Multi-Agent Systems Hardware Development and Deployment for Smart Grid Control Applications

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Abstract **− A Multi-Agent System (MAS) for Smart Grid control is developed as part of the West Virginia Super Circuit (WVSC) Smart Grid Demonstration project. Both software and hardware deployment of the technology is being carried out on an Analog Power Simulator upgraded and automated to meet the Smart Grid requirements. The Multi-Agent System which is developed is based on mimicking the Human Immune System Cells behavior to intelligently perform feeder fault location, isolation, reconfiguration and restoration for a specific layout of the existing Allegheny Power West Run circuit.**

Index terms **— Smart Grid, Demonstration Project, Distribution System, Multi-Agent System, Immune System, Reconfiguration, Restoration.**

I. Introduction and Motivation

The Electric distribution system is facing a great challenge by responding to the rapidly changing customer needs for electricity in the modern world. The increased use of electricity has increased the number of outages, voltage and frequency violations, and other power quality disturbances. In addition, rising interest in renewables, distributed generators and storage devices is forcing the power grid into modernization, or what we call the Smart Grid, to meet the demands of the 21st century. The advances in microprocessors and communication technology can gear the power grid towards a modern and sustainable grid.

The US Department of Energy (DoE) has set a primary goal in modernizing the grid to support demonstration projects of key technologies that can serve as the foundation for an integrated modern power grid. They identify the inability to evaluate how the deployment will affect the electricity infrastructure as the largest barrier in the deployment of Smart Grid technologies [1]. The West Virginia Super Circuit (WVSC) project is part of the Modern Grid Initiative aiming at demonstrating and testing new technologies to enable the deployment and the implementation of Smart Grids. This work is part of the WVSC project which consist in developing the hardware and software platform laboratory to enable the development and testing of the new technologies before deployment in the real system. The distributed nature of Smart Grid technologies such as DERs, enabled load control and management at the customer level, advanced two way communication, etc., makes the Multi-Agent technology the most suitable to automatically manage and control the grid. To our knowledge, most of the work performed in the literature on the Multi-Agent system is still theoretical and lacks the practicality to be implemented as Smart Grid technology. We can identify the following major shortcomings in the literature [2-6]:

- Centralized Simulation of the MAS using computer based platforms. This approach tends to overlook the problems associate with the meshed two way communication system which is in its self a major source of challenging problems
- Most of the work is performed on radial systems while a high penetration of DGs are expected in Smart Grids
- Most of the work on power management is initiated without taking into account the voltage profile, which gives rise to problems in long feeder lines like the WVSC ones.
- Lack of experimental or laboratory testing.

In this work we try to develop a system that overcomes these shortcomings by using a more complete and robust MAS which consists in mimicking the Human Immune System. In the literature, the Immune System Algorithm is looked at as a centralized optimization algorithm [7-8] at the cell level or what we call the Clonal Selection technique. Yet in this work, the Immune System is viewed in its totality, meaning as a distributed system with its different types of cells, namely *Helper-cell*, *T-cell*, *B-cell* etc., including their behaviors and the communication that takes place between theses cells to build a complete, intelligent Multi Agent System for Smart Grid Control.

II. West Virginia Super Circuit [9]

The West Virginia Super-Circuit (WVSC) project will demonstrate improved performance, reliability, and security of electric supply through the integration of distributed resources and advanced technologies such as the Multi Agent System. It aims at:

- Achieving greater than 15% peak power reduction on the Allegheny Power (AP) and West Run #3 (WR-3) circuits - located in the Morgantown, WV, service area
- Demonstrate the viability of advanced circuit control through Multi-Agent technologies

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- Leverage advanced wireless communications to address interoperability issues between control and protection systems and distributed energy resources
- Demonstrate the benefits of the integrated operation of technologies such as rotary and inverter-based distributed generation, energy storage, advanced metering infrastructure (AMI), Price Driven Demand Response (DR), Automated Load Control (ALC), advanced wireless communications, and advanced system control technologies
- Demonstrate advanced operational strategies such as dynamic islanding and micro-grids to serve priority loads through advanced control strategies
- Demonstrate the reliability benefits of Dynamic Feeder Reconfiguration across several adjacent feeders

The circuit is divided into different zones connected through controllable switches as shown in Fig.1.

