Intelligent Distributed Autonomous Power Systems (IDAPS)

Saifur Rahman, *Fellow, IEEE*, Manisa Pipattanasomporn, *Member, IEEE* and Yonael Teklu, *Member, IEEE*

***Abstract*-- The electric power system is an enabling infrastructure that supports the operation of other critical infrastructures and thus the economic well-being of a nation. It is, therefore, very important to design for resiliency and autonomous reconfigurability in the electric power grid to guard against man-made and natural disasters. One way to assure such self-healing characteristics in an electric power system is to design for small and autonomous subsets of the larger grid. This paper presents the concept of a specialized microgrid called an Intelligent Distributed Autonomous Power System (IDAPS). The IDAPS microgrid aims at intelligently managing customer-owned distributed energy resources such that these assets can be shared in an autonomous grid both during normal and outage operations. The proposed concept is expected to make significant contributions during emergency conditions, as well as creating a new market for electricity transaction among customers.**

***Index Terms*-- Intelligent Distributed Autonomous Power System (IDAPS), intelligent microgrid, agent-based technology, web services.**

I. Introduction

ELECTRICITY supply is one of the most important utilities that underpin the survival of a nation's critical infrastructures and services such as natural gas supply, water supply services, transportation, telecommunications, financial services and healthcare services. The transition toward the deregulation of electricity supply has introduced profit-driven competition and market principles that apparently result in insufficient growth in capacity – both for generation and transmission – commensurate with the growing demand. Moreover, a spate of man-made and natural events – such as the northeastern USA and eastern Canada blackout in August 2003 and Hurricane Katrina in August 2005 – have additionally exposed the vulnerabilities of the electric power grid and their inability to recover quickly from failures.

To increase reliability of electric services locally, commercial and some residential customers have increasingly installed on-site distributed energy resources (DER). Despite the rapidly growing number of DER systems, there is yet no established mechanism for capturing and coordinating these "customer-owned" resources to serve critical loads at the distribution level. Previous practices merely focus on coordinating DERs that belong to the same utility. This may be due to the lack of a business model that can attract the attention of both entrepreneurs and end-users. Thus there is ground for a novel approach to organize, manage and dispatch "customer-owned" DER units in an intelligent microgrid so that they can contribute to the integrity of the critical electric power infrastructure at the distribution level.

This paper aims at providing an insight into our intelligent microgrid concept – an Intelligent Distributed Autonomous Power Systems (IDAPS) – that can be the building block for a resilient electric power system. Section II discusses related work and identifies the gaps in knowledge to be fulfilled. Section III presents the overview of the IDAPS concept, explains the supply-driven-demand management, and discusses the communication overlay architectures that enable seamless cooperation among elements in an IDAPS microgrid. Section IV summarizes the simulation setup of the IDAPS concept in the context of a small municipal electric utility at Virginia Tech.

II. Background Information

As elaborated below, there are four relevant research areas that are recognized as the background for our IDAPS concept. As differences in methodology, technique and philosophy are observed, conclusions are drawn with respect to the knowledge gap in each category.

A. The Microgrid Concept

The microgrid concept evolved with the need to organize and utilize generation capacities that began appearing in the distribution system following the restructuring of electric utilities. It is one of the key technologies recommended by policy makers drafting technology roadmaps for electricity delivery in many countries, like the United States [1, 2], the European Union [3] and Japan [4]. Subsequent studies have all promoted the microgrid concept citing the increased reliability and power quality it provides to the local grid. However, most of the previous work makes an assumption that distributed generators in a microgrid belongs to the same utility to allow no-conflict collaboration among them [5, 6]. Since there are typically "customer-owned" DER devices exist in a distribution feeder, the first missing element is the means to coordinate and dispatch DER units that belong to various residential and commercial customers. Based on a similar

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concept used in wholesale electricity markets, we suggest a market-based approach as an effective way to facilitate electricity trading within an IDAPS microgrid.

