Architecture of Solid State Transformer-based Energy Router and Models of Energy Traffic

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***Abstract*—Recently, a large number of renewable energy resources and DC loads spur the research spotlight of the future power grid, which is also referred to as Energy Internet. In order to achieve such a fundamental innovation to the novel energy paradigm, many devices are to be designed, manufactured, and evaluated. In this paper, we describe the solid state transformer-based energy router in which incoming energy traffic can be converted and routed to an outgoing energy traffic. In particular, we focus on the architecture design of such a router and models of energy storage devices, generators, and loads, for Energy Local Area Network (ELAN). The proposed energy router features plug-and-play Multiple-Input Multiple-Output (MIMO), and customized operating system, that providing a system level modeling for the optimal design and performance analysis of energy routers.**

***Index Terms*—Smart Grid, Microgrid, Energy Internet, energy router, electricity distribution, renewable energy resources.**

I. Introduction

According to the United States Energy Information Administration, the U.S total electric energy consumption is about 11 trillion kilowatt hours [1]. The majority of electric energy is generated by non-renewable and non-environmentally friendly fossil fuels, which cause the carbon dioxide emissions accounting for roughly 22% to 24% of global greenhouse gas emissions [2]. Recently, more and more residential level renewable energy resources and DC loads, such as Light-Emitting Diode (LED) lights and Electric Vehicles (EV) are connected to the power system to save energy and reduce CO_2 emissions [3]. Consequently, large-scale integration of Distributed Renewable Energy Resources (DRERs), Distributed Energy Storage Devices (DESDs) and emerging DC loads require a *revolutionary* paradigm shift from the legacy grid to the Smart Grid. Therefore, inspired by the development of information Internet, the Future Renewable Electric Energy Delivery and Management (FREEDM) center has developed "Energy Internet" concept, which may eventually shift the power and energy industry from the currently centralized mainframes to a client-based, distributed power infrastructure, such as to accommodate the myriad of DRERs, DESDs, and emerging DC loads, further allowing the customers to exchange energy freely and reliably [1], [4], [5].

In a broad sense, current research work towards to Energy Internet, also called "Smart Grid", falls into three major categories: 1) design and development of silicon based Solid State Transformer (SST); 2) control strategies of Microgrid, either utility connected mode or islanded mode; and 3) standard-based software and communication platform for traditional substations [6], [7]. Most works have been on the design and development of Generation-I silicon based solid state transformer, and discussed by the FREEDM systems center [8]–[13]. With the implementation of high voltage, high frequency SiC MOSFET, and IGBT devices, the prototype of envisioned SST can provide bi-directional energy flow control capability and perfect power quality, and further becoming an interface between distributed renewable resources and the grid. There are a lot of research efforts that investigate the control techniques and simulations of Microgrid operation and control [14]–[17], while using conventional power automatical control theory. However, these techniques lack the flexibility because they did not take into account potential renewable energy resources, and energy management policies. Recently, a communication platform is proposed according to IEC 61499 standard and IEC 61850 for distributed and embedded applications in substations [18], which are used to implement distributed grid intelligence in the FREEDM system and can be viewed as a prototype of the Energy Wide Area Network (EWAN) of the envisioned Energy Internet.

On the way to the Energy Internet, the FREEDM systems center focus on the revolutionary system theory development, application of enabling information and communication technologies, and development of advanced power semiconductors and electronics, as well as battery technologies. In particular, we aim to achieve the following objectives for the envisioned Energy Internet:

- Design and implementation of a revolutionary architecture of energy routers such that they can be plugged in with multiple energy resources and loads, and interconnected toward the envisioned Energy Internet.
- Development of an open-standard-based specification for plug-and-play interfaces to accommodate diversified access techniques, including WiFi, ZigBee, Ethernet, and 3G cellular systems.
- Design a new light-weight operating system for energy routers, which combines the power conversion control techniques and energy management policies.

The desired objectives of the Energy Internet devolve to the same desires for the energy router. The expected functions of the proposed energy router are as below: i) integrate a number of distributed renewable energy resources to address energy crisis due to shortage in traditional energy resources and increase in energy demand, and even worsening environmental problems; ii) improve efficiency of power grid through fully

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utilization of renewable energy resources and optimal management of DRERs, DESDs and loads through smart energy routers; and iii) enable flexibility of Energy Internet for open market of future electrical and renewable energy.