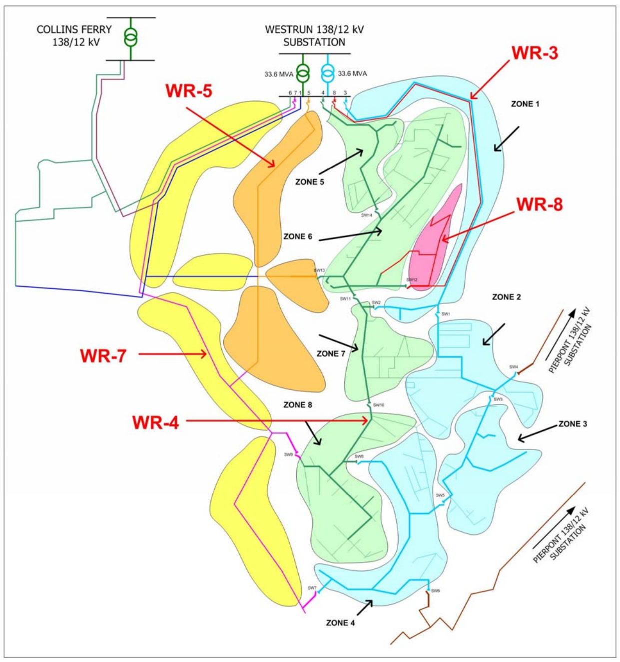

Fig.1. West Virginia Super Circuit diagram [9]

In this work, the fault location isolation and restoration part of the project is carried out in the laboratory by deploying agents' hardware with wireless communication capability on Analogue Power Simulator hardware.

III. Multi-Agent System

In this section, a brief definition of Multi-Agent System (MAS) is given as well as a reason for applying it to power systems. Weiss [10] defines an agent as "an autonomous computational entity such as software program that can be viewed as perceiving its environment through sensors and acting upon this environment through its effectors". So, a Multi-Agent System is composed of several of this type of agent which interact with each other to achieve a global goal. Hence, this type of technology can allow us to distribute and localize the control of power systems. By incorporating intelligence at the device level the reliability of the system should improve dramatically since there is no single point of failure as compared to the centralized control.

The Smart Grid technologies such as distributed generators, smart meters, costumer load control, adaptive protection, and microgrid control are expected to be highly distributed since controlling all of these distributed technologies from a central location would be very complex and needs vast computing capabilities to process the different types of data and controls of these systems.

The Multi Agent technology is expected to help distribute the processing and control at the device level. The inter agent communication allows coordination and exchange of data to achieve a global solution.

Communication is the most important characteristic of a Multi-Agent System. It has to be simple and universal. In this work, the Agent Communication Language ACL by FIPA (Foundation for Intelligent Physical Agents) is adopted.

IV. Laboratory Hardware Test Bed Circuit

The laboratory hardware prototype is an Analogue Power Simulator (APS) upgraded to meet the requirements for implementing Smart Grid technologies. In Fig.2 and Fig.3 we show the front and back panel of the APS. The one line diagram of the APS is shown in Fig4.

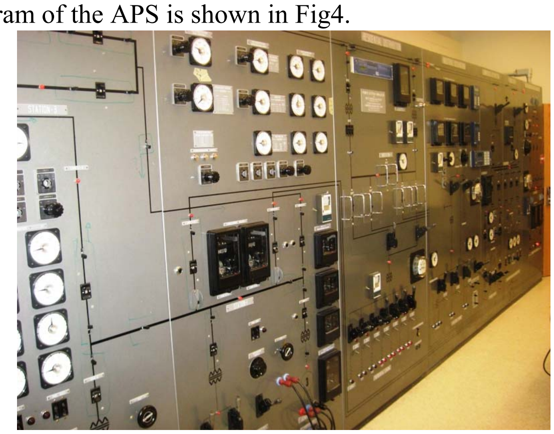

Fig.2. Power Simulator front panel

Fig.3. Power Simulator back panel

Microprocessor based agents are being installed along with a two way wireless communication platform to allow inter-Agent and Device-Agent communications to effectively perform the testing of the technology, shown in Fig.5. Also, the APS is now equipped with electronic switches that can be locally controlled by agents or remotely controlled through wireless communication. Microprocessor based relays are installed to allow flexible and adaptive protection schemes to be implemented. In addition, the APS offers the capability of connecting distributed generators whether connected to the grid or performing in microgrids. The APS is a powerful tool for testing and implementing advanced algorithms and new technologies to enable Smart Grid implementation in the real system by analyzing the transition from the old system of control where not much automation is employed to an advanced, automated and smart one.

