Toward Digital Ecologies:Intelligent Agent Networks Controlling Interdependent Infrastructures

Valeriy Vyatkin, Gulnara Zhabelova
Department of Electrical and Computer Engineering,
The University of Auckland
Auckland, New Zealand
e-mail: v.vyatkin@auckland.ac.nz

Mihaela Ulieru
Department of Computer Science
University of New Brunswick
Fredericton, Canada
e-mail: ulieru@unb.ca

Don McComas
Eaton Corporation,
Pittsburgh, PA
e-mail: dontmccomas@eaton.com

***Abstract*— Universal, intelligent and multifunctional devices controlling power distribution and measurement will become the enabling technology of the ICT-driven SmartGrid. In this paper we discuss a design and simulation environment which provides a virtual model of such devices and at the same time enables their interoperability and configurability. The solution is based on the combination of IEC 61850 interoperable communication and IEC 61499 executable specification. Using the simulation environment we demonstrate the possibility of multi-agent control to achieve self-healing through fault location and power restoration.**

***Keywords*-- Smart Grid, multi-agent control, simulation modeling, IEC 61850, interoperability, distributed intelligent automation, IEC 61499**

I. BACKGROUND AND MOTIVATION

Critical infrastructures, such as power distribution systems are designed according to two contradictory design metrics. On the one hand, they have to be robust to avoid power outages even in the presence of serious external disturbances, such as natural disasters or supply and demand fluctuations. Achieving this would require redundancy and sophisticated control systems. On the other hand, such systems have to be economically viable, and, moreover, providing for efficient power consumption in accordance with the latest "green" trends. To add to the complexity, critical infrastructures are highly interdependent, and their simulation and analysis is a major challenge due to the complexity and heterogeneity [2].

Governments throughout the developed world are investing in modernization of their energy grids. The SmartGrid initiatives are aiming at a breakthrough in achieving a synergy of these design metrics by suggesting revolutionary Information Communication Technologies (ICT) infrastructures that will add to the robustness adaptability, self–healing and self–protective capabilities to support highly dynamical networks of power producers and consumers (*prosumers*). The advanced ICT will incorporate into the grid "the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level" [3].

The new generation of 'smart grids' uses information technology and next-generation controls to increase energy grid efficiency while decreasing the environmental impact of production, distribution, and final use of energy. Two-way communication between power supply and end-users enables increased efficiency. 'Smart' devices such as household appliances, for example, are programmed to use energy only when signaled that peak demands times have passed. Decreased peak demand for energy enables reduction in total energy production, reducing demand for non-renewable energy sources just at the time that smart grid technologies additionally permit integration of new, renewable forms of energy production into the grid (e.g., wind, solar). As demand falls and non-renewable sources are phased out, end-users pay less for energy, and the energy they do use imposes a smaller footprint on our environment.

Designing such ICT-driven SmartGrids imposes major challenges concerning the high dynamics and enormous computational complexity of such large scale control environments [4] which approach the complexity of natural systems. To this extent, lessons learned from biology have recently been found very useful in managing the complexity of the plethora of competing and collaborating autonomous self-configurable units [5], similar to natural ecosystems where the balance between production and consumption of resources is achieved and maintained as a result of competition between populations. The striking success of the Internet resides in fast-moving, *bottom-up* processes allowing people to get directly involved in the technological changes that affect society and the economy. Its key aspect is the *decentralized* or peer-to-peer (P2P) paradigm of information generation and distribution. Beneficial collective user behavior can be catalyzed and reinforced by a P2P-enabling ICT infrastructure based on a network of intelligent social and collaborative agents (Figure 1, [1]). In what we refer to as 'digital ecology' theory and practice [5], research aims to understand and advance the interweaving of humans and ICTs to create a world with social, physical, and cyber dimensions enabling a kind of social network in which humans are not just 'consumers' of data and computing applications. Actors in the social network operating within the new digital eco-system are much more: they are producers, 'players,' and 'inputs' whose interactions use the 'invisible hand' of the market as they interact in complex, interdependent global-scale systems in areas such as energy production and use, and neighborhood, district, city, and regional transport.

