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A network model for the real-time communications of a smart grid prototype

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ABSTRACT

Within a large-scale distributed (or centralized) smart grid, the communication network is designed to connect multiple power management systems and collect data from hundreds or thousands of power sensors over a large geographical area. Due to the ripple effect of inconsistent communication delays, the network performance becomes a major concern to support power system applications. For example, in a large NSF project Future Renewable Electric Energy Delivery and Management (FREEDM), we implement a smart grid prototype, called the FREEDM Hardware-in-the-loop (HIL) testbed. The Distributed Grid Intelligences (DGIs) in the prototype can group specific peers to exchange the power among the power demands and supplies. But the grouping sometimes is not successful due to the inconsistent delays. In this paper, we present a queueing model to describe the performance of the grouping network that supports the communications among the DGIs in our smart grid prototype. First, we develop a queueing model to describe the communication traffic among the DGIs in the network with different topologies. Second, based on the network model, we analyze the delay performance and illustrate that the model can be used to predict the grouping delays. Third, we have collected extensive experimental data which is used to demonstrate the accuracy of the model. Finally, we have implemented the HIL testbed with the capabilities of integrated real-time communication and power exchange. The network model is used to investigate the influence of the communication inconsistency on the total cycle time of power operations so that new grouping protocols can be designed in the future.

1. Introduction

The prospect of smart grids (SG) are green, power efficient, and economical to its customers. Many emerging innovations have reached a consensus that the traditional power grids need to be combined with modern data networks, in order to establish a new platform that supports distributed renewable energy devices, electrical measuring sensors, intelligent energy management and control systems, etc. For example, an energy management system is proposed to connect data aggregators with renewable energy devices Q3 within the network area (Cecati et al., 2011). A wireless sensor network is used to provide the communications between SG data centers and consumers, and manage residential energy with an optimization-based scheme (Erol-Kantarci and Mouftah, 2011). In smart grids, the stability of an energy management scheme becomes heavily dependent on accurate real-time communications among intelligent energy management agencies in residential homes, microgrids, and the main grid (Adika and Wang, 2014).

The existing work contributes a variety of SG platforms to integrate power and communication systems. In the FREEDM project, we build a smart grid testbed, which is a new platform that combines an HIL power system and a real-time communication system. The power system devices are managed by the DGIs that are connected to the communication networks. The DGIs act as intelligent energy management agencies for the power system, while information nodes for the communication networks. The DGI instances are coded on embedded computer boards with processing and communication capabilities. A DGI represents its power device to communicate with other DGI instances or DGI nodes. DGIs being connected in LAN and WAN may be grouped together to meet the power demand and supply requirement. A DGI group may cover a LAN, or a LAN and WAN simultaneously, depending on the location of DGI nodes. When electrical faults isolate a section from the power system, in communicational sense, the section is still connected to and can exchange the information of grid states with other sections in the power system. The real-time and HIL features of the testbed are reflected in the design of both power and communication systems. To implement the concept of HIL

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in the power system, some power devices are implemented by real-world electrical hardware, while other devices are simulated in the Real Time Digital Simulator (RTDS) platform (Meka et al., 2013). To implement the concept of HIL in the communication system for the DGIs, the DGI LANs are implemented by Ethernet switch, while the DGI WAN is simulated in real-time by OPNET, a network simulator program. Within OPNET, there is a system-in-the-loop (SITL) interface that interprets the DGI traffic between real-packet formats and simulated formats (Cai et al., 2013).

There are two major research issues regarding the smart grid communications.

The first issue is how to trade-off the network capacity and scalability for specific interface access scheme or consistent local service rate. In practice, the traditional power line communications (PLC) or fieldbus control systems are used to support smart grid applications. The traditional systems for communication and control are also combined with large-scale data networks to build smart grids. Thus, we need to find specific access schemes at the junctions of traditional systems and data networks.

The second issue is how to find a practical solution to model and connect the distributed energy management agencies (e.g., DGIs). The agencies are inter-connected by large-scale and timing-inconsistent networks to support many power applications such as dynamic grouping under power demand and supply constraints. For power system applications, the innovative algorithms are based on specific data networks, which must be able to provide a communication environment with some timing or delay guarantees, i.e., QoS. Usually, there is inconsistency in the delay among different packets of the same applications. The inconsistency is caused by not only the internal events of communication networks, such as queueing, link failure, and re-routing events, but also the applications of distributed agencies, such as the dynamic grouping.