Although great progress has been made on the solid state transform-based Microgrid [19], [20] and architecture of smart Microgrid distributed operating system [21], little attention has been focused on Solid State Transformer (SST)-based energy router. Therefore, in this paper we focus on three specific issues, which can also be considered as our contributions. First, we establish definitions and assumptions of energy routers for building the Energy Internet, as well as input resources and output loads, with an analogy of information technology. Second, we propose an architecture of the energy router with specific communication architecture between an energy router and plug-and-play inputs and outputs, which are also referred to as generic *end-users* throughout the paper, because each of these users may either be an energy input, or outputs, or even both. Finally, we move on to the modeling of potential energy traffic of different end users to lay the foundation for future research regarding the performance and optimal design of energy routers.

The rest of this paper is organized as follows. In Section II, we describe the definitions for Energy Internet and energy routers from the point of view of information technology. In Section III, we propose an prospective architecture of energy routers and discuss the design issues. To further analyze the performance of energy routers, we derive the generic traffic models of end-users based on measurement data of three types of resources and loads in Section IV. We finally conclude this paper in Section V.

II. Definitions of Energy Internet and Router

Energy Internet may be the single, worldwide cyber-energy network that interconnects with other cyber-energy networks through energy routers in which end-users can exchange the energy flexibly. The Energy Internet has two critical and unprecedented elements: 1) *end-user*, a machine that can be programmed to manipulate the generation, storage or consumption of the power energy, and to communicate with others regarding energy exchange; 2) *energy router*, the SST-based novel machine that is used to accommodate the intelligent energy devices to exchange the energy through the plug-and-play interface for simplified and universal operation, and an open-standard Distributed Grid Intelligence (DGI) operating system to optimize energy management. The intelligent end-users are divided into three major types: DRERs, DESDs, and loads. Specifically, DRER end-users can perform complex and repetitive energy generation and conversion procedures quickly, precisely and reliably. On the other hand, load end-users can perform the complicated and customized energy consumption, since consumers will be able to optimize their usage, including remote control of electronic appliances and the trade of renewable energy. Furthermore, DESD end-users may perform complex and periodical energy storage and generation. Energy router, as one of the most important elements, must be able to interpret plug-and-play communication protocols, regulate the power flow arbitrarily with high quality and reliability, control the power balancing, and implement the energy management application software and communication functionality.

Recall the definition of "Internet" from the Networking and Information Technology Research and Development (NITRD) program, we interpret the definition for "Energy Internet", which refers to the global energy system that is: (i) logically linked together by a globally unique address space based on the *Energy Protocols* (EP) or their subsequent extensions/follow-ons; (ii) able to support energy and information communications using the specific *Energy Transmission Control Protocol* (ETCP)/Energy Protocol (ETCP/EP) suite, and/or other EP-compatible protocols; (iii) able to provide, or make accessible, either publicly or privately, high level energy services layered on the communications and related infrastructure described herein. Similar to the Internet, which is a global data communication system that provides connectivity between computers, the Energy Internet is expected to be a global energy system that provides energy connectivity between DRERs, DESDs, and loads. Therefore, the Energy Internet is extremely heterogeneous, with diversified delay requirements, voltage and power characteristics, in order to provide the real-time, reliable energy delivery. Similar to the TCP/IP, the Energy Transmission Control Protocol manages the conversation of energy into the specific format that are transmitted over the Energy Internet at the higher layer. The lower layer, Energy Protocol handles the address part of the devices of Energy Internet. Unfortunately, current power and electronics technologies can not switch power to specific loads, as information package does. Therefore, the power is exchanged through the stable shared bus in envisioned energy routers.

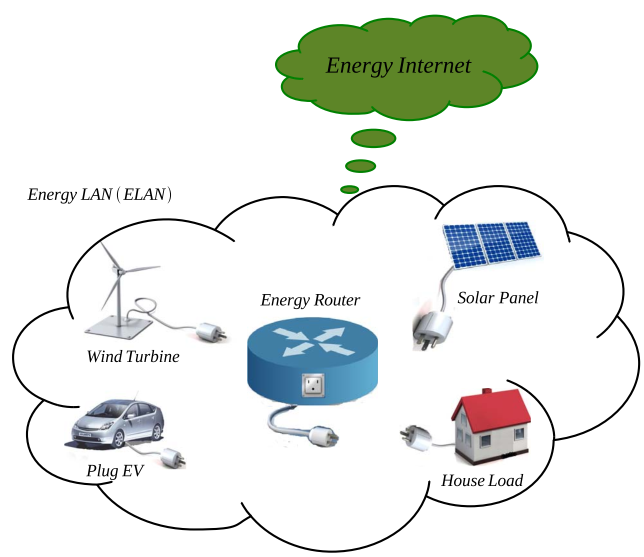


Fig. 1. Energy Internet: End Users, Energy Routers, and Energy Local Area Network (ELAN).