With advances in sensor and wireless communications technologies, digital ecosystems are poised to connect and even fill existing and newly created applications connecting different environments thus giving rise to many promising solutions to pressing problems. Imagine energy and communication webs using software applications enabling users to better regulate

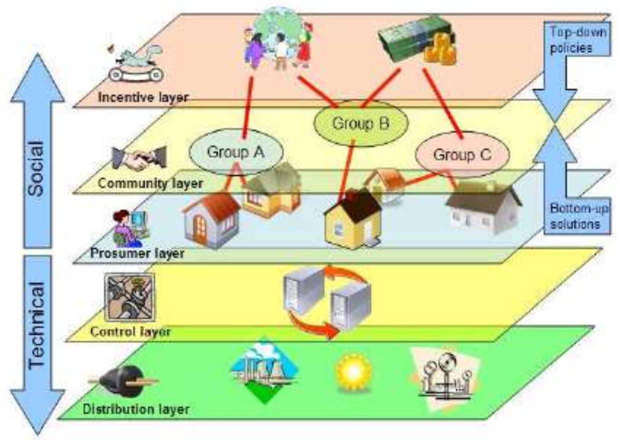

Figure 1. ICT infrastructure of SmartGrid [1].

power consumption and cost, through behavioral change and automated monitoring of home appliance energy use through smart meter networks, in turn connected to time-of-use pricing applications. Closely associated environments include intelligent transportation systems whose data are fed to smart power grids, enabling them to forecast and meet demand from plug-in hybrid electric vehicles in a city. At the same time as networks of small-scale communicating devices are interacting to form a "skin" that covers physical and virtual spaces, a second major parallel development of ICTs is concentrating computing and storage at optimal locations. Very substantial economies of scale are driving the deployment of cloud computing, where massive-scale data centres concentrate high densities of computing resources at ideally sited locations to support software applications on demand. The very large scale of these data centres results in total savings by factors of five to seven times through reductions in expenses for equipment, power, cooling, facilities and operations [6]. These applications share a common set of features:

- All are driven by the aggregate behavior of communities of human users.
- All contribute to energy efficiency in turn contributing to reduction in greenhouse gas emissions and overall reduction of the ecological footprint of industrial and private activities.
- All have performance and reliability requirements that if unmet have deleterious socioeconomic impacts to the extent that poorly designed applications can create more problems than they solve, ultimately becoming eco-negative.
- All involve control and management mechanisms that mediate the supply and demand of some critical resource.
- All attempt to estimate the supply and demand for the resource using data gathered by a network of sensors.

Our purpose is to design a multi-agent modeling approach acting as a 'nervous system' to control large scale interdependent grids in the digital ecology by combining the seemingly irreconcilable features of increased reliability, economic feasibility and efficiency.

II. BEYOND THE STATE OF THE ART

Our vision pushes the boundaries of current approaches. Existing ICT systems and the Internet were not deployed to act as a control backbone of physical infrastructures (or interdependent infrastructures such as communication, energy and transportation grids). Yet, at the same time, the Internet is already acting as a vital ganglion of the current globalised society and economy, controlling critical infrastructures on a global scale. Intertwining a complex ICT system (as the Internet can well be considered, [7], [8]) and a physical complex system (as for example the electrical power grid) [9] [10] or a system of systems (such as when the networked electric vehicles will juxtapose over the current power grid) is leading to what are usually referred to as *cyber-physical systems* (CPSs) [11]. As a CPS, a digital ecology is an open ICT control infrastructure, in which intertwined interdependent systems of systems (electrical grid and networked transportation) weaved by the Internet together with social networks of prosumers (producers and consumers) of applications and services, co-exist and co-evolve, in much the same way as different species share the resources of a common habitat and provide mutual benefits in an ecosystem-like manner [4, 12]. The inclusion of the users themselves as key players in shaping and tuning the ICT part as a "Web 2.0"-style architecture of participation [13] gives rise to a unique techno-social system, with the possibility of dramatically changing the way we live in a sustainable green planetary ecology. We envision a future in which the traditional distinction between producers, distributors and consumers of resources and services is replaced by the new role of *prosumers*, for example industries, cities, communities or individuals who can act both as producers and consumers of energy. Prosumers will strive and collaborate to define new energy saving measures and new consumption models. Given the right technical support and incentives, it is expected that these local and small-scale initiatives will be much more innovative than any solution implemented through global policies at a national level. Because they would emerge on the basis of individual interest and volunteering, making choices about getting involved or not, "peoples' solutions" have the potential to reach faster and far beyond the limits imposed by political restraint and slow societal changes. In a digital ecology distributed systems at various levels of resolution, ranging from single devices to spaces, departments and enterprises, are brought together into a larger and more *complex* 'system of systems' in which the individual properties or attributes of single systems are dynamically combined to achieve an emergent desired behavior of the synergetic ecosystem [14].

