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A Unified Information Network Design Framework for Information-Centric Future Smart Grid

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Abstract

Smart grid is defined as an advanced power grid for more effectively managing the dynamic power flow and demand and for enhancing the reliability and efficiency of grid. The key technique of smart grid is the convergence to the information network. The generated and transmitted information from each grid parts makes it possible to achieve the benefit of smart grid. But, the burden for implementing the smart grid information network is raised up for monitoring more complicated grid environments. In this paper, it is discussed how to design the secure smart grid information network considering the environmental change of grids. Firstly, the problem for the smart grid information network implementation is formulated with an example of Jeju smart grid test-bed in Korea, and also indicated the requirements for the information network for smart grid. The smart grid information network design strategies are suggested for supporting the reliable and efficient grid operation considering that.

***Keywords**: Smart grid, intelligent grid, information network, network design, generation, transmission, consumption, accuracy, latency, security, interoperability*

1. Introduction

Energy is the essential resource for human being and developing an economic growth. With enhancing economic progress and population, energy needs are pushed up over the coming decades. By the report of International Energy Agency (IEA), demand for energy is increasing by one-third from 2010 to 2035, and global investment in energy supply infrastructure of $38 trillion is required over the same period with the assumptions of a global population that increased by 1.7 billion people and 3.5% annual average growth in the global economy [1].

The huge growth of energy demand has been increasing the harmful effects to the environment caused by green-house gases emissions. The need to develop in efficient and low-carbon technologies is growing overall parts from energy generation, transmission and consumption. In the energy generation part, renewable energy sources such as wind, photovoltaic power is considered for reduced the CO_2 emission [2][3]. The distributed grid techniques such as micro-grid is researched for enhancing the efficiency in the energy transmission part [4]. More energy efficient device and operation are integrated for communication network [5], building [6] and factory [7] in the energy consumption part.

The development is highly correlated to the dynamic electric power flow. Renewable and distributed energy sources make the bidirectional and variable power flow, and energy-aware device and operation increase the dynamic power demand. For all these reasons, the grid (power network) have been exploring ways more reliable and effective implementation in all parts for supporting the dynamic environments.

The future grid (saying smart grid or intelligent grid) is being introduced for the purpose of facilitating effective integration of these dynamics into the system based on information technologies. The information network provides the room for tighter

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coordination between power generation and consumption. Smart devices (*e.g.,* sensors and smart meters) measure the information of power generators including distributed/renewable sources, status of transmission/distribution line and individual power customers. Two-way communication networks link the power dispatch and customers. Grid operation systems control the dynamic power flow using the information. The information network plays the key role of the implementation of smart grid.

Information networks for smart grid have been researched including the part of the information generation (measurement), transmission, and consumption. A number of these efforts have focused on the information transmission by communication networks and consumption for grid managements. For instance, wired/wireless network techniques are suggested for delivering the information, *e.g.,* power line communication, wireless sensor network and cellular networks [7]. Others issues have considered for reliable communications such as privacy and security. In addition, grid operation methods have evaluated using the information for reliably managing the dynamic power flow and effectively sup-porting the dynamic demand [8]. The communication platform using DNP3 protocol is suggested for adaptive volt-VAR optimization [9]. However, implementing the information network for smart grid incurs the important question:

"Is the information always helpful for the smart grid operation?"

For the reliable operation of smart grid, the amount of measurement unit and the information from that should be increased, and then the implementation of smart grid is grown. Also, the near-real time control is required for enhancing the effective grid management based on the analysis of the information. The increased information volume is a burden for computing that. It constraints the information network design for smart grid.

The basic concept about the information network design for the future smart grid is introduced focused on the smart grid information network model in [10]. In this paper, it is explored overall information network mechanisms and requirements for smart grid to understand the grid aspect as well as the information aspect. Smart grid achieves the diminution of the grids operational expenditure by the reliable and effective operation under the enhanced information and grid infrastructure and the increase of system and computational complexity. The reliable smart grid information network design strategies are suggested that arise in implementing these environments, and discussed with an example of Jeju smart grid test-bed in Korea.

The paper is organized as follows. In Section 2, it is described the information network model generally considered for smart grid, and briefly explain the problem which is faced with the smart grid information network by an example. The requirement of information networks for smart grid is presented in Section 3. In Section 4, it is discussed the design strategies for implementing the reliable smart grid information network considering requirements and characteristics of information networks and grids. Last, the paper is concluded in Section 5.