B. Electricity Markets

A market-based mechanism is widely adopted in the wholesale electricity market where generators competitively sell their electricity to retailers. The most common form of competition is to bid into a mandatory power pool. This system is deployed in various forms in various countries, such as the NordPool, the Electricity Pool of England and Wales, and the US-PJM pool [7]. This system requires that the demand for electricity is known or can be forecasted. As a result, generators can adjust their offers based on the "known" demand. Based on this concept, [8] model electricity market in a microgrid by having local loads announce their demand every 15 minutes in advance. Since a microgrid may contain only one distribution circuit, the demand in such a small system is so instantaneous and fluctuates so widely that it is almost impossible to make a load forecast in advance. Because of these reasons, the market-based approach implemented in a microgrid must be different from the mechanism currently used in large electricity markets – this represents the second knowledge gap. The IDAPS concept addresses this knowledge gap by proposing a new market-based concept for microgrid operation, called the "supply-driven-demand management". More details will be provided in section III.

C. Control and communication architectures

Central to the operation of any power system is the control and communication architecture comprising of hardware and protocols for exchanging critical status and control signals. In conventional electric power systems, this can be accomplished by the Supervisory Control and Data Acquisition (SCADA) system [9, 10]. Since our focus is to control and monitor a small-scale network of DER, previous work related to the two variations of SCADA systems based on commercial products and agent-based technologies are discussed below.

Commercial off-the-shelf products: several commercial off-the-shelf products are available to provide SCADA functionalities at the microgrid level [11]. Some are for the control of microgrids, such as RSView32 from Rockwell Automation, the Networked Distributed ResourceTM from Celerity Energy, and the Central Operation Management System from Connected Energy Corp. Others are more focused on distributed building energy management such as 6D iNET network from Comverge, Inc. and Johnson Controls Metasys Building Automation System. Manufacturers of DG equipment have also developed communication interfaces for monitoring and controlling their products, such as Capstone Microturbines that utilize the Capstone remote monitoring software [12].

Agent-based technologies for microgrid control: in recent years, the automated agent technology has been proposed for use in the control and operation of microgrids. A recent report from the Sandia National Laboratories [13] demonstrates a framework for agent-based management of DERs and provides an example of how their design can be implemented in a small demonstration system. [14] discusses the in-depth theory of autonomous systems. Other related work include: [15, 16] that discuss the operation of a multi-agent system for the control of a microgrid; [17] that describes an agent-based technology deployed to solve the allocation problems of electrical and heating energy; [18] that formulates an agent-based framework for use in energy management systems; and [19] that presents a scalable multi-agent system for real-time electric power management.

A major problem faced when utilizing commercial off-the-shelf products, as well as agent-based technologies discussed in the open literature, is their proprietary nature which limits effective communications among DER devices owned by multiple individuals or institutions who are not likely to have hardware and systems from the same vendor. Thus, the third challenge is to design the communication overlay architecture that can ensure portability and interoperability among various systems. To create such control systems, one such approach is to implement web-based communication architecture, using web services, and ensuring that common DER architecture standards [20, 21] are applied.

D. Web-based Communication Architecture

Web services is fast becoming the de facto protocol for information exchange in a decentralized or distributed environment over the internet. Although web services is primarily geared to implementing e-commerce and e-business transactions, its architecture and platform-independence makes it a candidate tool for developing the information exchange and messaging protocol of a microgrid. The World Wide Web Consortium (W3C), an international body developing various standards for the World Wide Web, defines web services as a software system designed to support interoperable machine-to-machine interaction over a network. The key attribute of web services is that it is not tied to any one operating system, proprietary program, hardware or communication medium. Rather, it utilizes the eXtensible Markup Language (XML) over the HTTP protocol to structure, represent and exchange data in a common syntax readable by all.

III. IDAPS – An Intelligent Microgrid

A. Control and communication architectures

In order to bridge the three knowledge gaps listed in section II, we propose to develop the framework for an Intelligent Distributed Autonomous Power System (IDAPS). IDAPS is a specialized microgrid for coordinating "customer-owned" DER's for residential and commercial consumers.

As shown in Fig. 1, the building blocks of IDAPS include physical and cyber layers. The former is composed of loosely connected DER devices and loads which can communicate with one another via the latter, i.e. web-based communication overlay architecture employing multi-agent technology and web services.

