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A demand side management based simulation platform incorporating heuristic optimization for management of household appliances

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ABSTRACT

Demand-Side Management (DSM) can be defined as the implementation of policies and measures to control, regulate, and reduce energy consumption. This paper introduces dynamic distributed resource management and optimized operation of household appliances in a DSM based simulation tool. The principal purpose of the simulation tool is to illustrate customer-driven DSM operation, and evaluate an estimate for home electricity consumption while minimizing the customer's cost. A heuristic optimization algorithm i.e. Binary Particle Swarm Optimization (BPSO) is used for the optimization of DSM operation in the tool. The tool also simulates the operation of household appliances as a Hybrid Renewable Energy System (HRES). The resource management technique is implemented using an optimization algorithm, i.e. Particle Swarm Optimization (PSO), which determines the distribution of energy obtained from various sources depending on the load. The validity of the tool is illustrated through an example case study for various household situations.

1. Introduction

The present day utility grids in the United States and other nations are source-defined centralized power distribution systems. The major issue with the present day grid is the outdated design of the infrastructure, owing to which, the infrastructure cannot easily be expanded to meet the ever increasing power demands of the 21st century. In the next decade, power demand is expected to rise by 19% and the current infrastructure has the capability to increase its productivity by only 6%. The increase in production of electricity in the past few decades without major changes to the infrastructure has made the system highly unreliable. Blackouts and grid failures have been common problems to be addressed, having resulted in as much as billions of dollars in losses. A solution envisioned by academia and industry is the "smart grid". Smart grid has a potential to enhance grid modernization thus making it more capable of addressing future requirements [1]. Smart grid defines a more distributed, communication driven, and consumer-involved power system. Such systems promise to change the scenario of the energy distribution model and redefine the relationships of all the entities involved with energy consumption and distribution. Despite the allocation of billions of dollars for the development of new smart grid technologies, it is imperative that economic benefits for residential customers are justified [2].

Both communication and consumer participation are extremely important components of smart grid systems. In the last decade, the Internet has emerged as an efficient and reliable communication medium for transferring large quantities of information [3]. Lately, the Internet is being utilized for electric power-oriented communication. Currently, Advanced Metering Infrastructure (AMI), Meter Data Management System (MDMS), Home Area Network (HAN), and Demand-Side Management (DSM) are being provided as options for a smart grid [1].

AMI measures, collects, and analyzes energy usage of a household from data measured through advanced devices (e.g. state-of-the-art electricity meters for collecting real-time data), which communicate through various mediums including Broadband over Power Line (BPL), Power Line Communication (PLC), Fixed Radio Frequency (RF), etc. Specifically, the meter data is received by the AMI host system and send to the MDMS that manages data storage and analysis to provide the information in a useful form to the utility. Advances in AMI technology and integration with HAN have resulted in the development of DSM techniques [4]. The development of smart grid has resulted in an increased interest in DSM programs [5].

DSM can be defined as the implementation of policies and measures to control, regulate, and reduce energy consumption [6]. Typically, DSM determines the various activities undertaken by an electric utility and the consumers and uses such activity-related data to regulate the quantity and time of energy consumption.

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Such an approach is critical to effectively manage the overall electricity demand across North America [7]. DSM manipulates the residential electricity usage to reduce cost by altering the system load shape [8]. The common techniques used for load shaping are peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape [9]. DSM techniques such as demand dispatch provide round-the-clock deployment and assessment, thereby providing a qualitative approach to balancing energy generation and load for the electric grid [10]. DSM plays a vital role in facilitating greater connection of intermittent renewable generation [11]. The future of the overall energy scenario will constitute the increased utilization of small distributed energy resources for generating electricity [12].

One of the important applications of smart grid is that it encourages home and business owners to invest in microgeneration technologies in order to supply some of their own energy and reduce the demand on the electric grid. Among the various renewable sources of energy, the most popular sources are the solar and wind energy. These energies are non-exhaustive, site-dependent, and green. Microgeneration models consist of various sources of energy such as wind turbines, Photo Voltaic (PV) panels, and fuel cells [13]. The combination of these energy sources in different patterns result in multiple designs of Hybrid Renewable Energy Systems (HRES) [14]. A generic architecture of HRES is as shown in Fig. 1.

HRES technology can be generalized as a system that utilizes energy from both conventional and renewable sources. In comparison to conventional power systems, HRES reduces fuel consumption and emissions thereby making the system cost-effective, green, and highly reliable in terms of producing power. Proper load and energy management is important for better efficiency and endurance of HRES [15].