In core of Energy Internet, energy router, an electrical power networking device, can communicate with the attached multiple end-users (e.g., DRERs, DESDs, loads), and other peers to efficiently exchange energy in the correct frequency, electric current and voltage, either as direct current (DC) or alternating current (AC). A network consisting of an energy router and its attached multiple end-users is referred as an Energy Local Area Network (ELAN), as shown in Fig. 1. Further, several ELANs can be configured as an Energy Wide Area Network (EWAN) for which the energy routers, can exchange energy between the attached end-users in the ELAN over the Energy Internet. In addition, the energy routers are expected to have the following functions: 1) bidirectional high-quality power conversion between multiple end-users through the design of ; 2) plug-and-play interfaces using energy Universal Plug-and-Play (UPnP), since large input control bandwidth of converters [8] enables end-users to connect seamlessly to the electrical network through the shared 400V DC or 120V AC buses; 3) optimal energy management in the ELAN, EWAN, even the energy Internet. To achieve these goals, the energy router need to not only provide the communication and energy flow path, but also perform the necessary converting and routing function for power flows such that energy can be exchanged between end-users through the shared 400V DC or 120V AC buses. In addition, the energy router can operate in such fashion: receive business requests from one end-user, search the real-time business partners listed in a demand-and-supply table, and then inform the business partner, setting up the power flow connection for them. Further, they need to maintain the transaction with perfect power quality and stability, as well as clear the power flow connection once the business is closed [22]. The transaction process could be energy converting or forwarding, or both of them. The envisioned energy router also has three operational modes: grid-connected mode, EWAN isolation mode, and ELAN isolation mode. More importantly, it can provide smooth, uninterrupted transition between three operational modes by executing different control strategies [1], [19], [20].

It is worthy of noting that a similar, yet different concept from the Energy Internet is the Microgrid, which is defined as a localized group of electricity sources and loads that normally operate as connected to and synchronous with the traditional centralized grid (macrogrid) but can disconnect and function autonomously as physical and/or economic conditions dictate [23]. Both the Microgrid and the Energy Internet aim to integrate the DRERs and DESDs into the legacy grid and the operation and control of them are the key to ensure the safety and stability of the power grid. It is evident that an energy router and its attached end-users can be considered as a Microgrid, however, specific communication infrastructure and monolithic design of SST-based energy routers provide much more flexible and efficient venue of energy management.

III. Architectural Design of Energy Router

In this section, we present the unique design requirements for energy router and end-users, respectively. And then we describe the architectures of energy router and different end-users. Furthermore, such design is discussed.

A. Design Requirements of Energy Routers

As mentioned in the previous section, the nature of the Energy Internet leads to several basic design requirements for the energy router and end-users, which are as blow:

1) The energy router can connect to the 7.2kV AC/DC distribution bus located at the distribution level of power system, and provide the regulated either a 400V DC bus or a 120V AC bus, or both of them with approximatively perfect power quality through power conversion and management functions, such as the regulation of the low-voltage AC and DC bus, high-voltage side voltage sag ride through, power factor correction, harmonic elimination, and load side fault current limiting [1].
2) The energy router also provides bidirectional power flow, such that the energy from the renewable resources could be sold back to the utility or other customers.
3) The energy router is equipped with the auxiliary power supply structure. Energy router has to operate as a stand-alone unit and it has to be able to start up either from the 12kV AC/DC distribution bus or from the regulated 400V DC as the source side [9], since we consider that a SST-based energy router can be deployed in the Energy Internet, either standalone, or interconnected.
4) The energy router has multiple identified plug-and-play interfaces with either a 400V DC bus or a 120V AC bus, through which any end-user coupled to the Energy Internet can be instantly recognized as soon as it is connected, then communicate between them automatically. These physical power interfaces should be universal and standardized.
5) The energy router hosts an light-weight open-standard-based operating system, which is able to support real-time power conversion with high quality, communications between energy routers, plug-and-play interface management, state collection, power balancing management inside an ELAN, fault detection, and energy optimization management with other energy routers through consensus distributed control algorithm.
6) An end-user is also supposed to host a custom micro operating system, as the cell phone does, which is able to recognize the plug-in and pull-out operations, report its real-time state information to the energy router, and receive the dispatching demands from it automatically.

B. Architecture Description

Based on above design requirements, we propose the architectures for the energy router and diverse end-users, as shown in Fig. 2. In such architecture, the generic end-user need to have a controller with dual-functions of control and communication, corresponding power converter, and energy devices (e.g., generation, consumption, or storage devices). On the other hand, the energy router has four components, that is, *system controller*, *grid adapted model*, *regulated 400V DC bus*, and *multiple standard-based interfaces* consisting of sockets and breakers. This architectural design features high quality power conversion, plug-and-play MIMO interfaces, and monolithic custom operating systems.