The IDAPS operation is divided into two modes: (1)

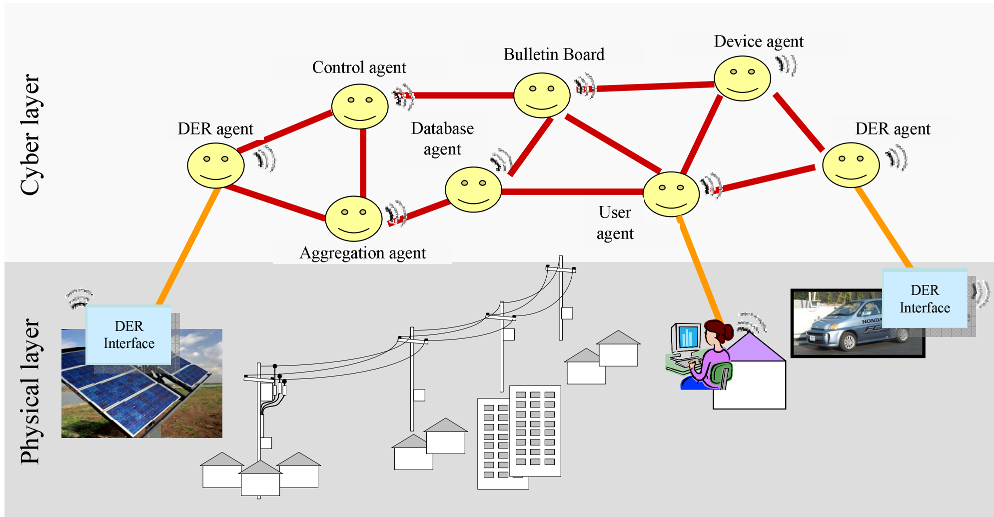

Fig. 1. Physical and cyber layers in an IDAPS microgrid.

normal operating conditions and (2) emergency conditions when upstream grids fail. During normal operating conditions, the IDAPS structure is complementary to the main electricity grid. Households or businesses can purchase electricity from the grid as usual. Yet, their membership in the IDAPS microgrid allows electricity customers to purchase electricity from their neighbors. The end-use customers will thus have the choice of buying a part of their electricity from the DER units available locally if the offers are price competitive, or have other attractive features like green power. Once upstream outage conditions are detected, an IDAPS microgrid will island itself from the grid and start to operate autonomously. IDAPS agents will communicate with one another, as well as reconfigure and coordinate IDAPS components in such a way to secure critical loads during outages. Critical loads within an IDAPS microgrid will first be served by their internal sources, and any shortfall can be made up through open market purchases among different IDAPS microgrids.

Since the IDAPS microgrid deals with the power systems of the future, important assumptions are listed below.

- It is required that sufficient DER capability be placed in each IDAPS micro-grid to secure critical loads located in each cell during outages.
- It is assumed that some of the current technical, regulatory and economic barriers to DG interconnection can be bypassed.
- It is assumed that DER units and electronic devices, including circuit breakers, have communication interfaces and are addressable by IP addresses.
- It is assumed that at least one type of communication medium must be available to facilitate communications among local generators, loads and electronic devices. Such communication means can be a wired local area network (LAN), a wireless network based on 802.11 or 802.16, etc.

B. The IDAPS Supply-Driven-Demand Management

Currently, the most common form of competition in a wholesale electricity market is to bid into a mandatory pool. This mechanism represents a demand-driven-supply approach where offers from generators are dependent on the "known" demand. On the other hand, the IDAPS concept deals in much smaller systems where the demand in an IDAPS cell can be highly fluctuating and not known in advance. As a result, the traditional demand-driven-supply approach cannot be used. Instead, a "supply-driven-demand" mechanism – where the demand for electricity beyond the basic minimum is driven by available supplies – must be implemented to allow an interactive matching of flexible load and available generation at a "correct" price.