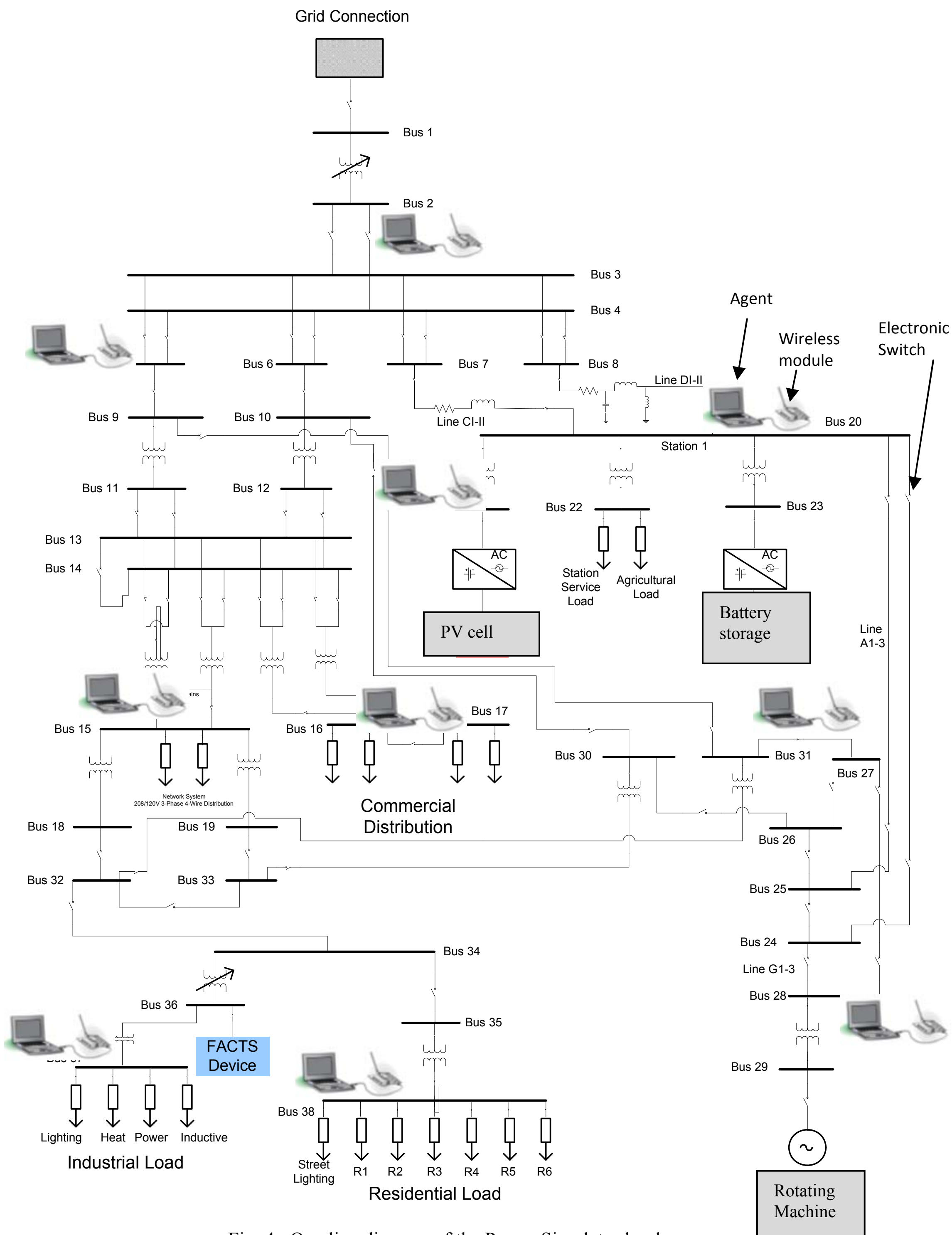

Fig. 4. One line diagram of the Power Simulator hardware

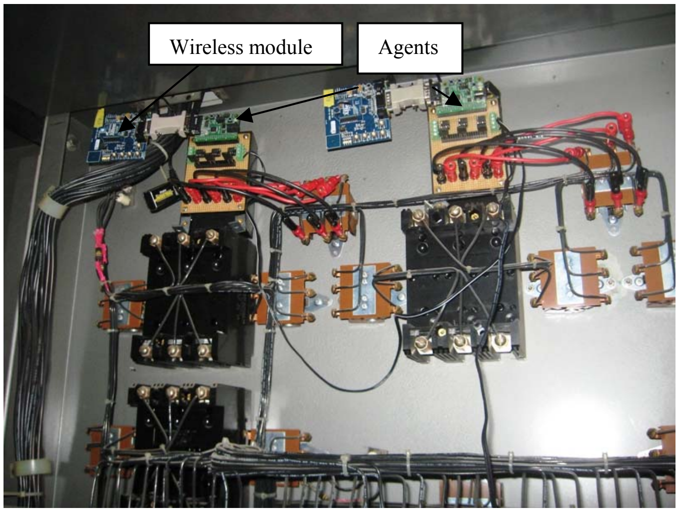

Fig.5. Agents deployed on the simulator

V. IMMUNE BASED MULTI-AGENT SYSTEM DESIGN

In this section, a MAS as defined above is designed using an Immune System approach. By observing natural systems such as Ant colonies, bee colonies or Human Immune Cells System, we realize that many of them act or form a natural Multi-Agent System. The Immune System is a highly organized, distributed and intelligent Multi-Agent System which is composed of millions of cells acting as an independent agent. These agents work together and communicate to mount global strategies against any bacteria or virus that invade the human body. In the following we shall give an overview on how the Immune System behaves as an intelligent MAS in the case of a body invasion by a bacterial substance, Fig.6.