In the following, we describe the architecture of the energy router starting from user interfaces to the system controller. First, multiple standard-based interfaces consist of sockets

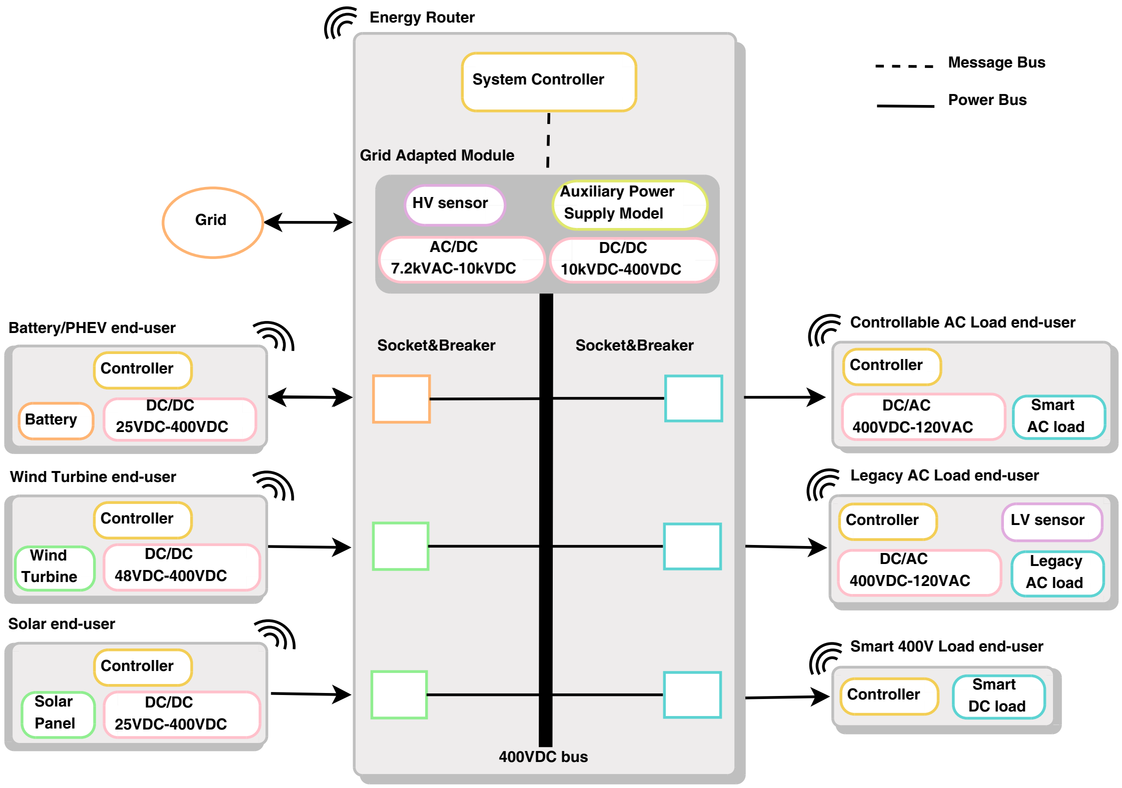


Fig. 2. Architectures of the Energy Router and End-users.

and breakers. They may have the rated voltage of 400V DC, the maximum current, even the specifications for manufacture of such sockets and breakers. Second, the regulated 400V DC bus is used to connect end-users. There is a capacitor to maintain the 400V voltage level. Third, an energy router is connected with Grid firstly, such that there exist a grid adapted module used to convert the 7.2kV AC power into the regulated 400V DC bus. The grid adapted module is composed of High Voltage (HV) sensors, 7.2kV AC-to-10kV DC rectifier, 10kV DC-to-400V DC converter, and auxiliary power supply system. This module has dual functionalities with power supply for stand-alone energy router device and interface model for other ELAN connection. In such module, the 7.2k AC-to-10k DC rectifier features high voltage, high frequency operation, bidirectional power conversion, and unit power factor. The development of 15kV SiC MOSFET and IGBT will enable the high voltage high frequency 10kV DC-to-400V DC bi-directional converter with the stable regulated 400V DC bus and much smaller size for the 10kV DC-to-400V DC converter. The auxiliary power supply module converts 7.2kV AC and 400V DC to 24V DC, which is used to power the energy router solely. Note that the FREEDM researchers had put great effort on the development of solid state transformer, which will reach the first three design requirements once the 15kV SiC MOSFET and IGBT is successfully developed.