The concept of the supply-driven-demand approach is that an IDAPS microgrid will employ a bulletin board that represents an electricity market place for electricity buyers and sellers to transact business in. However, instead of matching the supply with the demand and producing market clearing prices, end-use customers will make a decision whether to buy electricity or not for their deferrable demand. This decision will be based on the real-time electricity pricing information offered by suppliers in the grid. As a result, residential or small commercial customers will have the choice of buying electricity from the most economic DG available locally during both normal and outage conditions. This represents a supply-driven-demand business model where customers will be able to choose which of their deferrable demands will be serviced based on the real-time cost of electricity. In addition, the offers from local generators will not only include price and quantity of electricity to be sold, but also the schedule of electricity supply availability which can be posted on the bulletin board up to 24 hours in advance.

C. The IDAPS Agent-based Framework

Central to this topology is an open source SCADA capability that will enable IDAPS physical and cyber components to communicate with each other, as well as with the distribution utility. This is built upon the multi-agent concept that is overlaid on a web services layer. An agent is a software-based entity that can sense and respond to changes in signals to accomplish its individual goal. A generic architecture of cooperation among multiple IDAPS agents is illustrated in Fig. 2. Fig. 3 summarizes the activities and interactions of IDAPS agents, whose roles and responsibilities are explained below.

