGHBOUR_TRIP and a BACKUP_TRIP, it will infer a problem has occurred with one of its primary agent neighbours, and will trip its breaker (rule 9).

On the backup agent side, if a fault is detected, it sends a BACKUP_TRIP to all primary agents inside its backup protection zone and starts a timer (rule 3). If after a 100 ms of fault detection there is still a differential current present in its backup protection zone, it assumes all first zone relays have failed to clear the fault, and opens its breaker (rule 4).

V. The Power System Utilized and The Agents System Configuration

All tests conducted with the agent system were based on the well-known IEEE 14 bus system. The complete data set for this system can be found at [9].

TABLE 1 – RULES FOR PRIMARY AND BACKUP AGENT BEHAVIOUR

Rule	IF	THEN
	Electrical Event	
	Primary Agent	
1	Primary_Differential_Current > Limit	- Fault_Status = Detected - Send INTERTRIP to correspondent primary agent - Start trip_timer
2	Local_Current still present after 50 ms of fault occurrence (breaker_timer > 50 ms)	- Breaker_Failure = Detected - Send NEIGHBOUR_TRIP to the primary agents located at the same bus
	Backup Agent	
3	Backup_Differential_Current > Limit	- Fault_Status = Detected - Send BACKUP_TRIP to correpondent primary agents - Start backup_timer
4	Local_Current still present after 100 ms of fault occurrence (backup_timer > 100)	- Open breaker (FORCED_TRIP)
	Communication Event	
	Primary Agent	
5	No message arrives within 15 ms of fault detection (trip_timer > 15 ms)	- Open breaker (FORCED_TRIP) - Check for breaker failure → Start breaker_timer
6	Receives INTERTRIP or BACKUP_TRIP and FAULT_STATUS = Detected	- Open breaker
7	Receives INTERTRIP and BACKUP_TRIP	- Open breaker
8	Receives INTERTRIP_RESPONSE = Negative	- Disable trip_timer and wait for BACKUP_TRIP
9	Receives NEIGHBOUR_TRIP and BACKUP_TRIP	- Open breaker

All transmission lines were modeled based on the PI model of the line, and all sources were modeled as constant power sources. The communication links were set up on the top of the transmission lines, resulting in a communication system with the same topology as the power system grid. All links were assumed to have a bandwidth of 5 Mb/s and a 1 ms traversal time. All communication was based on the UDP/IP standard.

In the next examples, we deployed 15 agents as follows:

- 8 primary agents (PRIM_12-13, PRIM_13-12, PRIM_13-14, PRIM_14-13, PRIM_06-13, PRIM_13-06, PRIM_14-09, and PRIM_09-14);
- 5 backup agents (BACK_09-13-14L, BACK_13-09-14L, BACK_06-12-14-13L, BACK_12-06-14-13L, BACK_14-06-12-13L);
- 2 load agents (LOAD_13 and LOAD_14).

As we can see, the agents' names follow a simple rule. The first four letters indicate their type, the next number shows were the agent is sited, and the following numbers indicate the location of the agents that it must communicate with in order to perform its differential protection. Just as an example, at initialization agent PRIM_12-13 is informed that it must communicate with agent PRIM_13-12 and agent BACK_09-13-14L must communicate with agents BACK_13-09-14L and LOAD_14.

All agents calculate the phasor currents seen on their terminals based on a moving window of 1 cycle with a sampling rate of 1 kHz. Additional effects such as anti-aliasing filters, current transformers and digital sampling were taken into account for all agents. The agents' locations can be seen in Fig. 4. This figure includes buses 4, 5, 6, 9, 10, 11, 12, 13, and 14 of the IEEE 14 bus system. It should be pointed out that the power system bus numbers are not equal to the communication system node numbers. This happens because buses 5 and 6, and buses 4 and 9 delimitate a transformer and not a transmission line. For this case we assumed no delay

between these buses since they are located at the same substation, making buses 5 and 6, and 4 and 9 to become the same nodes.