As a matter of fact, the architecture design of the energy router and end-users is heavily dependent on the communication architecture between them, which is used to monitor and control energy time-varying conversion and scheduling for end-users. The proposed communication architecture requires that not only the system controller hosts a novel operating system which is able to support real-time monitor and control functions driven by the time-sensitive characteristics of power operation. In addition, it acts as a controller for universal plug-and-play, thus communicating with the attached end-users. In particular, it performs power balance management between the attached end-users and electrical energy exchange with other energy routers through communication technologies, e.g., WiFi, and ZigBee, optical fiber, etc.

C. Discussions

The design principle of energy router lies on three aspects: a) instantaneous power balance, b) stability, and c) operating constraints. Since many applications (e.g., monitoring, control and relay protection) in the ELAN are delay-oriented with rigorous timing requirements, delay should be the primary performance metric for the communication architecture design of the ELAN. Compared with the current solution with dual-board framework of communication and control [24], [25], the monolithic design of energy router combining with physical control for power devices, communication functionality, and further energy optimization through specific operating system will significantly improve the delay performance by reducing the message delivery processes. Thus it further ensures the moment-to-moment power balancing operation. Note that in such architecture design, the DESD end-user is necessary and very crucial that its capability decides the smooth mode transition. Specifically, in the ELAN-isolated mode, the DESD takes such responsibility of maintaining stability of the 400V

DC bus through D-Q control strategy [26]. In other two modes, the grid adapted model is responsible to maintain the stability of the 400V DC bus. The features of UPnP and custom operating systems for energy router and end-users dramatically simplify the operation of the energy route.

From the point of view of traditional centrally controlled power systems, the architectures for the Mcirogrid in prior works fall into three types: DC Microgrid, AC Microgrid, and hybrid AC/DC Microgrid. Traditional AC power systems have been in use for over 100 years due to their efficient transformation of AC power at different voltage levels and over long distance as well as the inherent characteristic from the fossil energy driven rotating machines [3]. To address energy and environmental issues, numerous renewable DC generations and loads are developed and required to integrate into the existing AC grids efficiently, which leads the development of the DC Microgrid. The hybrid AC/DC Microgrid [3] has been proposed to reduce the processes of multiple DC-AC-DC or AC-DC-AC conversions in an individual grid to facilitate the connection of various renewable AC and DC sources and loads to power systems. Therefore, the envisioned energy router, combining with the attached end-users to compose a conceptual Microgrid with more prevailing features, belongs to the DC type Microgrid in order to address the high penetration of renewable DC energy resources, and the population of LED lighting.

IV. Modeling of Incoming and Outgoing Energy Traffic of Energy Routers

The variability and uncertainty of the incoming and outgoing energy traffic poses a number of challenges for construction of the energy router, especially from the following three concerns: 1) the response time requirements of hardware and software, 2) energy management policy issues, and 3) configuration issues of storage devices. Therefore, in this section, we dive into details in energy traffic arriving at and departuring from the energy router, which is a customized MIMO system. In the following, we briefly describe three common types of end-users attached to the energy router: generation end-users, load end-users, and storage end-users. The generation end-user refers to the renewable energy resource with features of the renewal and randomness. Due to the intermittent nature of the renewable energy, we will model their generation via time as a stochastic process and their power curve is highly nonlinear. Although the power consumption of the load end-users are also time-varying, different type of the load end-user usually has a specific pattern for each day. Additionally, the most common DESD end-user of energy router is a stationary battery with its specific bidirectional DC-DC converter. At a typical residential ELAN system, there exits an energy router, a house load, a photovoltaic (PV) renewable resource, and a stationary battery.

A. Arrival Traffic and Demands

Multiple inputs of the energy router are the renewable energy resources. Consider the intermittent and renewal nature of renewable energy resources, multiple distributed renewable energy resources are assumed to arrive at the energy router randomly with the variable power.