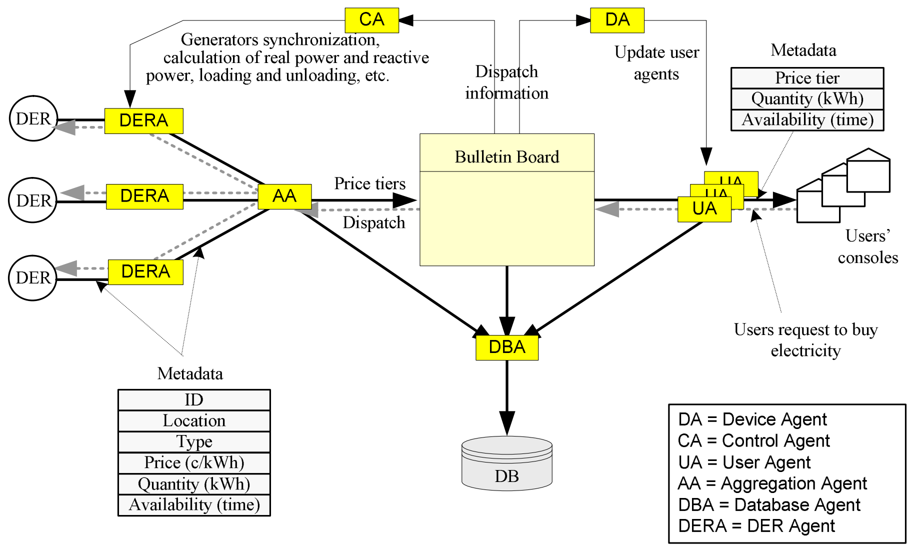

Fig. 2 The multi-agent framework in an IDAPS cell

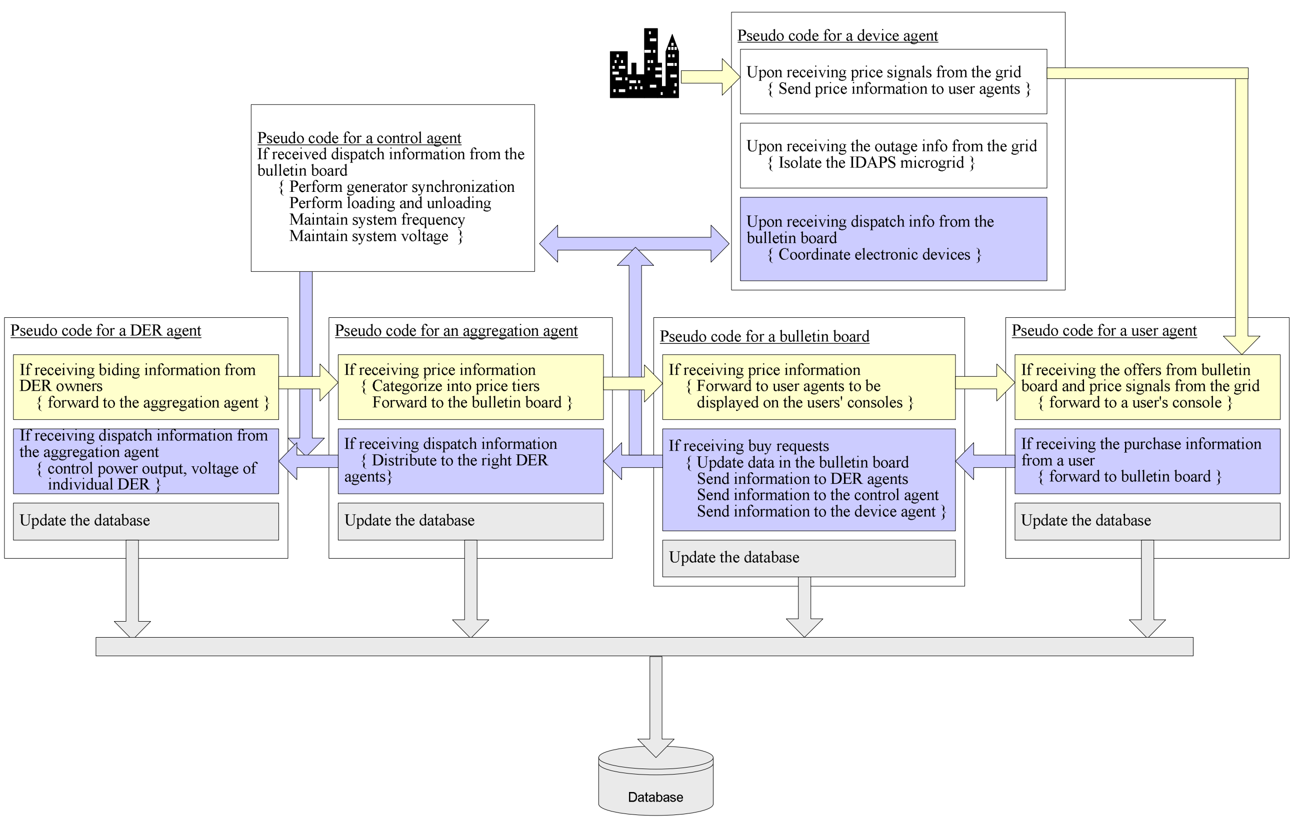

Fig. 3 IDAPS Agent Interaction

1. User Agent. A user agent is the gateway to connect a user to the rest of the system. It is responsible for retrieving real-time information and displaying all relevant information on an electronic console on the end-user premises. This may include price ($/kWhr), quantity (kWhr) and duration (clock time) of electricity available for purchase from the bulletin board, as well as electricity pricing information from the utility.

2. DER Agent. A DER agent sends the metadata to the aggregation agent. This metadata includes ID (identification number, owner name, address, etc); LOCATION (circuit number, distribution branch, etc); TYPE (diesel engines, electric vehicles, battery, etc); PRICE (asking price); QUANTITY (kW rating and kWhr); and AVAILABILITY (e.g., available from 3pm to 8pm). The DER agent is also responsible for controlling the operation of each individual DER once it is dispatched.

3. Aggregation Agent. This agent receives bids from DER agents and aggregates supply into price tiers according to their bid prices. By accumulating available supply, it makes it much easier for end-use customers to purchase electricity when there are many DER owners wanting to sell their electricity. Upon receiving dispatch information from the bulletin board, the aggregation agent will forward this information to the right DER agents.

4. Bulletin Board Agent. The bulletin board is a special agent which represents a dynamic contact point through which user agents and the aggregation agent share and retrieve bidding information. The bulletin board sends necessary information to user agents to be displayed on the user console, as well as matches requests to buy electricity with the available supply.

5. Database Agent. A database agent is responsible for collecting and storing electricity price and demand information in a database, and providing access to the database for other agents.

6. Device Agent. A device agent controls electronic devices, such as circuit breakers and switches.

7. Control Agent. A control agent contains software to perform generator synchronization, maintain operating frequency and voltage, sustain suitable real and reactive power, loading and unloading, and others.

D. IDAPS Web Services

The IDAPS microgrid's multi-agent framework calls for a web-based communication infrastructure capable of exchanging information and control data among elements in an IDAPS microgrid. Web services will be used for controlling most of DER operations, as well as for hosting a competitive bidding process amongst the members.