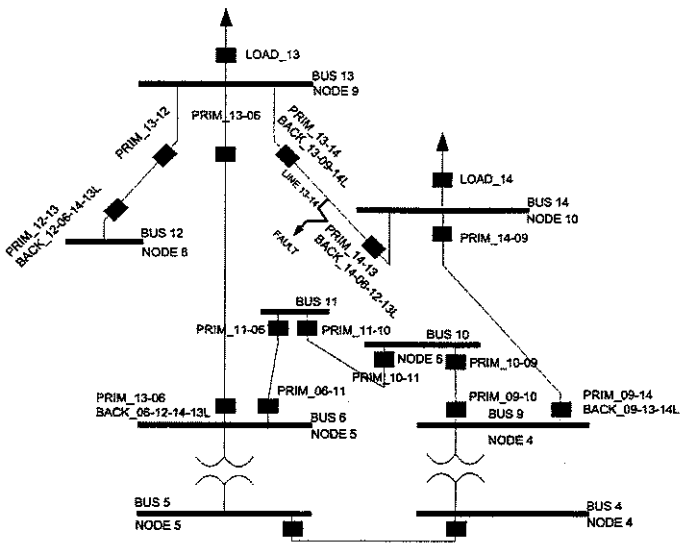

Figure 4 – Snippet from the IEEE 14 bus system showing the agent's locations

VI. CASE STUDIES

A. Case 1 – Correct Primary Protection

As our first test, we present a correct primary protection operation. A three-phase fault occurs at 0.1500 s in the middle of transmission line 13-14. In this example, agents PRIM_13-14 and PRIM_14-13 detect a fault at 0.157 s and after 1.4 ms and 1.2 ms respectively, they receive an INTERTRIP message, which leads them to open their breakers (rule 6). The sequence of events can be seen on Table 2.

TABLE 2 – SEQUENCE OF EVENTS FOR CASE 1

Time (s)	Sequence of Events for Agent PRIM_13-14	Sequence of Events for Agent PRIM_14-13
0.1570	- Differential_Current > Limit - Fault_Status = Detected - Send INTERTRIP to PRIM_14-13	- Differential_Current > Limit - Fault_Status = Detected - Send INTERTRIP to PRIM_13-14
0.1580	- Send INTERTRIP to PRIM_14-13	- Send INTERTRIP to PRIM_13-14
0.1582	-	- Receive INTERTRIP from PRIM_14-13 (0.1570 s) - Open breaker
0.1584	- Receive INTERTRIP from PRIM_14-13 (0.1570 s) - Open breaker	-

B. Case 2 – Link Failure

In this second case, a link failure occurs at 0.100 s, making the link 9-10 inoperative. At a first glance, this could cause problems to the correct agent operation. However, through a standard dynamic route algorithm, a new path is found. Messages that should go from node 9 to node 10, now go from nodes 10 to 4, from 4 to 5, from 5 to 9, and vice-versa. In this scenario the primary protection is delayed, but still works correctly. Initially, the fault is detected at 0.159 s by agents PRIM_13-14 and PRIM_14-13. At 0.1592 s, agent PRIM_13-14 receives a BACKUP_TRIP and opens its breaker (rule 6). The same happens to PRIM_14-13 at 0.1594 s. The sequence of events can be seen on Table 3.

TABLE 3– SEQUENCE OF EVENTS FOR CASE 2

Time (s)	Sequence of Events for Agent PRIM_13-14	Sequence of Events for Agent PRIM_14-13
0.1590	- Differential_Current > Limit - Fault_Status = Detected - Send INTERTRIP to PRIM_14-13	- Differential_Current > Limit - Fault_Status = Detected - Send INTERTRIP to PRIM_13-14
0.1592	-	- Receive BACKUP_TRIP from BACK_09-13-14L - Open breaker
0.1594	- Receive BACKUP_TRIP from BACK_06-12-14-13L - Open breaker	-

C. Case 3 – Agent PRIM_13-14 Fails

In our third case, we show a test where agent PRIM_13-14 fails to detect a fault in line 13-14. As we can see, despite being incapable of detecting the fault, the agent system still works correctly. At first, agent PRIM_13-14 receives an INTERTRIP at 0.1584 s. Later on, it receives a BACKUP_TRIP at 0.1595 and finally opens its breaker (rule 7). On the agent PRIM_14-13 side, it detects the fault at 0.1590 s, receives a BACKUP_TRIP at 0.1592 s and finally opens its breaker (rule 6). This example shows the strength of a cooperative system based on communication. Despite having a defective agent, the agent system was capable to detect and eliminate precisely the fault only 0.6 ms later than case 1, where no problems occurred. The sequence of events can be seen on Table 4.