The inherent feature of the new ICT-enabled critical infrastructures is flexibility manifested as the ability to accommodate different functions (which may evolve during the system lifetime) and combine them in various structures. With flexibility, the validation of such control systems becomes a challenge since the traditional simulation approaches are no longer easy to apply. To simulate such a complex system, its explicit modeling is required. However, if the control components come from different vendors, it is a major effort to even integrate them into a single system. When it comes to modeling, the overhead of designing a model is comparable to the system development from scratch.

We propose a solution that solves both these problems at once. First we rely on open standards. This aims at interoperability of the intelligent control devices. We use executable specification in form of function blocks of IEC 61499 to encapsulate and implement the agents. In this form, the agent solutions can be easier validated and immediately deployed to embedded control devices. The agents are structured according to and communicate via the services of IEC 61850 [15] – the international standard proposing an open communication and object-oriented data model for intelligent control devices.

Our solution will pave the way to industrial adoption of Grid automation and monitoring devices which will be capable of combining different functions and achieving goals in collaborative effort with other such devices. Prior to the deployment, the behavior of such systems can be verified through multi agent simulation.

The rest of this paper is organized as follows: In Section III we survey the key concepts of the multi-agent approaches to Grid automation. In Section IV we propose a design framework based on the combination of function blocks of IEC 61499 and logical nodes/intelligent electronic devices of IEC 61850. Section V illustrates the simulation potential of this framework, demonstrating achievement of a fault location and service restoration scenario.

III. CHALLENGES IN TRANSITIONING THE POWER SYSTEM AUTOMATION ARCHITECTURE FROM CENTRALIZED TO MULTI-AGENT DECENTRALIZED CONTROL

One of the first steps towards the Smart grid concept is the idea of automated fault location, isolation and service restoration (FLISR), so-called “self-healing grid” [16]. In this paper we show how our framework is capable of achieving FLISR in a purely distributed way through the collaboration of agents.

There are different power system automation architectures presented and proposed in the power system utility and research environment [1, 17-24]. There is no single substation automation configuration which will fit every power system configuration. However, [25] states that there is a basic architecture toward which the advanced systems tend to converge, Figure 2 (left hand side).

There are three basic components. The object component comprises intelligent electronic devices (IEDs), microprocessor-based relays, remote terminal units (RTUs) and PLCs. They perform local control and mathematical calculations, send and receive signals to/from other peers or the SCADA (Supervisory Control and Data Acquisition) master. The component consists of two levels: primary equipment and bay level (local intelligence in the form of IEDs and RTU). Communication network interfaces bay level functions with SCADA station level control; and is realized in the form of fibre-optic cable in advanced modern systems. SCADA master is central control; it receives data and information and makes decisions, displays information for SCADA operator, and controls the power system through bay level devices.

Several researchers propose the multi agent approach to power system restoration. For example, T. Nagata and H. Sasaki in [19] define the multi-agent system as a computational system where the agents exhibit collaborative behavior to achieve a particular goal. The proposed system has a number of bus agents (BAGs) and a single facilitator agent (FAG). The BAG has a goal to find suboptimal target configuration after fault has occurred by cooperation with other peers (BAGs); the authority to make a decision is given to FAG which is acting as manager.

The BAG uses the following negotiations tactic:

- If the bus has a several branches to restore supply, BAG selects the branch with most available headroom capacity;
- If the available power is not enough then the BAG tries to restore supply though its neighboring BAG; In case of insufficient power available, BAG makes a decision to shed the load and cuts off the load as small as possible.
- All the actions and decision making are in the area of responsibility the bus the BAG belongs to.