The IDAPS web services platform will have three components: (1) a messaging engine to carry out information exchange between the sender and the receiver via the Simple Object Access Protocol (SOAP); (2) Web Services Description Language (WSDL) which is a set of XML documents describing what the IDAPS web services is, list how the services can be accessed and provide specific instructions on how the services can be executed; and (3) the Universal Description, Discovery and Integration (UDDI) which is an XML based registry of all DER systems. UDDI provides a platform for all services and clients involved to publish information about themselves, i.e., their metadata, hence making them discoverable on the IDAPS web services.

Fig. 4 shows how SOAP is implemented over an IP-based network where an IDAPS control agent requests a measured value such as line voltage from the DG interface which sends back the response.

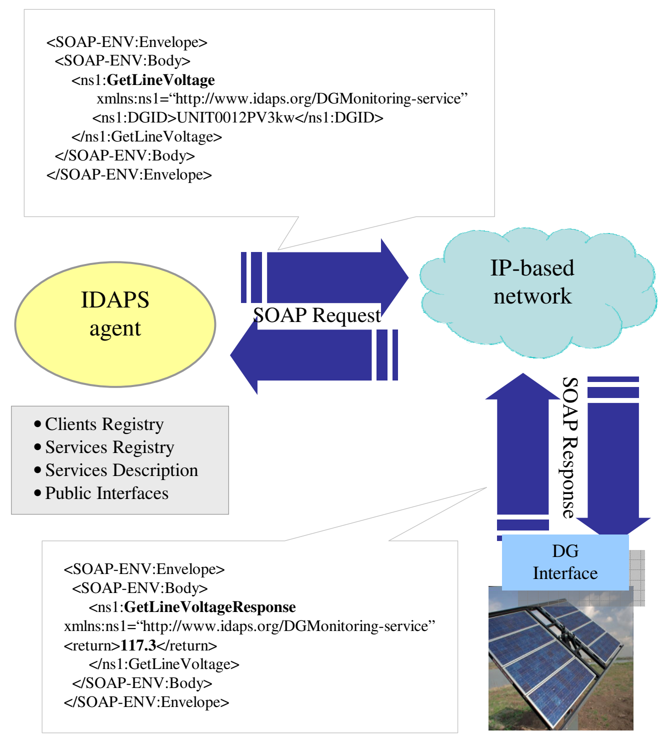

Fig. 4. Example of information exchange via web services SOAP

It should be noted that in order to maintain interoperability, the SOAP transaction, the WSDL platform and the UDDI registry will all use the same namespace. In this case, the IDAPS web services will adopt the naming conventions used in the utility communication architecture (UCA-DER, 2003) draft standard.

IV. IDAPS Simulation

In order to operationalize and test this idea, the proposed IDAPS microgrid concept is being simulated and analyzed using real data from a small distribution system that serves Virginia Tech campus and surrounding communities in Blacksburg, Virginia.

A. The Virginia Tech Microgrid (VTM)

The VTM is an ideal example of a microgrid in a small university town, comprising of two substations with twelve distribution circuits as shown in Fig. 5. Local generation comes from coal and gas steam generators, rooftop solar photovoltaic panels and fuel cells. The single line diagram of the twelve VTM distribution circuits, as well as load and generation profiles are used as inputs to the simulation.

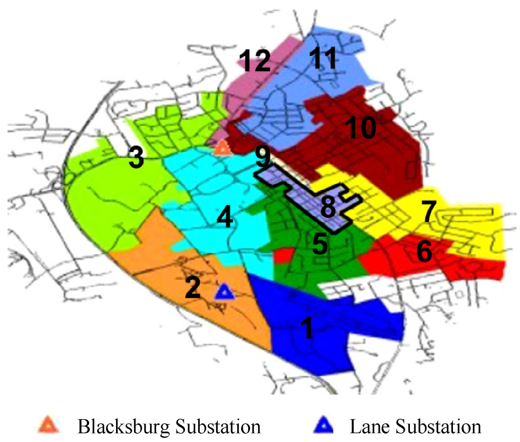

Fig. 5. VTM Distribution Circuits (Source: Virginia Tech Electric Services)

B. Simulation Setup

Our simulation model comprises two key subsystems – hardware and software models – that interact with each other through the web services platform within an IDAPS environment, as shown in Fig. 6.