2. Smart Grid Information Network Model

In smart grid environment with intelligent grid devices, participating customers, newly connected renewable sources and plug-in vehicles, *etc.,* the grid has distributed and bi-directional power flow. The information network for smart grid needs to handle complex and massive data to meet the smart grid requirements. In this section, we formally describe a general smart grid information network model, and formulate problems for implementing the smart grid information network based on an example deployed on the Jeju smart grid test-bed in Korea.

2.1. Overall Smart Grid Information Network

Similar to grids, an information network for a grid is also made by the form of generation, trans-mission and consumption. In conventional grids, the information supports a part of the grid management. The information is measured for grid operations *(i.e.*, the control of bulk power generators, the con- figuration of transmission/distribution topology) in unilateral and limited ways. The grid management are separated by two parts: The high/medium voltage part (*i.e.*, power generation and trans-mission) is controlled by the supervisory control and data acquisition/energy management system (SCADA/EMS), and distribution grids of low voltage parts are managed by the distributed automation system/distributed management system (DAS/DMS). Each operation systems are worked using the information which is measured from their own operational part, respectively. That is because the conventional grid has a unidirectional power flow.

Smart grid has bidirectional power flow by various power sources such as renewable generators, energy storages, electric vehicles, and so on. It adjures the enhancement of grid management. Particularly, the importance of the customer management systems (CMS) of residential part is increased be-cause the role of customer in grid are extended from a mere power consumer to one of the active participants with demand response and power generators. Each grid management systems not only control the dynamics of their own part, but also cooperate for enhancing the grid operating reliability and efficiency by interchanging the information. For supporting these enhanced grid operation, the information network is overlaid on each parts of grid, as shown in Figure 1.

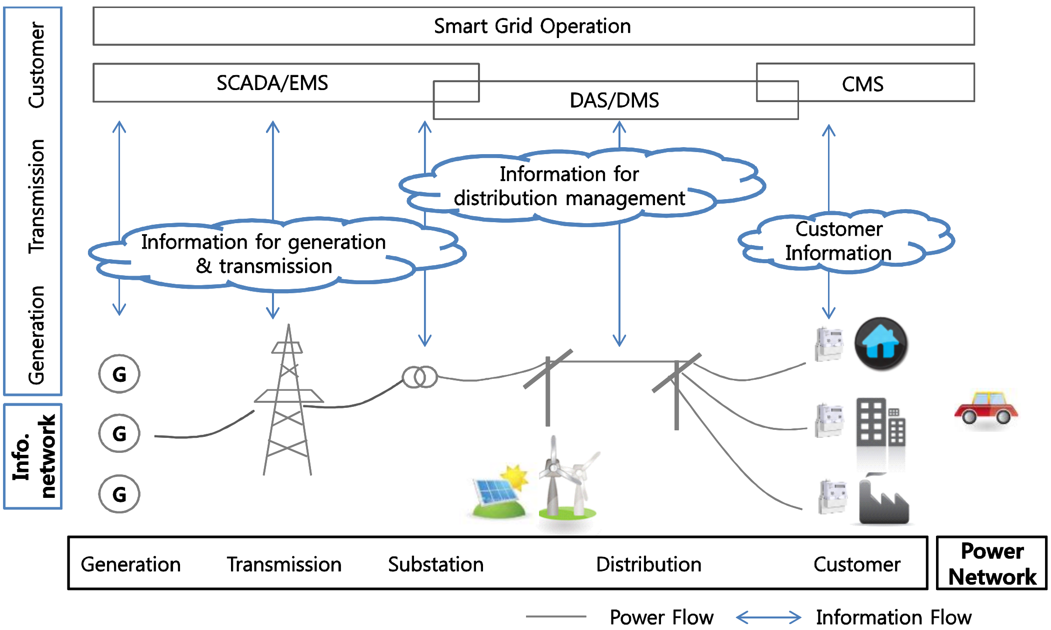

Figure 1. A General Model of Smart Grid with an Information Flow

Note that the information network for smart grid has bi-directional flow: the measurement information flow from devices to operation systems and the control flow with the opposite direction. Generally, the control information has light volumes, and has similar characteristics with the information which is handled in data networks. So, we focus the measurement information flow generated from devices and consumed for grid operation.