The communication between BAGs is done by using knowledge query and manipulation language (KQML). The simulation has proved that the multi-agent system is effective and efficient as it uses only local information and simple negotiation strategies.

The proposed architecture of multi-agent system is derived by using object-oriented techniques. BAG is allocated to each bus and there is a single FAG for the system.

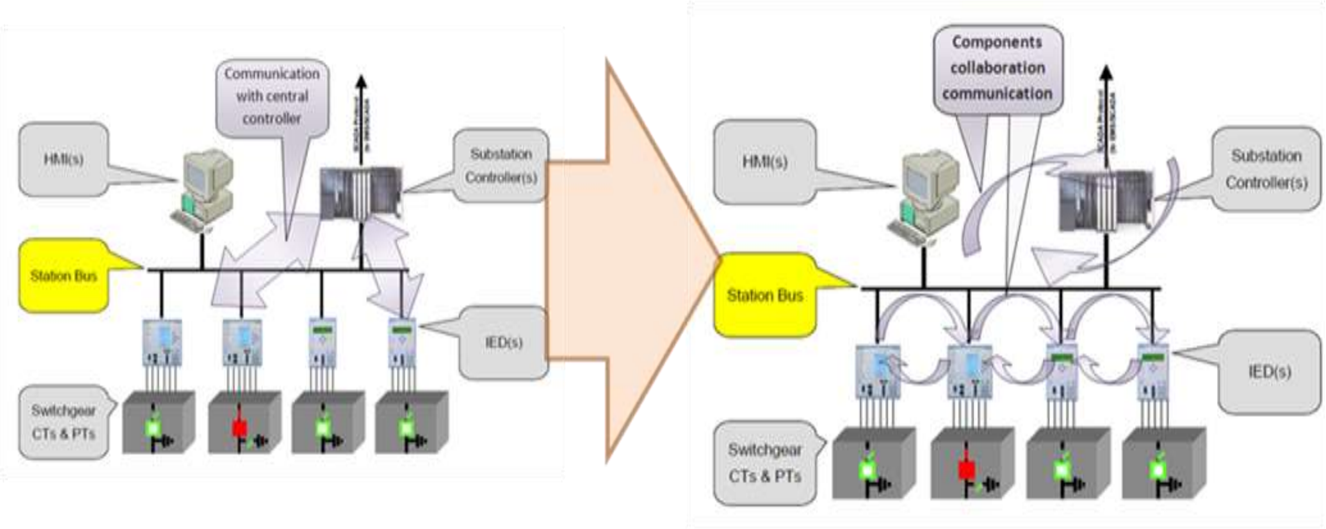

Figure 2. The shift from traditional architecture with central control towards Smart Grid with decentralized decision making.

Once the fault has appeared the BAG sends request to FAG for supply restoration on the bus it is allocated to. This message triggers the functions of the multi-agent system. In response the FAG sends start signal to requesting BAG and thus initiates algorithm of the agent: it starts negotiation with the neighboring BAGs. FAG as manager classifies the de-energized buses into groups depending on the voltage group. Then it chooses the BAG on the highest voltage bus and sends a start message. The same process is carried out with other de-energized groups in parallel. So the restoration process occurs concurrently in the de-energized network. The selection of the target configuration is based on comparison of the available power and load needing to be energized. The tool used to implement the concept is Java using JDK 1.1.

However, the gap between the multi-agent control and the state of the art seems to be insurmountable, as situation is exacerbated by the huge imposts of safety requirements and other domain specific standards and practices which simply block any attempt to innovate. It is frustrating to have available technologies, [26],[27] and not be able to use them to improve grid automation simply because the existing control devices are based on proprietary hardware/software platforms.

As the substation automation is usually based on proprietary hardware/software platforms, the advanced technologies such as multi-agent system are hard to be used to improve and enhance grid automation [28]. The complicated implementation and algorithm of the multi-agent control cannot yet deliver sufficient real-time performance and determinism even on top-end hardware [28].