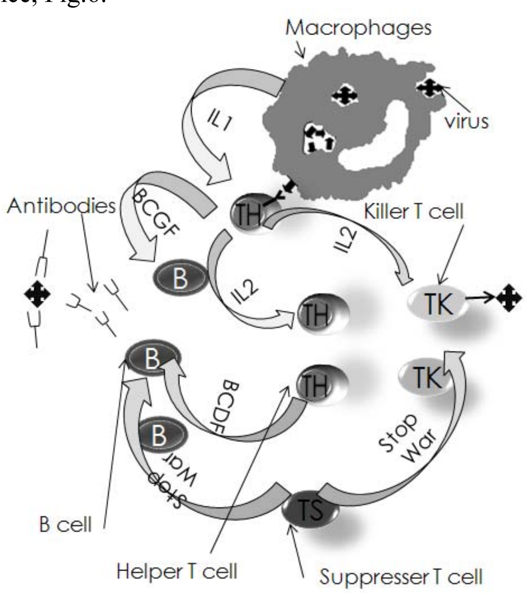

Fig.6. Immune Multi Agent System

First, the Macrophage (eater cell) takes in and ingests the invader organism (Virus, Bacteria) and binds to a helper T cell (TH) for antigen presentation. The secretion that activates the helper T cell (interleukin, IL-1) also stimulates the brain to increase the body temperature. This causes the common cold, which in turn increases the activity of immunity cells.

Once activated, the Helper T cell produces interleukin 2 (IL2) which causes the other helper T cells, B-cells and killer-T cells to develop and divide (BCGF-B Cell Growth Factor).
When the number of B cells increases, helper T cells produce another substance, which orders B cells to stop multiplying and start producing antibodies (BCDF-B Cell Development Factor). With the same signal, helper T cells also activate killer T cells (TK).
After the bacterial invasion is neutralized Suppressor T cells (TS) send a signal to the other cells to stop the attack. Memory T and B cells remain in the blood and the lymphatic system in order to become immediately activated in case a virus or bacterial substance of the same type invades the body again.
Now we have seen how the immune system operates as MAS with its entire characteristics, we shall try to design a MAS that operates on power systems based on the behaviors explained above.
In the case of the power system, the bacteria or virus is analogous to faults on the grid such as short circuit faults, overloading of the feeders, voltage violations, power generation shortage, etc.
The operation performed by the Macrophages of ingesting the virus and presenting it to the others cells is incorporated as an Agent behavior *MacrBehavior* in the body of each Agent to be designed by which an agent accesses information about abnormalities or violations in the current or voltage through the sensors or through the inter agent communication, Fig.7.
One of the requirements set by Allegheny Power (AP) in their Super Circuit is that no action can be taken by the agents after a fault in the system unless a lock out signal from the recloser is received. In this case the Macrophage behavior consist in the fault location by the agents using the prefault data. Once the fault is located, the faulted area is isolated first then the information is shared with the agents that can be involved in the reconfiguration restoration process.

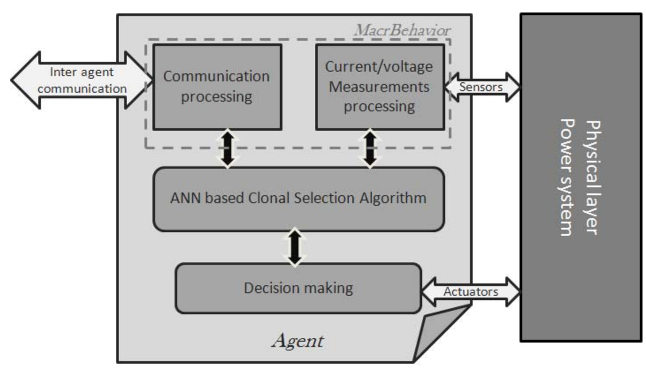

Fig.7. Single Agent Architecture

The second block in the agent body is designed by mimicking the *thymus* organ in the Human Immune System. This organ is responsible for training and teaching new born cells about the body and how to deal with foreign substances. In designing our agent we shall use the Clonal Selection Theory in order to perform the training process.
This theory proposes that as antigen (bacteria) enters the body certain cells are selected based on their reaction to this antigen to undergo rapid cloning and expansion. Those cells with a sufficient affinity are allowed to produce offspring in relation

to their degree of stimulus. Some cells transform into plasma cells and others are selected to become long lived memory cells which allow for a more rapid secondary response to the same or similar antigen. The training process is then incorporated as a Neural Network Block in the agent body for it to be used as a brain to help make decisions.