TABLE 4– SEQUENCE OF EVENTS FOR CASE 3

Time (s)	Sequence of Events for Agent PRIM_13-14	Sequence of Events for Agent PRIM_14-13
0.1570	-	- Differential_Current > Limit - Fault_Status = Detected - Send INTERTRIP to PRIM_13-14
0.1580	-	- Send INTERTRIP to PRIM_13-14
0.1584	- Receive INTERTRIP from PRIMARY_14-13 (0.1570 s)	-
0.1590	-	- Send INTERTRIP to PRIM_13-14
0.1592	-	- Receive BACKUP_TRIP from BACK_13-09-14L - Open breaker
0.1595	- Receive BACKUP_TRIP from BACK_12-06-14-13L - Open breaker	-

D. Case 4 – Breaker Failure

As our final test, we present a breaker failure, where the associated breaker to agent PRIM_13-14 refuses to open. As

we can see on Table 5, the sequence of events for agents PRIM_13-14 and PRIM_14-13 are exactly the same as case 1 until 0.1584 s. At 0.2070 s, agent PRIM_13-14 realizes there is still current flowing through its breaker, which leads it to contact its primary agent neighbor to open their breakers (rule 2). Agents PRIM_13-06 and PRIM_13-12 receive this message almost instantaneously, and trip their breakers at 0.2070 s (rule 9).

TABLE 5– SEQUENCE OF EVENTS FOR CASE 4

Time (s)	Sequence of Events for Agent PRIM_13-14	PRIM_14-13
0.1570	- Differential_Current > Limit - Fault_Status = Detected - Send INTERTRIP to PRIM_14-13	- Differential_Current > Limit - Fault_Status = Detected - Send INTERTRIP to PRIM_13-14
0.1580	- Send INTERTRIP to PRIM_14-13	- Send INTERTRIP to PRIM_13-14
0.1582	-	- Receive INTERTRIP from PRIM_14-13 (0.1570 s) - Open breaker
0.1584	- Receive INTERTRIP from PRIM_14-13 (0.1570 s) - Open breaker	-
0.2070	- Breaker failure detected - Send NEIGHBOUR_TRIP to PRIM_13-06 - Send NEIGHBOUR_TRIP to PRIM_13-12	-
	PRIM_13-06	**PRIM_13-12**
0.1591	- Receive BACKUP_TRIP from BACK_06-12-14-13L (0.1580 s)	-
0.1592	-	- Receive BACKUP_TRIP from BACK_06-12-14-13L (0.1580 s)
0.2070	- Receive NEIGHBOUR_TRIP from PRIM_13-14 (0.2070 s) - Open breaker	- Receive NEIGHBOUR_TRIP from PRIM_13-14 (0.2070 s) - Open breaker

VII. CONCLUSIONS

In this paper we have described the use of wide area agents for primary and backup protection. Initially we defined the concept of agents for power systems, and pointed out that one of its main strengths is their ability to communicate. We believe that power utilities will have private communication networks as depicted in this paper in the near future. Based on this, we defined a utility intranet on the top of the power grid. This utility intranet is based on TCP/IP and UDP/IP standards. To analyze the agent technology for power system protection, EPOCHS, a platform that integrates a power system simulator (PSCAD), and a network communication simulator (NS2) was created and implemented. Our first two tests showed how agents can perform a primary protection scheme by exchanging basic information. As depicted in case 2, even though a communication link failure exists, a primary protection scheme based on a utility intranet can perform its goal successfully. The last two examples showed how agents can cooperate through communication to overcome different kinds of failures. The ability to communicate shows in these cases the power of agents over traditional systems. In all cases, the agent approach proved to be faster and more reliable than the traditional standalone alternatives.

VIII. ACKNOWLEDGMENTS

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