Utilities and involved parties prefer and have a strong reliance on microprocessor–based relays and controllers, as they provide high reliability and determinism, while the multi-agent systems demand powerful workstation to run. Thus practical usage of the intelligent multi-agent technology in power system control and operation is depending on the progress of the next generation of IEDs to have open architecture and be industrial standard compliant in the areas like information configuration and distributed automation [29].

IV. PROPOSED INTEGRATED STANDARDS FRAMEWORK: IEC 61850 AND IEC 61499

To facilitate the adoption of intelligent multi-agent solutions at the transmission and distribution layers of the Smart Grid demands an open architecture for the next generation of IEDs, based on industrially accepted standards in the areas of information, configuration, communication and distributed automation. In alignment with these requirements, our work proposes an innovative integration of the IEC 61850 and IEC 61499.

The IEC 61850 standard (Communication networks and systems for power utility automation) [15] refers to substation information, information exchange and configuration aspects mainly for protection, control and monitoring. While the automation functions that produce and consume the exchanged information are outside the scope of the standard. when it comes to the future Smart Grid envisioned as a truly intelligent, self-healing distribution network [30] the core operational principles must be built on centralized and distributed automation functions to enable the necessary “plug-and-play” self-reconfiguration, “self-awareness” in various forms, and collaboration between subsystems for achieve optimum performance and natural scaling with minimum risk [3].

Subject to the availability of pervasive communications, we suggest that this behavior can be achieved with a distributed automation architecture provided by the IEC 61499 standard [31] which describes a general purpose *Function Block* architecture for industrial process measurement and control systems. A Function Block is a software unit (or, more generally, an *intellectual property* capsule) that encapsulates some behavior. The standard provides a framework for gluing functions together in patterns of increasing capability and complexity. We believe that the resulting ability to customize control and automation logic will greatly enhance the flexibility and adaptability of automation systems, speeding progress toward the Smart Grid.

In [32, 33] we have proposed ideas for a Smart Grid ICT architecture that is based on a combination of these proven industry standards. In [34] we have discussed in detail the methodology of implementing the IEC 61850 data model by means of IEC 61499. This would replace the current rigid hierarchical structure of centralized decision-making with the decentralized flexibility and open nature of IEC 61499 seamlessly endowing the architecture with bio-inspired control patterns. However to realize this vision, in turn requires a revolution in how IEDs are designed, to accommodate a network approach [3] that enables horizontal communication, negotiation and collaborative decision making. Most advanced versions of such devices are currently based on microcomputers with communication capabilities, but the architectural focus – a legacy of current SCADA systems – is on the bottom-up flow of the data, from IEDs to the control centre, and the top-down flow of control (from the control centre to IEDs).

Since the IEC 61850 standard protocol has been introduced, the main tendency of substation automation is focused on object division of the automation architecture discussed above. There is quite a diversity of researches carried out, implementing advanced technologies such as multi-agent systems [1], local controller [18], dynamic topology engine [22], advance DMS [21] and method of island operation of the grid [35].

The open function block architecture of IEC 61499 can help to achieve the properties of bio-inspired grid control. Intelligent electronic devices can be built “on top” of standard Programmable Logic Control (PLC) devices or Remote Terminal Units (RTUs) by adding function block libraries as shown in Figure 4. Representation of Logical Nodes (LN) as function blocks enables the simulation of the whole distributed automation system.

The internal architecture of such controllers will be customizable during their life-cycle, thus providing for implementation of bio-inspired design patterns such as design for learning, development and evolution. Moreover, validation of the control and automation functions will be possible by simulation of the corresponding function block applications, taking into account the structure and logic of the whole substation.