Let X_k denote the k^{th} interarrival time, that is, the time between the $(k-1)^{st}$ and k^{th} arrivals. Assume that $X = (X_1, X_2, ...)$ is a sequence of independent, identically distributed, random variables. This is a reasonable assumption because the time of energy generated of each resource may not be deterministic, even though they may be predicted, depending on the resources and dynamic and fluctuation of impacting factors. For example, the system controller at the energy router may not necessary be aware of the power generation process of a wind turbine. Let us denote

$$T_k = \sum_{i=1}^{k} X_i, k \in \mathbb{N}. \tag{1}$$

Let P_k denote the power level, where $k = 1, 2, 3, ...$ and $P_k \geq 0$. It is widely agreed that the sum over an empty index set is 0, thus $T_0 = 0$ [27]. On the other hand, T_k is the time of the k^{th} energy arrival for $k \in \mathbb{N}_+$. The sequence $T = (T_0, T_1, ...)$ is called the *renewable energy resources arrival time process*. An example of this process is illustrated in Fig. 3. For instance, at time T_0, the solar panel starts to generate the electrical energy with power level P_1, which continues during X_1 time period. Due to the stronger wind, the wind turbine begins to generate the energy, then the generated power increases to P_2 at time T_1, and continues during X_2 time period. Since the load has the similar time-varying characteristic, we also use such two correlated random variables to describe the characteristics of the outgoing energy traffic of loads.

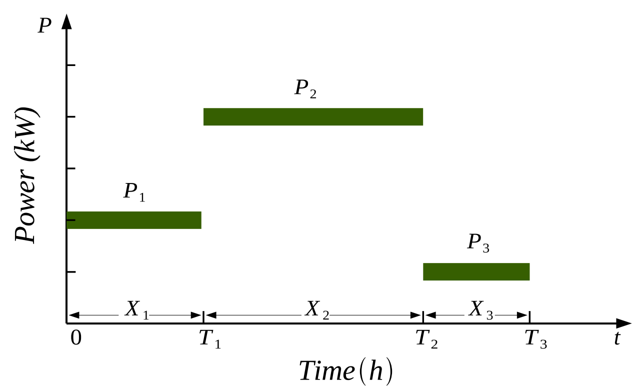
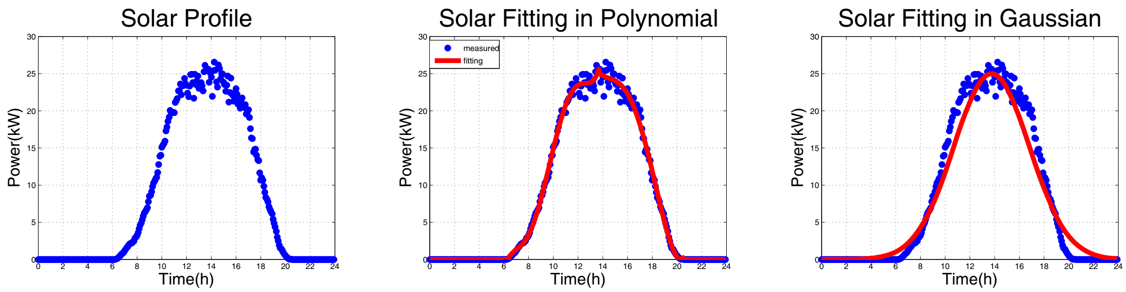


Fig. 3. Arrival Process of Renewable Energy Resources.

Consider that there can exist many renewable energy resources, storage devices, and loads in the future Energy Internet, we take one step further to model the traffic at the incoming and outgoing ports of an energy router for each type of traffic. Next, we focus on the modeling of the solar energy, four generic types of loads, and the battery storage device.

B. Modeling of Renewable Energy Resources Traffic

We assume that the renewable energy resources can also be replenished with the passage of time [28]. Following the above energy arrival modeling, we define the traffic of renewable



(a) (b) (c)

Fig. 4. Modeling Solar Panel Output Profile with Polynomial and Gaussian Fittings.

$$R(t) = \begin{cases} 0, & 0 \le t \le 6.617, \\ 0.0211t^5 - 1.0329t^4 + 19.659t^3 - 181.7557t^2 + 819.4919t - 1447.3, & 6.617 < t \le 13.75, \\ 0.0585t^4 - 3.8362t^3 + 93.0761t^2 - 993.3217t + 3968.1, & 13.75 < t \le 20.58, \\ 0, & 20.58 < t \le 24. \end{cases} \tag{2}$$

energy resources with two random variables of the arrival time and the power level.

Definition 1 (Renewable energy resources): Let $I(T_k, P_k)$ denote the renewable energy resources traffic of the energy router, where T_k is the time of the k^{th} renewable energy arrival event and P_k is the power level during the X_k inter-arrival period.

In the following, we consider only power random variable to represent the single renewable energy resource.

Example: A solar renewable energy resource is represented by $R(t)$, where $|R(t)| \in (0, R_{max})$ and R_{max} is the maximum output power of solar panels. An example solar power supply profile is used in Fig. 4(a) where X axis represents the time with the range $[0, 24\text{hour}]$ and Y axis represents the power level with with the range $[0, 30\text{kW}]$. In this example, we do consider a unique feature of solar energy daily pattern, that is, the diurnal pattern, which is variable, depending on the weather and geographic location at which these solar panels are used.