The intermittency of renewable energy sources results in unpredictable fluctuations that may appear in the power output [16]. The energy obtained from renewable sources is not subject to the demand, which results in an imbalance in the system. These problems can be resolved by including intermediate storage mechanisms such as batteries, water pumping, compressed air, fly wheels, and ultra-capacitors [17].

HRES invariably includes battery storage to meet the demand during either peak demand or non-availability of renewable sources of energy [14]. The effectiveness of a battery storage system is present during peak demand or non-availability of renewable sources, and is dependent on the amount of energy stored in the battery. The presence of multiple sources of energy results in the requirement of a resource management system that supervises the energy resources.

The energy obtained from various renewable sources can be either utilized for powering the load or for recharging the battery. This results in the requirement of an optimization algorithm that creates a balance between the consumption of energy from the renewable sources and the recharging of the battery source.

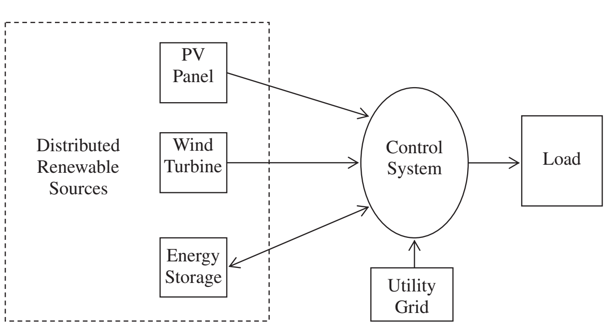

Fig. 1. Architecture of hybrid renewable energy sources.

The smart grid is still in the development phase and much research involves paper designs, and laboratorial experiments. The developments of these techniques have to be implemented by rigorous simulations of real-time environments [18]. Several energy management software such as Energy Lens – Energy Management Software and Greendash Home Energy Management Software have been developed in the recent past [19,20]. These smart applications act as energy monitoring hubs that obtain real-time data from various household energy devices and communicate the data to the end-user. The software packages provide frequent energy information and control options to the end-user. The software tools run intelligent algorithms for providing optimal, profitable solutions to the end user.

This paper presents the design and development of a DSM based simulation tool, demonstrating two-way data communication in a smart grid. This platform utilizes a Binary Particle Swarm Optimization (BPSO) algorithm for determining the operation of appliances and real Particle Swarm Optimization (PSO) for energy resource management in a given household. The platform can be used for simulations that help determine the financial benefits of a smart grid facilitated by active DSM. The tool is suitable for educational purposes in terms of understanding the what-if and how of DSM. For instance, this platform has been demonstrated for introducing DSM in a graduate course entitled "Renewable Energy and Smart Grid" in the Department of Electrical Engineering and Computer Science at The University of Toledo, and was well received by the students.

2. Overview of the simulation tool

The proposed real-time simulation tool has been designed based on a Load Management DSM program. Load management programs may either reduce electricity peak demand or shift demand from peak to off-peak periods [21].

The tool simulates the operation of a smart home which consists of a HAN connected to a Wide Area Network (WAN) which is in turn connected to the "communication backbone" (e.g. Internet). The tool monitors the electricity consumption, retrieves and controls the appliance data, and manages the distributed renewable resources. Each HAN has a set of user-defined or predefined appliances connected to a central processing unit/metering device, which in turn is connected to a larger network. The tool simulates the functioning of the central processing unit through the "control-of-appliances" based operation of the algorithm [21].

The architecture of the simulation tool is shown in Fig. 2.

The simulation tool has been developed using Java and SQL database and is deployed online using Java Web Start. A user can login to the tool through an online website and remotely access the tool.

As shown in Fig. 3, the Graphical User Interface (GUI) provides the user with the option to select various appliances and their

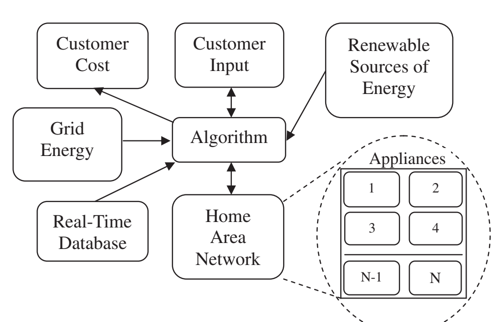

Fig. 2. Architecture of the proposed simulation tool.