Subsystem 1: Matlab/Simulink for hardware elements: The first subsystem is related to modeling the hardware elements of an IDAPS microgrid using the SimPowerSystems toolbox over Matlab's Simulink platform. In addition to modeling distribution networks and loads, the toolbox is used to create Simulink blocks representing devices (e.g. switchgears, power conditioners, transformers, circuit breakers and relays) and distributed energy sources (e.g. diesel reciprocating engines, solar cells, microturbines, fuel cell systems and electric vehicles).

Subsystem 2: Model for IDAPS agent management: The second subsystem is the coding of agent functionalities to control electricity transactions and the operation of DG units within an IDAPS microgrid. Sample agent functionalities are, for example: (a) for the control agent – control the system voltage and frequency, perform generator synchronization and calculate real/reactive power flow; and (b) for DG agents - accept offers from DG owners (this agent can be given an objective to maximize profit which is defined as the difference between revenue and cost), forward the metadata to aggregation agent and control power output of DGs.

Since all interactions among hardware elements (DGs) and software elements (agents) require message exchanges, the web services model is a necessary building block to facilitate communications and ensure interoperability among various

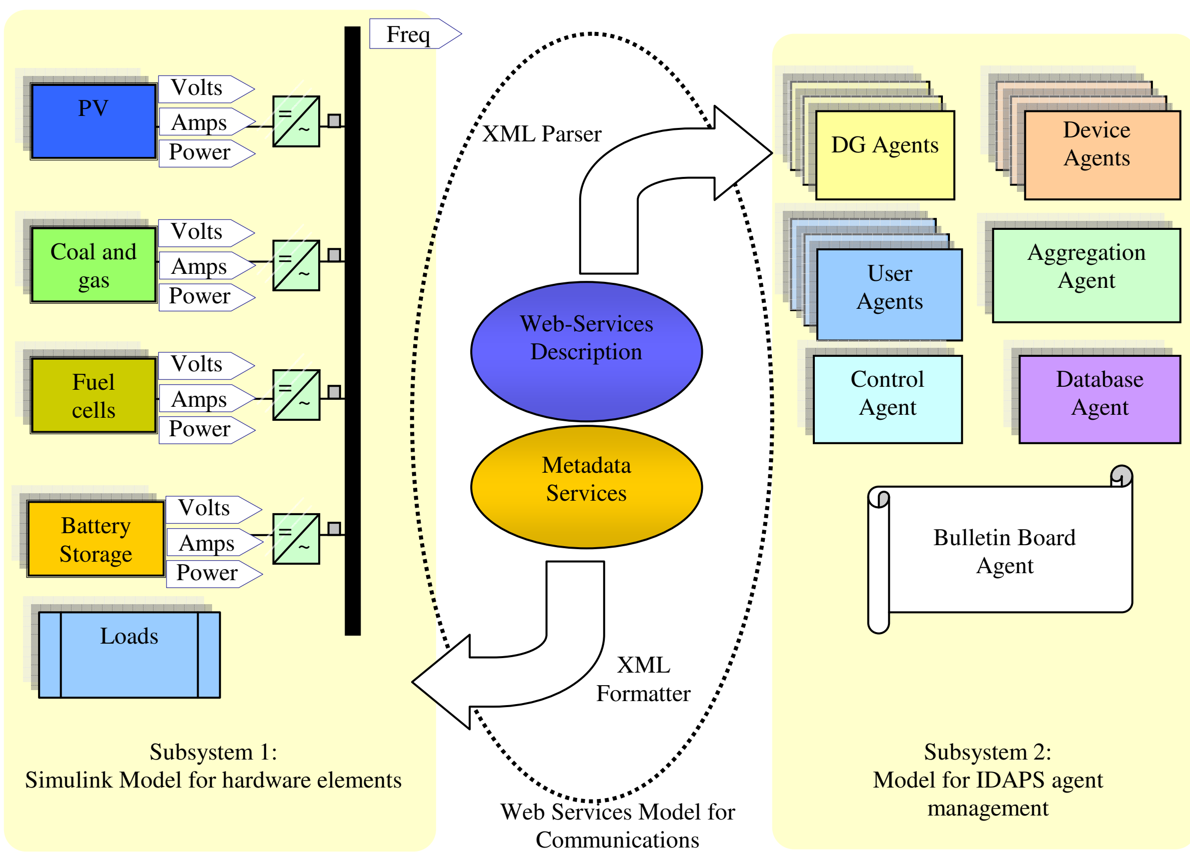

Fig. 6. The IDAPS microgrid simulation model

systems. All data from the hardware models will be encapsulated into proper metadata with the help of an XML parser to be sent to the software models. After analyzing the data, the software models will issue commands to be encapsulated into a proper metadata format with the help of an XML formatter to be sent back to control any appropriate hardware.

The simulation exercise is expected to be CPU-intensive even for a simple microgrid model consisting of one or two DER devices. Accordingly, the simulation will be designed as a parallel computation model. An existing 16-node high performance compute cluster at the VT Advanced Research Institute will be used as the test-bed for the simulation.

V. Conclusions

This paper presents the Intelligent Distributed Autonomous Power System (IDAPS) concept, as well as describing the IDAPS simulation setup at the Advanced Research Institute of Virginia Tech. While the existing literature focuses on coordinating DER units that belong to the same utility, the IDAPS concept provides a useful framework for managing customer-owned units in the distribution network. The development of the novel supply-driven-demand management model makes demand side management (DSM) possible within the IDAPS microgrid under normal operating conditions, and allows critical loads to be served during emergency