Smart meters have the information about the power consumption of customers which is transmitted from distribution grid parts. Smart meters deployed in Jeju smart grid test-bed project generate the information about customer load profile per 15 minute with 120bits data volume. However, when the smart meter is worked as the synchronized measurement rate of IED considering the information usage for the distribution grid operation, the total data volume generated from the meters is increased to 34MByte per 30 second with 280,000 meters in Jeju area. If, for supporting the smart grid application, the smart meter and device measure the additional information, the data rate for transmitted the information is dramatically increased. Similar results are shown in the research of Electric Power Research Institute (EPRI). They are estimated that 3.31MByte/sec data transfer is required for smart grid applications on one substation area and, for supporting the typical control area which has 500 substations, the data volume of about 16.6GByte is generated per second (see Table I [12]). The huge growth of the data volume not only rises up the problem for the information transmission, but also becomes the burden of the near-real time grid operation by increasing the computational complexity.

Table 1. Required Transfer for Smart Grid Applications

Control hierarchy	Value [MByte/sec]
Substation	3.31
Zone/Vicinity	8.1
Control area	5.089
Region	0.548
Grid	2.65

In addition, IED has a sensor precision of about 0.5%, but the sensor of smart meters has 97 to 99% precision about the measured information. The information from smart meters could be reduced the reliability of grid operation even if the amount of the information is increased. A sensor precision of 2-3% leads to only 30-70% of satisfactory estimation of the grid information [12].

That is why we should design the secure information network from the information generation to consumption for the reliable and effective smart grid implementation.

3. Information Network Requirements

Enhancing the operation and service of smart grid is based on increasing the amount of information. It is the main constraint to design the information network for smart grid how to generate, transmit, consume the information. In this section, we discuss about requirements of information networks for smart grid.

3.1. Accuracy

Information accuracy for smart grid is related with the parts of information generation and trans-mission. Particularly the accuracy of the information is decided by the information sensitivity at the information generation part because information transmission parts for smart grid are constructed by using modern data communication networks which have various techniques for guaranteed the information integrity. Information for smart grid is generated by sensors and smart devices (*e.g.*, IED, phase measurement unit (PMU) and smart meter) at each grid parts. Power (both active and reactive) and power quality (current, voltage and time tag for 3 phases) are measured for monitoring and operating of grids. For reliable operation of grids, more precise and frequent information measurements are required by smart devices supporting the various smart grid services (*e.g.,* Table 2 [13]). In addition, smart devices encompass control equipment of grid such as line reclosers, voltage regulators, capacitor banks, sectionalizers, line switches, fault indicators, circuit breakers, load tap changers, and trans-formers. So, for the development of smart device, the problem of device functionality is significantly treated rather than the problem of power consumption and computing power which are the traditional problem of low cost sensors.

Table 2. Smart Device Requirements for Smart Grid Services

Service	Requirement	Value
Telemetry	Sensing error rate	≤ 0.5%
	Sampling rate	128sampling/cycle
Error detection	Detection	Auto detection
	Wave record(normal)	≥ 1cycle
	Wave record(incident)	≥ 20cycle

3.2. Latency

Increasing the precision and frequency of the measured information, the amount of the information for smart grid is grown up. For transmitted the information, information networks for smart grid have a heterogeneous network architecture related with information customers. For example, wide area, local area, and neighborhood area net- works are constructed and transmit the information for the grid operation systems such as SCADA/EMS, DAS/DMS and CMS. Various data communication techniques are considered including wired techniques with optical fiber, twisted pairs, and power line as well as the wireless techniques such as Wi-Fi and cellular radio. Internet protocol (IP) based backbone are used for the information exchange between systems. For the effective operation of smart grid, the timely transmission of the information is required through these data communication networks. Latency at the information transmission part is an important design constraint for the smart grid information network. Various latency constraints are required for smart grid services as well as operations, as shown in Table 3 [14].

Table 3. Latency Requirements for Smart Grid Services

Service	Latency allowance	Comments
Teleprotection	8ms, 10ms	
PMU	16ms	Class A service
Smart meter	200ms	Short time
SCADA data	200ms	Poll response
VoIP signaling	200ms	Non-incident
Smart meter	≥ 1sec	Periodic reading

3.3. Security

The information enhancement provides the reliable operation of grids, but introduces the security problem. That is because the measured and transmitted information for smart grid includes the information about customer’s (human and society) behaviors. Security problems are occurred by the physical attack to grid equipment such as smart devices on the information generation part and the cyber-attack targeting the information transmission part. Solutions for security problems could be learned from other industries such as banking and mobile phone service on data communication networks.