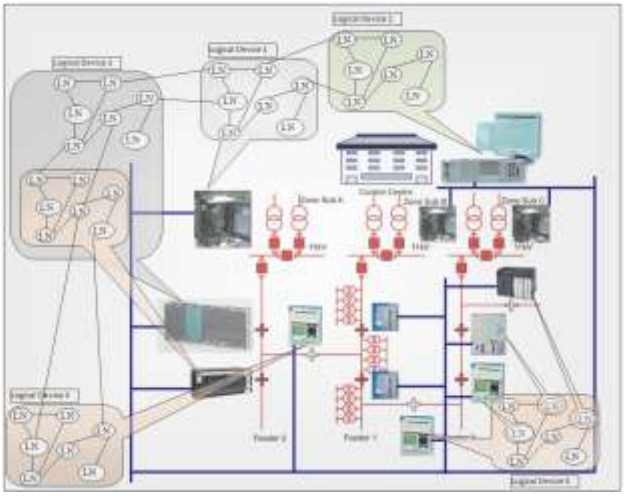

Figure 3 Proposed approach: distributing the control and functions to the autonomous intelligent component.

In terms of IEC 61499, the distributed utility control is represented as a system composed of a number of devices. For simplicity, at this stage we have grouped the functions related to each feeder to one device, and implemented IEDs as resources in the IEC 61499 terminology.

V. SIMULATION ENVIRONMENT

To validate the proposed architecture we built an example system (Figure 4) and created a test bed by combining a function block execution environment with a model of the “uncontrolled substation” in Matlab.

Measurements are sent to the controllers and control signals are delivered back to the substation model using a TCP/IP communication channel. Thus, the test bed enables closed-loop control simulation and can be used for validation of the decentralized communicating multi-agent controllers. In real distribution networks the communication would be implemented with the IEC 61850 communication methods sampled measured values, GOOSE and client/server.

Several tests of increasing complexity were done to verify correctness of the collaborative control architecture and algorithms.

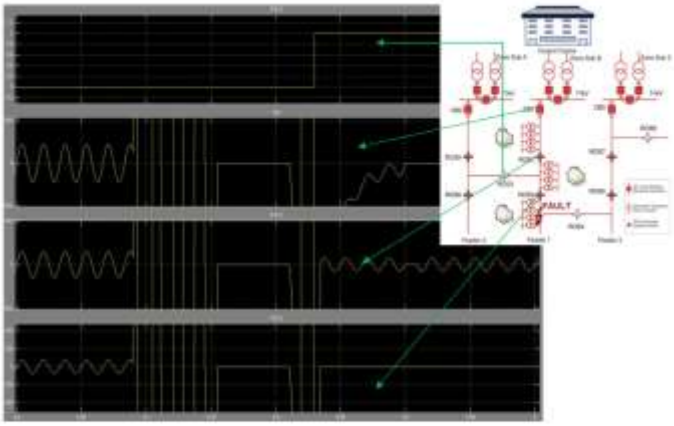

Figure 4. FLISR scenario: fault is on ROS2 section, supply restored on ROS1 section.

An interesting scenario is when fault occurs on tail section of feeder 1 (ROS2). In this case ROS2 should isolate fault and section ROS1 should get supply from feeder 2, CB1’s part of feeder 1 will stay power off as this part does not have tie switch. Figure 3 illustrates this scenario. Graphs show normal current before fault occurred at 4.069 second. All sections along feeder 1 should detect fault current as the fault is on the tail section of the feeder. This can be seen on graphs “CB1”, “ROS1”, “ROS2”: the current value is become extremely high around 2000 A. The protection detects the fault and trips circuit breaker at 4.751 s, thus all sections are cut from power and current is zero. After “dead time” (the time RREC waits to reclose circuit breaker again) has elapsed CB1 is reclosed (4.82 s). Protection detects the fault current again and trips the circuit breaker CB1 permanently this time, cutting the power on the feeder 1, so that after 4.87 s and on the feeder 1 does not have power (graphs “CB1” and “ROS2”). After RREC has gone to lockout state, the PIOCs performs their fault location algorithm and have agreed that fault is on the last ROS2 section, that’s why corresponding graph shows zero current after fault occurred and on.

The sections CB1 and ROS1 have to get supply from alternative sources. They both sends request to adjacent tie switch; however CB1 does not have ties switch connected and the alternative supply for this section is not possible. ROS1 part of the feeder will get the supply through tie switch ROS3. And it is illustrated in Figure 3 graph “ROS2” at 4.87s when the tie switch ROS3 closes (graph “ROS3” moves from “0” to “1”). Graph “ROS1” shows that current value has come back to normal level: 70A.