As for our FREEDM testbed, a time-varying set of DGIs dynamically exchange with each other the power state information. The DGIs form a logically connected group so that the represented power devices can exchange power between the supply and the demand. If some group participants (DGI nodes) change, the logical group is altered accordingly, which may even need to cover different networking areas. The DGIs communicate over different networks will cause inconsistent communication delays to the power applications. A direct impact is that it may take too long for the grouping to succeed, and thus no power application can be supported, such as power exchange.

In this work, we focus on modeling the communication networks that support the DGI operations. We want to find a practical solution to estimate the queueing time of DGI networks so that the grouping can succeed by adjusting the grouping timer dynamically.

2. Related work

Currently, there are two methods to approach the above communication issues. The first one is to build special communication tunnels for certain I/O ports within a local SG system, or combine such a system with other wide packet switching networks. The second one is to address and connect different power devices unanimously by using various customized Ethernet switching networks.

The first method is for solving specific problems for SG communications, particularly, in medium-voltage grids covering vast and complex suburban geographical areas. If the existing public WANs cannot satisfy the performance requirements, e.g., capacity, security, and stability, one choice is to build a new wide area data network. For such a fast control system, the cost is substantially considerable. The long distance transmission of wireless signals is easily faded by environmental noise (Papadopoulos et al., 2013). Although the PLC technique leaves much to be desired, it indeed has very attractive deployment cost in comparison with wireless technology, since the lines are already there. In Lel̀vesque and Maier (2014), the optical access control is quantified by a metric, i.e., the availability of connected equipment, with a real-world scenario of SG communication traffic. To solve the problem of QoS degradation on the junction link between a WLAN and an optical network, a QoS control scheme based on cooperative strategy is proposed for real-time SG communications (Md Fadlullah et al., 2013). In Galli et al. (2011), the authors elaborate the possible applications of PLC techniques in modern SG.

Nowadays, PLC begins to share its dominant field at electrical metering and sensoring grids with other packet switching networks. Many advanced meters or sensors have been loaded with real-time Ethernet protocols for local control applications. They have been used to implement the Internet monitoring and management functions for large-scale applications. The communication quality of PLC is compromised by its low data rate and electromagnetic compatibility issues. The complex SG system needs to exploit not only the PLC network, but also multiple data communication technologies, either wired or wireless. The PLC also adopts some techniques from data networks. As shown in Yoon et al. (2014), the single-hop PLC transmission is extended to be a multi-hop multi-path routing data network. The opportunistic routing mechanism is used to overcome the PLC disadvantages in transmission performance. An actual local Ethernet scheme with processing buses for the field applications in smart substations is proposed in Zhao et al. (2015). A purely localized timing synchronization system is implemented to manage various substation devices on the local Ethernet network.

The second method is to utilize the Ethernet switching networks for various SG communication needs. There are many standardized protocols for SG applications over the Ethernet, such as DNP3/TCP, Modbus/TCP, and IEC 61850. In Yang et al. (2014), the authors evaluate the performance of a multi-vendor protection scheme based on the IEC 61850-9-2 processing buses in a substation LAN with Ethernet mesh transmissions. To solve the problem of interference between home WLAN and Zig-Bee metering, a SG home network is proposed to be a cognitive local network that supports the management of home appliances (Lee et al., 2012). To aggregate the sporadic data of smart meters and sensors in a large-scale placement, a WAN is deployed to connect the data fusions, for which the optimal planning is handled by a minimum-cost-forwarding-based asynchronous distributed algorithm (Lu and Wen, 2014).

In this work, the proposed network models can be used to facilitate the distributed systems on the communication LAN of substations, because the DGIs are potentially equipped on the substation apparatus. The network models can be also migrated into the PLC WAN systems, because the evolved PLC networks are similar to packet switching networks. Based on the above-related work, it is clear that the design of SG distributed systems can be relied on the supportive Ethernet technologies either in LAN or in WAN.

3. The SG prototype: FREEDM real-time HIL testbed

The SG prototype is shown in Fig. 1, which is our testbed for the FREEDM project. It can be seen that the power system has multiple rings hanged up on a large power transmission loop, which is sketched as a double straight line at the top of Fig. 1. The prototype is built with two grids, as shown by *Grid_1* and *Grid_2*, each with a ring topology. The communication system is implemented by two Ethernet packet switching LANs, and a real-time simulated Gigabit IP-routing WAN. The LAN is a geographically deployed Gigabit switching network.

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