The source data of Fig. 4 was sampled from the solar panels on the roof of the FREEDM Systems Center during May,2011. The power output data was fetched once every 5 min from the four inverters each day. We first sum the power outputs of these four inverters for each sample point, then take the average of each sample point value for the whole month. From these measurement data, simple models of solar energy output were derived and verified by comparing measurement and fitting models through Matlab. After data analysis, we obtain the two models for solar energy profiles through polynomial and Gaussian fitting, shown in Fig. 4(b) and Fig. 4(c), respectively. Specifically, we have the polynomial fitting in Equation. 2 and the Gaussian fitting in Equation. 3.

$$R(t) = Ae^{\frac{-(t-\mu)^2}{\sigma^2}} = 25e^{\frac{-(t-13.76)^2}{3.06^2}}. \tag{3}$$

In general, the solar resource end-user consists of solar panels with $25 \sim 50$V DC of output power rate, a boost DC/DC converter and the controller. The boost DC/DC converter is used to regulate the solar output into 400V DC to convenient with the regulated 400V DC bus. Main functions of the controller are to communicate with the energy router for reporting time-varying states, receiving commands and reference points, then further control the energy conversion.

C. Modeling of Loads Traffic

Loads of an energy router are supposed to withdraw energy from other end-users through multiple outputs of the energy router randomly. The characteristic of loads is that they do exist the apparent daily pattern from analysis of the historical data. Compared with renewable energy resource end-users, the load end-users have different distribution functions for random variables X_k and P_k. Therefore, we give the similar definition with DRERs for load end-users.

Definition 2 (Loads): Let $O(T_k, P_k)$ denote the loads traffic of the energy router, where T_k is the time of the k^{th} load energy departure event and P_k is the power level during the X_k inter-departure period.

Similar with the single renewable energy resource, we consider only one power random variable to represent the single load.

Example: A load is denoted as $L(t)$, where $|L(t)| \in (0, L_{max})$ is the daily power demand profile with maximum power L_{max}. The representative four types of residential level loads are shown as the distribution functions of time in Fig. 5, and the source data is from the website of New Hampshire Electric Co-op (NHEC) [29]. This hourly KW data includes NHEC consumer demands for each load profile, sampled from January 2009 to September 2010.

By taking a similar method as we find the models of renewable resources, we obtain the models of loads based on polynomial and Gaussian fitting as follows to describe the characteristics of four representative load: residential (L_1), small commercial (L_2), large commercial (L_3) and street lighting (L_4) loads in Equations.4,5,6,7, respectively.

$$L_2(t) = \begin{cases} 2.4e^{\frac{-(t-14.6)^2}{3.4}} + 1.27, & 1 \le t \le 10, 18 < t \le 24, \\ 2.35, & 10 < t \le 18, \end{cases} \tag{5}$$

$$L_1(t) = \begin{cases} -0.0013t^4 + 0.0216t^3 - 0.1114t^2 + 0.2054t + 0.3915, & 1 \le t \le 8, \\ -0.0175t + 0.9462, & 8 < t \le 15, \\ 0.4e^{\frac{-(t-19.6)^2}{2.23^2}} + 0.61, & 15 < t \le 24, \end{cases} \tag{4}$$

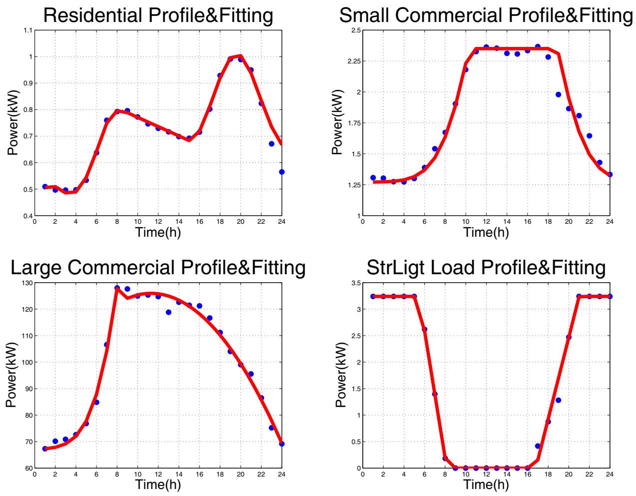


Fig. 5. Modeling of Load Profiles with Polynomial Fitting.