This scenario proves that the distributed control of the power grid is possible. Autonomous components of the power distribution system can collaborate and sustain power grid operation. The components are distributed by nature, enhancing the components with the intelligence makes the system “self-controlled”: control is distributed across active elements which are able to interact with the peers and solve arose problem.

The graph demonstrates that FLISR mechanism carried out by intelligent components of the system without central control intervention works: the supply has been restored on the non-fault sections of faulty feeder regardless of fault location. The fault has been simulated on every section on each feeder of the sample distribution system, and proposed approach successfully carried out FLISR scenario: supply has been restored in each scenario (where it is possible to restore supply: subject to presence of the adjacent tie switch).

VI. CONCLUSIONS

In this paper we have presented a design and simulation environment for Smart Grid controls. We have demonstrated that self-healing can be achieved via distributed multi-agent control in a multilayered ICT architecture combining IEC 61850 interoperable communication and IEC 61499 distributed control. Other intelligent functions possibly can be easily added. The developed architecture simplifies adding intelligence to logical nodes as an extra layer extending the capabilities of substation automation devices and not interfering with their safety-critical functions.

Future work will be dedicated to the implementation of IED prototypes based on the combination of IEC 61499 and IEC

61850 as well as to extending the framework by adding the intelligence required to combine energy production and consumption in micro-Grids. Our work on digital ecologies will help understand how to design a bottom-up infrastructure and provide top-down incentives to create the right conditions for people to organize themselves, in tight interaction with devices and information communication technologies.

Further we also plan to investigate ways of combining our simulation environment with models of other critical infrastructures in order to achieve a holistic view of the interdependent infrastructures environment.

VII. REFERENCES

[1] Pipattanasomporn M., *et al.*, "Multi-agent systems in a distributed smart grid: Design and implementation," in *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, 2009, pp. 1-8.

[2] S. D. Porcellinis, *et al.*, "Simulation of heterogeneous and interdependent critical infrastructures," *International Journal on Critical Infrastructures*, vol. 4, 2008.

[3] "Report to NIST on the Smart Grid Interoperability Standards Roadmap," Electric Power Research Institute (EPRI)August 10, 2009 2009.

[4] S. Grobbelaar and M. Ulieru, "Complex Networks as Control Paradigm for Complex Systems," presented at the IEEE Systems Man and Cybernetics Conference, International Workshop on eNetworks Cyberengineering, Montreal, Canada, 2007.

[5] M. Ulieru, "Foreword," *Special Issue on Cyber-Physical Ecosystems, IEEE Transactions on Systems, Man and Cybernetics*, 2010.

[6] W. Vogels, "A Head in the Clouds -The Power of Infrastructure as a Service," presented at the First workshop on Cloud Computing and in Applications, 2008.

[7] K. Park and W. Willinger, Eds., *The Internet As a Large-Scale Complex System*. Oxford Univ. Press, 2005, p.^pp. Pages.

[8] Alderson and Doyle, "Contrasting views of Complexity and their Implications for Network-Centric Infrastructures," *Transactions of IEEE Systems, Man and Cybernetics, Special Issue on Cyber-Physical Ecosystems*, July 2010.

[9] M. Dahleh, *et al.*, "Information and control: a bridge between the physical and decision layers," presented at the NSF Workshop on CyberPhysical Systems, 2006.

[10] B. McMillin, *et al.*, "Cyber-Physical Systems Engineering: The Advanced Power Grid," presented at the NSF Workshop on CyberPhysical Systems, 2006.

[11] in *Cyber-Physical Systems Summit*, St. Louis, MS, USA, 2008.

[12] M. Ulieru, "e-Networks in an Increasingly Volatile World: Design for Resilience of Networked Critical Infrastructures," presented at the Proceedings of 1st IEEE International Conference on Digital Ecosystems and Technologies - IEEE-DEST 2007, Cairns, Australia, 2007.

[13] T. O'Reilly. (2005, *What Is Web 2.0: Design Patterns and Business Models for the Next Generation of Software*. Available: http://www.oreillynet.com/pub/a/oreilly/tim/news/2005/09/30/what-is-web-20.html

[14] M. Ulieru and R. Doursat, "Emergent Engineering: A Radical Paradigm Shift," *Int. J. Autonomous and Adaptive Communications Systems*, 2010.