In Table I, we try to map and extract analogies between cells and behaviors in the Immune System compared to agents and processes for power system control.

TABLE I
Power System Immune System MAS analogy

Biological System	Power Systems
Thymus training The *thymus* is an organ located in the upper anterior portion of the chest cavity which is responsible for training and teaching the newborn cells and has important information and characteristics of the body and its cells.	**Training Process** This behavior is mimicked by using the Clonal Selection Algorithm to train certain types of agents before they are deployed on the power system. This training will constitute the brain of the agent that helps it in taking decisions.
B-cells These cells are responsible for producing antibodies in case of an invasion of the body by harmful substances. The cells or the antibodies perform Clonal Selection to recognize the substances and destroy them.	**BusAgents** These agents are responsible for locating and isolating faults that occur between the buses then use the Clonal Selection Block to identify a solution for the problem. The potential solution is applied by means of communication and negotiation with the different agents involved in the process of applying the particular solution such as SwitchAgents or HelperAgents.
Killer T-cells These cells are usually activated by a signal from the Helper T-cells. They are equipped with a special molecule that enables them to recognize the foreign substances and the infected body cells without performing any mutation or Clonal Selection.	**SwitchAgents** These agents are located at switches and they are responsible for altering the configuration of the power network. They are activated by the HelperAgents in case of a request or a need to change the network topology. **LoadAgents** These types of agents are responsible for controlling the loads. **SourceAgents** These type of agents are located at the sources whether substations or distributed generators. They are responsible for controlling the power generation.
Helper T-cells These cells do not directly kill infected cells, as Killer T or B cells do. Instead they help activate and direct Killer T cells and macrophages to attack infected cells, or they stimulate B cells to secrete antibodies. They are the coordinators of the whole attack on the foreign substance.	**HelperAgents** These agents play a role of coordinator or mediator by helping other types of agents reaching their objectives. Some of the functions of these types of agents are: - Solving communication conflict between the agents - Creating communication bridges for distant agents - Checking limit violations - Distributed processing and analysis of data - Help in reducing the complexity of the other types of agents

VI. EXPERIMENTAL RESULTS

In the following scenario, a three phase fault is simulated on the Power Simulator Hardware. For illustration, a simplified version of one line diagram of the power simulator hardware showing the affected portion and the placement of the agent's hardware is depicted in Fig. 8. The figure also shows the zoning of the power simulator similar to the WVSC layout.

To test the Multi Agent System hardware developed, a three phase permanent fault is applied on the Feeder#1 in ZONE#2 (green color). In the pre-fault state, an unbalanced agricultural load is being supplied from one of the main feeders of the system (Feeder#1) and an unbalanced residential area is supplied through a second feeder (Feeder#2) see Fig. 8.

At the moment the fault is applied on the feeder, the first protective device, which is the developed electronic recloser, is automatically triggered. The recloser turns on and off 3 times before the permanent lockout since the fault is maintained on the feeder line.

As it can be seen from Fig.9, that the faulted feeder is totally de-energized to meet the requirement set in the WVSC design. Once the recloser locks out, the Agent residing at the substation send a permission signal to the zonal agents start the isolation and reconfiguration. Once the signal is received, Agent2 and Agent3 shown on Fig.8 isolate the fault and perform the reconfiguration by interacting with Agent4 residing on the Feeder#2. After reconfiguration Zone#3 is restored see Fig.10.