$$L_3(t) = \begin{cases} 185e^{\frac{-(t-13)^2}{3.35^2}} + 67, & 1 \le t \le 8, \\ -0.35t^2 + 7.91t + 81.31, & 8 < t \le 24, \end{cases} \tag{6}$$

$$L_4(t) = \begin{cases} 3.24, & 0 \le t \le 5, 21 < t \le 24, \\ -1.2(t - 8.16), & 5 < t \le 8, \\ 0, & 8 < t \le 16, \\ 0.77(t - 16.8), & 16 < t \le 21, \end{cases} \tag{7}$$

D. Modeling of Storage Traffic

In an ELAN system, the storage end-users refer to the stand-alone stationary battery or battery embedded in the PHEV. The outstanding feature of the storage device is that it works as the energy buffer of the energy router, that is, the storage device either supplies energy to other end-users or withdraw energy from them. Since the power grid attached by the energy router is assumed can supply or withdraw energy with other end-users, we also consider the attached power grid as the storage end-user.

Definition 3 (Storage devices): Let $B_k(s, C_{max})$ denote the k^{th} storage device, where s is the current state, defined as the current power level, and C_{max} is the capacity of the storage end-user in the unit of KwH.

Example: A stationary battery is denoted as $B_k = S_k(t)$, where $k = 1, 2, ...K$, and $S_k(t) \in (-C_{max}, C_{max})$ is the daily charge and discharge profile with the battery capacity C_{max}. We assume that the State of Charging (SOC) and State of Health (SOH) of stationary batteries are always at the good situation, thus the power state is a considerable metric. As shown in Fig. 6, $S_k(t) \in (-C_{max}, 0)$ means that the battery is on the charging state and works as a load end-user. The renewal process is defined as a counting process for which the interarrival times are independent and identically distributed with an arbitrary distribution. When the battery is discharging as an energy source, we gain $S_k(t) \in (0, C_{max})$.

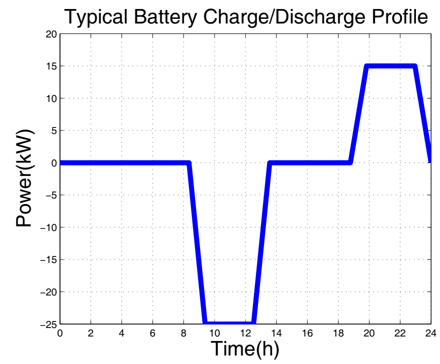


Fig. 6. Modeling of Battery Profile.

E. Discussions

The modeling of the traffic coming and leaving an energy router is important in that we can further specify the design principle of the energy router. In this section, we have modelled the traffic arrival and departure of the energy router through the stochastic process with two random variables of arrival/departure time and power level. Further we investigated the modeling for the single port and gained the following observations:

- For the solar energy, the polynomial fitting is more suitable than the Gaussian fitting by comparing with sub-figures (b) and (c) in Fig. 4, however, the Gaussian model may simplify the further modeling and analysis of the incoming traffic of an energy router.
- For the modeling of loads, four types of loads have the interesting and reasonable daily consumption patterns: 1) the residential load has two consumption peaks during [7:00-9:00], when people have morning activities, and [18:00-22:00], when people enjoy family time; 2) the small and large commercial loads share the similar diurnal pattern with slight difference that the small commercial load has the relevant flat consumption during daily time, while the large commercial load has the short peak point of 8:00 am and then slowly decrease after 12:00 am; 3) the public infrastructure - street lighting load has the typical nocturnal consumption profile.

Note that these models can be further extended by considering the stochastic process of the arrival time variable for multiple inputs and multiple outputs. For example, there can be more than one storage traffic models are integrated into the ELAN system, for example, the electric vehicle.

V. Conclusion and Prospective Work

In this paper, we presented the Energy Internet with the architecture, components, and protocols, analogy of the Information Internet. In particular, we defined the functions and design requirements of the energy router, based on which, we proposed an architecture for the energy router with four modules: the system controller hosting a novel operating system, grid adapted module, regulated 400V DC bus, and standard-based plug-and-play interfaces. We have also derived out the generic mathematical models for three types of end-users by analyzing the practical measurement data and built the basic MIMO model for energy router for further performance analysis. There is still much more work to do to analyze the performance metrics of the envisioned energy router. Finally, Our next-step work can be categorized into the following two directions: 1) identify the detailed functional models for operating system implementation of energy router and end-users; 2) further refine the traffic model for energy router and conduct the performance analysis of energy router as a MIMO energy system. This paper summarizes our progress toward the energy router design and implementation, and we expect the work presented in this paper advances our understanding of the architectures of Energy Internet and energy router.

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