[15] IEC61850, "Communication Networks and Systems in Substations - part 7, Basic information and communication structure," International Electrotechnical Commission2003.

[16] Z. Noorian, *et al.*, "An Autonomous Agent-based Framework for Self-Healing Power Grid," presented at the IEEE Conference on Systems, Man and Cybernetics, San Antonio, Texas, 2009.

[17] Khosrow M. and Ranjit K., "Vision for a self-healing power grid," in *ABB Review*, ed. Santa Clara, California, 2006, pp. 21-25.

[18] Chuang A. and McGranaghan M., "Functions of a local controller to coordinate distributed resources in a smart grid," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-6.

[19] Nagata T. and Sasaki H., "A Multiagent Approach to Power System Restoration," *Power Engineering Review, IEEE*, vol. 22, pp. 62-62, 2002.

[20] Spuntupong K., *et al.*, "Advantage of DMS design approach using knowledge engineering," in *Condition Monitoring and Diagnosis, 2008. CMD 2008. International Conference on*, 2008, pp. 1318-1322.

[21] Lothong P., "Conceptual Design of MEA's Distribution Management System (DMS)," ed. Bangkok, Thailand: Metropolian Electricity Authority (MEA), 2008.

[22] P. Tannlund and G. Bjorkman, "An advanced distribution automation system experience from application development and project implementation," in *Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on*, 2000, pp. 127-132 vol.1.

[23] McGranaghan M., *et al.*, "Utility experience with developing a smart grid roadmap," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-5.

[24] Wang J., *et al.*, "Smart grid technologies," *Industrial Electronics Magazine, IEEE*, vol. 3, pp. 16-23, 2009.

[25] Kock L. and Strauss C., *Practical power distribution for industry*. Burlington: Newnes, 2004.

[26] T. Nagata and H. Sasaki, "A multi-agent approach to power system restoration," *IEEE Transactions on Power Systems*, vol. 17, pp. 457-462, May 2002.

[27] M. Pipattanasomporn, *et al.*, "Multi-Agent Systems in a Distributed Smart Grid: Design and Implementation," in *Proc. IEEE PES 2009 Power Systems Conference and Exposition (PSCE'09)*, , Seattle, Washington, USA, 2009.

[28] Vyatkin V., *et al.*, "Towards the Energy Web via Standards-enabled Smart Grid," presented at the IEEE PES Conference on Innovative Smart Grid Technologies, Gaithersburg, Maryland, 2010.

[29] Vyatkin V., *et al.*, "Towards Intelligent Smart Grid Devices with IEC 61850 Interoperability and IEC 61499 Open Control Architecture," presented at the IEEE CONFERENCE ON TRANSMISSION AND DISTRIBUTION, New Orleans, 2010.

[30] Z. Noorian, *et al.*, "An Autonomous Agent-based Framework for Self-Healing Power Grid," in *IEEE Conference on Systems, Man and Cybernetics*,, San Antonio, Texas, 2009.

[31] IEC61499-1, "Function Blocks - Part 1 Architecture," International Electrotechnical Commission, Geneva, International standard2005.

[32] N. Higgins, *et al.*, "Power System Automation with IEC 61850, IEC 61499 and Intelligent Control," *IEEE Transactions on Systems, Machine and Cybernetics - Part C*, 2010.

[33] N. Higgins, *et al.*, "Concept of Intelligent Decentralised Power Distribution Automation with IEC 61850, IEC 61499 and Holonic Control," in *IEEE Conference on Systems, Machine and Cybernetics*, Singapore, 2008.

[34] V. Vyatkin, *et al.*, "Towards Intelligent Smart Grid Devices with IEC 61850 Interoperability and IEC 61499 Open Control Architecture," in *IEEE Conference on Transmission and Distribution*, NEW ORLEANS, 2010.

[35] Popovic D. S. and Boskov E. E., "Advanced Fault Management as a Part of Smart Grid Solution," presented at the CIRED Seminar 2008: SmartGrid for Distribution Frankfurt, Germany, 2008.