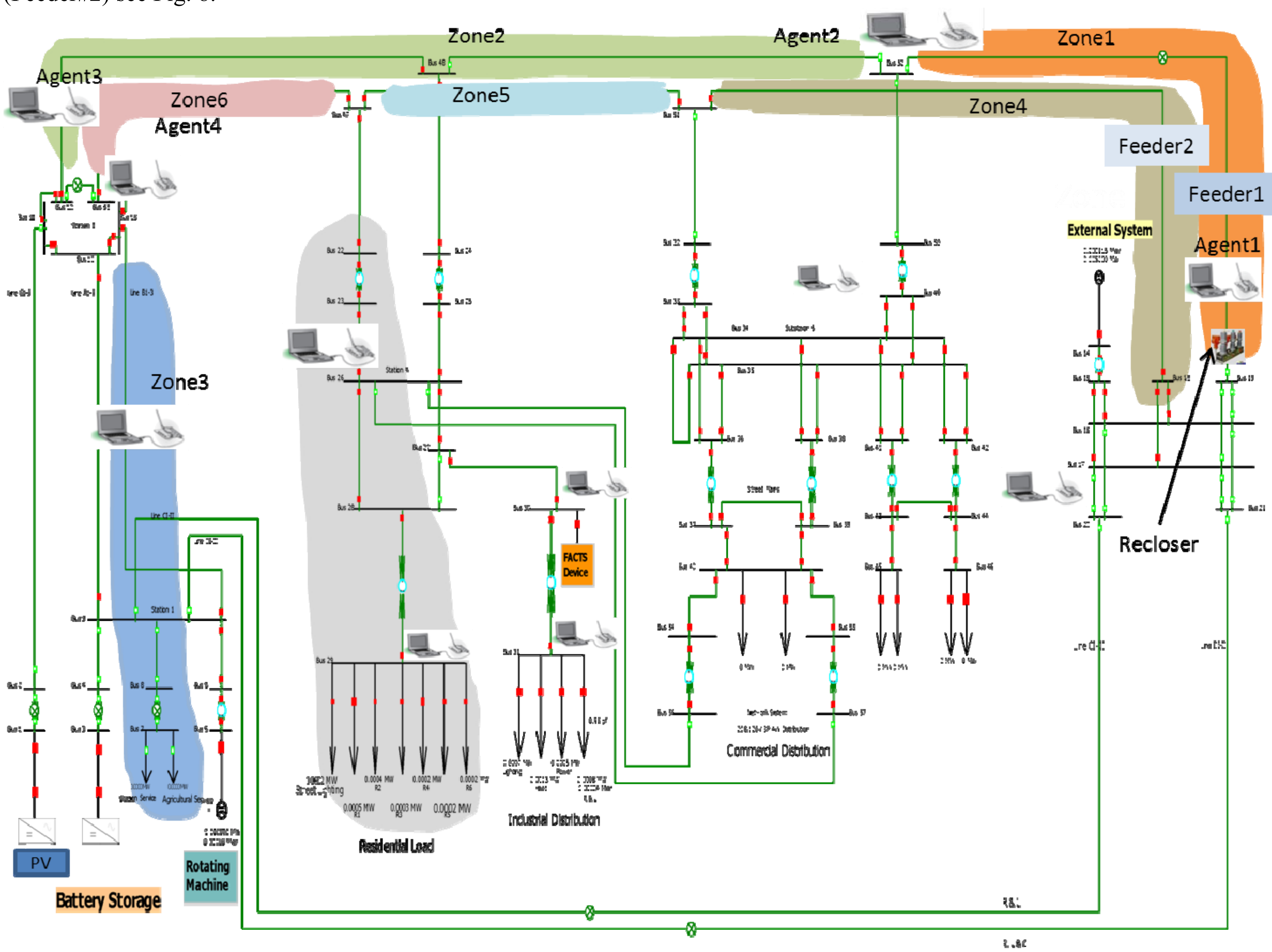

Fig. 8. One line diagram of the Power Simulator hardware

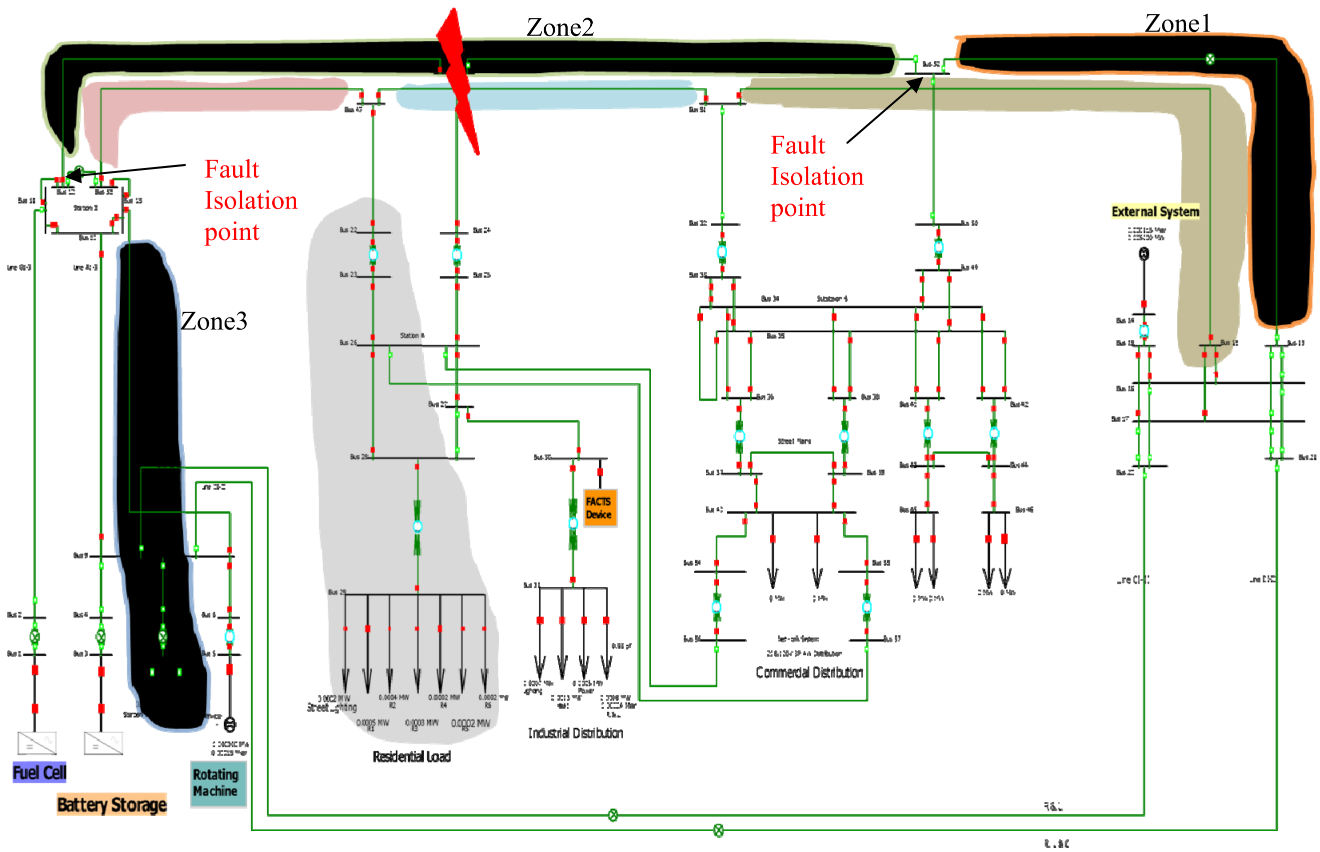

Fig. 9. One line diagram of the Power Simulator hardware

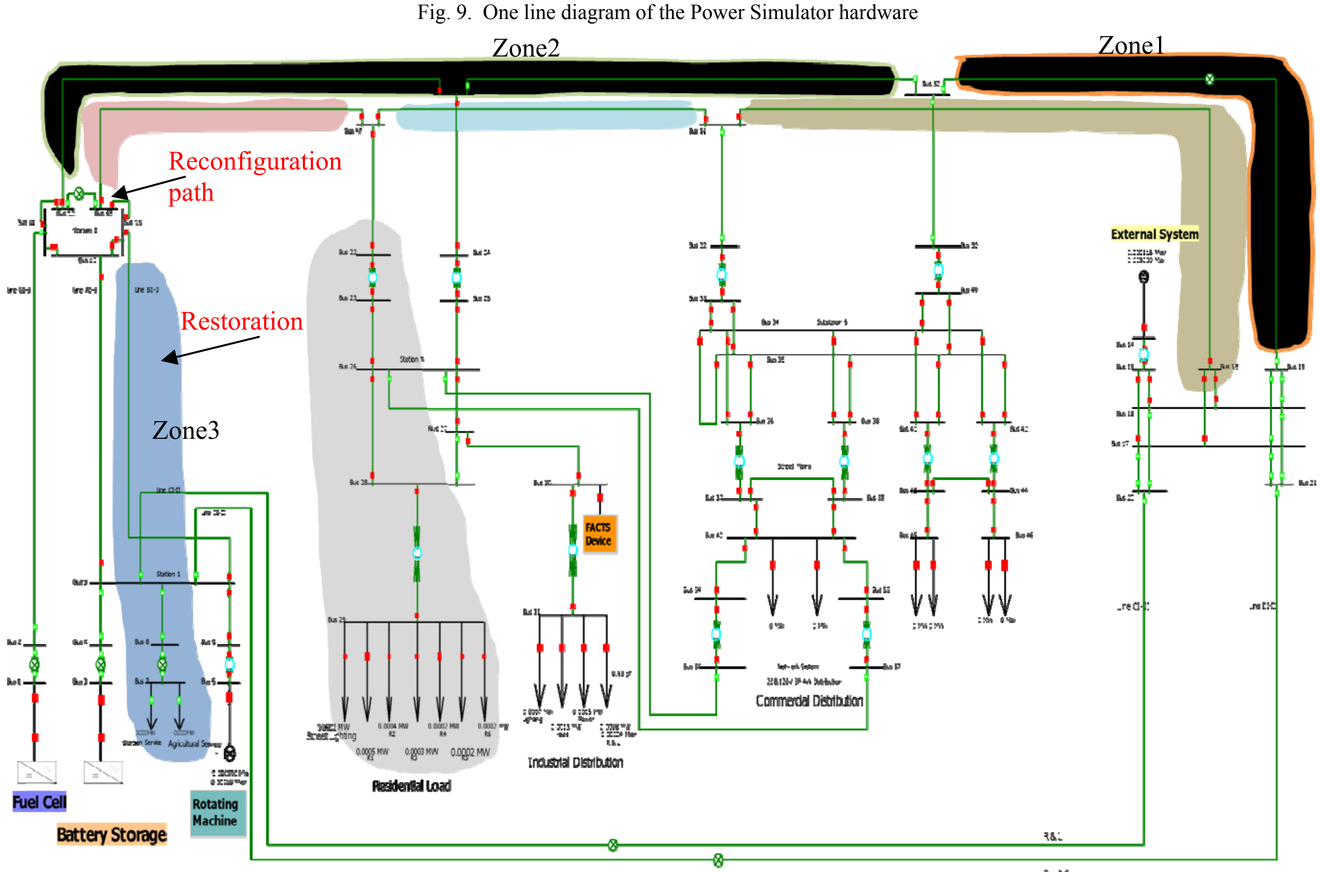

Fig. 10. One line diagram of the Power Simulator hardware

In the following we are showing the experimental data of current waveforms collected during the scenario.

Fig.11 depicts the current flowing through Feeder#1. The waveforms show the pre-fault, during fault, and after fault phases.

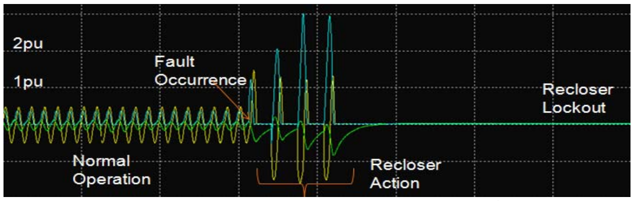

Fig.11. Experimental Data of the current on the 1st Feeder

Fig.12 depicts the current waveform measured in zone#3 of Feeder#1 (seen at the customer level). From data we can observe that the customer power outage period is about half a second for this particular scenario.

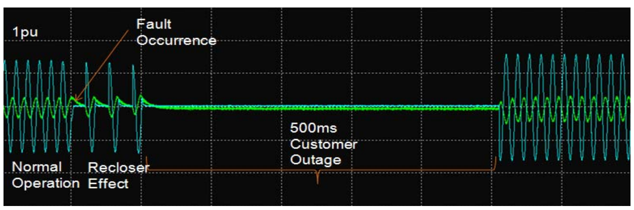

Fig.12. Experimental Data of the Current at the load level

Fig.13 depicts the current waveform measured in at the Feeder#2. We can observe that the increase in the current due to restoration of Zone#3.