conditions. This approach is unlike the traditional demand-driven-supply approach in pool-based markets where DSM and servicing of critical loads are not explicitly addressed. The utilization of web services enables components within an IDAPS microgrid to communicate with one another and also ensure portability and interoperability among various DG systems. Broader impacts of the IDAPS microgrid include the promotion of renewable energy technologies, the facilitation of customer choices in residential electricity markets and the design for more resiliency in electric power systems.

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VII. Biographies

Saifur Rahman (S'75, M'78, SM'83, F'98 – IEEE) is the Director of the Virginia Tech Advanced Research Institute and is the Joseph R. Loring professor of electrical and computer engineering at the university. He also directs the Center for Energy and the Global Environment at the University. In 2006 Professor Rahman is serving as the vice president of the IEEE Publications Board, and a director of the IEEE Board of Governors. He is an IEEE Distinguished Lecturer. He has served on the IEEE Power Engineering Society Governing Board for five years first as the Vice President for Education and Industry Relations and then as the VP for Technical Information Services. He is also a member-at-large of the IEEE-USA Energy Policy Committee. He has published over 300 papers on conventional and renewable energy systems, load forecasting, uncertainty evaluation and infrastructure planning.

Manisa Pipattanasomporn (S'01, M'06 – IEEE) joined Virginia Tech's Department of Electrical and Computer Engineering as an assistant professor in 2006. She received her Ph.D. in electrical engineering from Virginia Tech in 2004. She received the M.S. degree in Energy Economics and Planning from Asian Institute of Technology (AIT), Thailand in 2001 and a B.S. degree from the Electrical Engineering Department, Faculty of Engineering, Chulalongkorn University, Thailand in 1999. She is currently researching the application of a specialized microgrid called the Intelligent Distributed Autonomous Power Systems (IDAPS) to improve the resiliency of electrical energy infrastructures. Her fields of interest are renewable energy systems, distributed energy resources and critical infrastructures.

Yonael Teklu (S'96, M'01 – IEEE) received B.Sc. EE from Addis Ababa University, Ethiopia in 1981 and M.Sc. EE from Virginia Tech, USA, in 1994. He is currently the Information Technology Officer at Virginia Tech's Advanced Research Institute providing computational and computer network support for the research faculty and students at the institute. His research activities involve energy systems planning as well as renewable and distributed generation systems, and is currently working on his PhD in that area.