3.4. Interoperability

Interoperability refers to the capability of two or more networks, systems, devices, applications, or components to exchange and readily use information – securely, effectively, and with little or no inconvenience to the user [15]. Smart grid is a system of systems including hierarchical power net-works as well as heterogeneous in- formation networks, so the development of smart grid with interoperability is required for the effective usage of the information. Particularly the smart grid operation systems which is the information consumption part of smart grid information networks not only cooperate with between them for the reliable and efficiency grid control, but also be worked as distribution manner such as micro-grid systems. The information should be generated and consumed for supporting various services and applications considering the interoperability.

In Korea, Jeju smart grid test-bed project was begun in last 2008. The project has an intention of the evaluation of various smart grid techniques including information networks on Jeju Island in Korea. The distribution network of Jeju Island consists of 52 distribution lines, and has 541 intelligent electronic devices (IEDs). Each IEDs measures the voltage, current and phase information of the line with the period of 30 second, and the information with about 2.4Kbits data volume is generated per each measurement. It is enough to monitoring and controlling the conventional grid, but the error such as the state estimation and the fault current detection will keep increasing with the dynamic power flow when considering innovative smart grid elements such as renewable sources, energy storages and plug-in electric vehicles. Because devices are sparsely installed on the main distribution line, it is hard to observe the exact status of the branch line of distribution grid parts. For enhancing the reliability of operation, additional information is required. And, it could be achieved from smart meters at the customer part for the distribution grid operation without supplementary installation of smart devices.

4. Information Network Design Strategies

In this section, it is suggested strategies for the reliable smart grid information network design related with requirements at each information network parts – information generation, transmission, and consumption, as shown in Figure 2.

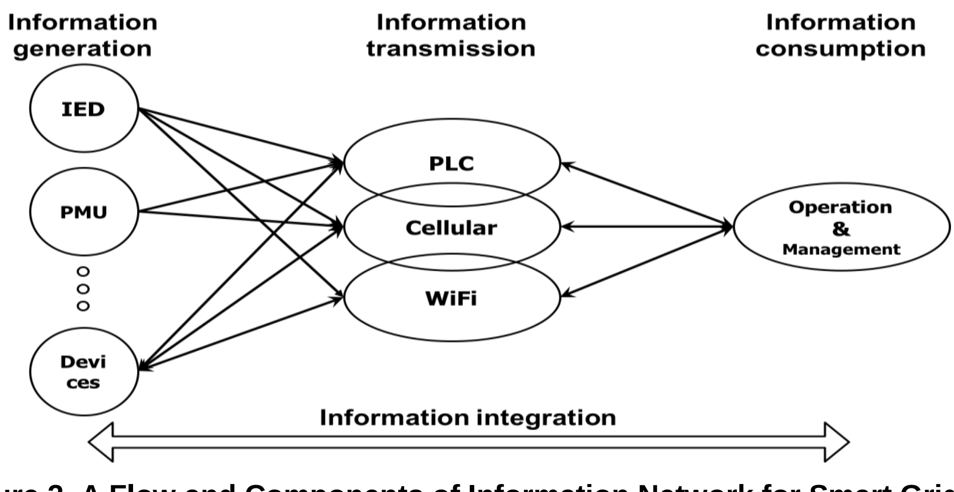

Figure 2. A Flow and Components of Information Network for Smart Grid

4.1. Information Generation

As discussed above sections, requirements for the information generation part are the accuracy and interoperability of the information, and it is affected from the functionality and topology of smart devices.

For increasing the information accuracy, enhanced smart devices could be used which have the improved processing and power units and high-resolution sensors, but it increases the cost of smart devices as well as the amount of the information as shown in an example of Section 2.2. It has an exponential relationship between the device cost and performance because the smart device measures various parameters. With diversity techniques, the information could be generated using multiple normal smart devices which have low-cost units. In this case, the device cost is linearly increased, but the cost for installation and maintenance is added. In addition, the deployment of low-cost unit is eliminated by the interoperability requirement constraints. For the information usage for supporting the reliable operation and applying the various smart grid services, the secured information measurement from the enhanced smart device is required. The information generation part should be constructed with mixed (enhanced/normal) smart devices considering the device and implementation cost as well as the requirements.