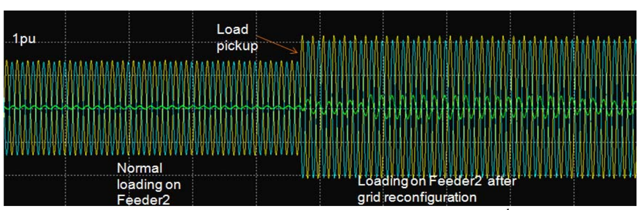

Fig.13. Experimental Data of the current on the 2nd feeder

VII. Conclusion

The Focus of this work is the development of a laboratory Smart Grid Test Bed and the development and deployment of emerging technologies such as the Multi-Agent System. The paper address the use of the Human Immune System viewed as a Multi-Agent System to perform self-healing and control of the grid by automatic fault location and isolation, reconfiguration and restoration. The preliminary experimental results show that the technology is very promising and effective. The detailed model of immune system based multi-agent system described above is still under hardware development and testing in order to design a reliable system to be implemented on the WVSC.

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IX. Biographies

Rabie Belkacemi received the *Diplôme d'Ingénieur d'Etat en Electrotechnique* from the *Ecole Nationale Polytechnique* of Algiers, Algeria, in 2004 and a Master’s degree in Electrical Engineering from the Institute National des Sciences Appliquées de Lyon, France, in 2005. He is currently a Ph.D. student and research assistant at the Lane Department of Computer Science and Electrical Engineering. His main interests include Power Systems Control and Protection, software and hardware development of Multi-Agents System, Intelligent Control, Smart Grid, Renewable Energy Resouurces, Artificial Immune System.

Ali Feliachi received the MS and PhD degree in electrical engineering from Georgia Tech in 1979 and 1983 respectively. He joined the faculty of Electrical and Computer Engineering at West Virginia University in 1984 where he is now a Full Professor, the holder of the endowed Electric Power Systems Chair position, and the Director of the Advanced Power & Electricity Research Center. His research interests are in modeling, simulation, control and estimation of large-scale systems with emphasis on electric power systems.

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