One of the important benefit of smart grid is reducing the operational expenditure of grids by reliable and effective operation, but the cost for implementing the information generation part could be increased by using the enhanced smart device and the installation of more devices. That is why the information generation part should be designed considering the trade-off between the benefit by the information usage and the cost for implementing this part.

4.2. Information Transmission

The information transmission part of smart grid information networks is able to be modeled as an application of conventional data communication networks. However, for satisfying the requirements such as the information latency, some characteristics of smart grid are carefully considered at this part.

Firstly, smart grid information networks should be transmitted the huge growing data volume measured at information generation parts. More smart devices are deployed, and frequently generates the information for controlling and monitoring the grid and satisfying the requirements of the information generation part. The security requirement for the information is added the burden at the information transmission part for supporting the latency requirement. Particularly smart meters are in-stalled for billing and supporting services at each customer side. It brings up problems such as in-creasing the control overhead for transmitting the information similarly with that of femto-cell implementations on wireless communication networks.

Other consideration for constructing the information trans- mission part is the asymmetric data volume between up and downlink. In the smart grid information network, the data transmission rate between up and downlink is approximately 10000:1 [12]. That is because, in the uplink information trans- mission, the heavy and frequent information is transmitted from devices to operation systems, but the downlink information is intermittently generated for the grid control. The use of wireless cellular networks such as 3GPP-LTE(A), WiMAX are considered for the information transmission of customer parts, but the conventional cellular networks are designed to supporting the asymmetric transmission rate of up/downlink as 1:3 to 1:10. Even if cellular networks have flexible data frame structure, it is hard to cover the asymmetric transmission which has heavy uplink data volume.

For the reliable information transmission, the data volume from devices to operation systems should be separated and reduced. Learning from the researches about data communication network design, the information transmission part could be constructed by hierarchical structures with sectoring and multi-priority transmission techniques considering the requirements (*i.e.*, latency and security) and the information usage.

4.3. Information Consumption

Effective smart grid operation based on the increased information allows us to benefit from economies of scale. For example, as little as a 1% load reduction due to demand response can lead to a 10% reduction in wholesale prices, while a 5% load response can cut the wholesale price in half [16]. It indicates that the operation more sensitively affects to overall grids.

For the effective grid operation, the smart grid operation systems have to handle the huge information which is generated and transmitted from each grid parts. The optimal operational performance requires the near-real time response analyzed the information. It intensifies the distributed operation of grids for reducing the computational burden by the big information data and enhancing of the management of the dynamics such as renewable source and plug-in electric vehicles. It is managed the risk of grids from the dynamics and enhanced the grid security in distributed way, but the global effectiveness of grids could be declined which is required the cooperation between systems.

In this reason, service-oriented functionality for grid operation should be evaluated at the information consumption part. Risk management such as self-healing and protection control of grids is locally operated with timely manner, and load balancing and asset utilization optimizations are required by globally cooperated with operation systems.

4.4. Information Integration

Information network architecture is constructed as information generation, transmission and consumption, as discussed above. However, information integration is additionally required to support information-centric smart grid.

In the information generation part, the information is generated from various sources which have difference purpose and characteristics. Moreover, the generated information is transmitted through different information network. The consumed information for the smart grid operator should be feedback to devices for reliable control. It means that the end-point elements such as smart grid devices (left-end in Figure 2) and operator (right-end in Figure 2) are not only the information generator but also the information consumer. As a result, the integration and optimization of the information network essentially affect to the performance of the information network such as reliability and stability.

In this reason, the smart grid interoperability should be considered for all information network design parts [17]. The standard interoperability supports the information exchange among devices and networks in each information progress parts. The interoperability also permits the convergence and interaction of information between information progress parts.

5. Conclusions

In this paper, it has been discussed the smart grid information networks design from the information generation to consumption for the reliable and effective smart grid implementation. It has been focused on supporting the information flow from the devices to the operation systems. Based on an example of Jeju smart grid test-bed in Korea, it is derived the problem faced on the smart grid information network for supporting the newly introduced smart grid environments with the dynamic power flows. And, we have presented the design strategies of the smart grid information network considering the problems and requirements.

In summary, it is argued that the information generation and consumption parts as well as the information transmission part should be considered, and the trade-off between the revenue and benefit of grids and information networks by increasing the amount of the information should also come up for the secure smart grid information network design.

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