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AMI BASED SENSING ARCHITECTURE FOR SMART GRID IN IPV6 NETWORKS

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Abstract- Advanced Metering Infrastructure (AMI) is a key part in the development of the smart grid, which integrates automatic meter reading, distribution automation, user data analysis, as well as real-time price adjustment functions. Existing AMI can offer good support for smart grid backbone. However, it still has some shortages when sensing the electric meter data acquisition, electric devices, and etc. Due to the vast number of meters, the use of IPv6 technology in AMI is an inevitable trend. Sensing architecture based on IPv6 can help AMI be aware of communication network topology and the access time of electrical devices, and calculate real-time electricity billing. Smart meter data is collected using cognitive architecture so that it would be more accurate and meaningful. In this paper, we firstly introduce the basic architecture of AMI, including master station system, smart meters and the key technologies of communication network. And then, for the existing AMI architecture, we analyze the current situation and challenges in the aspect of perception. Finally an AMI sensing architecture based on 6LowPAN and Mesh is proposed. Experiments show that the architecture can not only improve the accuracy of the meter data, but also sense the temporary access devices. As a result, the structure is feasible and could earn more commercial benifit.

Index terms: Smart grid, Advanced Metering Infrastructure, Sensing architecture, Monitoring, IPv6

I. INTRODUCTION

Smart grid is the first step towards the future energy Internet, and is the key coordinator among the power generation, distribution and usage processes. It is considered as an integration of power grids and information networks, and provides the communication service for each component in the power grids. As a result, the power grids become intelligent. Advanced Metering Infrastructure (AMI) which supports bidirectional communication plays an important role in smart grids. It not only provides communication and data collection architecture for the smart grid infrastructure, but also offers many valuable applications such as automatic meter reading, distribution automation, users' power consumption data analysis, and real-time price adjustment [1, 2, 3, and 4].

AMI is an integration of many information technologies [5, 6, 7]. AMIs may use different communication technologies, including wired technologies, such as fiber optics, power line communication (PLC); as well as wireless communication technologies, such as mobile technologies (3G, 4G, LET), WiMAX [8], ZigBee[9], and Wi-Fi [10]. Due to different communication standards, there are a lot of heterogeneous networks in AMI, which leads to low efficiency, poor stability, low one-time meter reading success rate and the problems that the devices frequently offline. In order to overcome these problems, a new AMI architecture based on IPv6 is proposed. AMI with IPv6 enables the communication network running on TCP / IP protocol, which greatly improves the compatibility of AMI.

This article is organized according to the following structure: Section II is the overview of the AMI, including the evolution process of AMI, main functions of AMI, and basic architecture of AMI. In Section III, we analyze the necessity of smart grid sensing based on AMI. After reviewing the major components of AMI, we discuss the challenges in the process of AMI sensing. In Section IV, by using AHP to analyze the AMI network critical safety factors, we come to the conclusion that the main security threats in AMI is from the network. In Section V， an AMI sensing architecture based on IPv6 is designed, which can sense the temporary access devices. Section VI summarizes the full text.

II. OVERVIEW OF AMI

Due to the development of the communication technologies and sensor technologies, the automation, informatization and interaction of smart grid, which include the power grid and the communication networks, have been enhanced. Distribution management of the power grid is based on communication network. The traditional power grid and the communication network added above constitute a smart grid. Communication networks can coordinate the electricity sector operators, optimize network efficiency and the energy efficiency based on the acquisition status and the measuring information of the power grid Power measurement system has also been evolved with the evolution of the smart grid. Manual reading had been firstly replaced by Automatic Meter Reading (AMR) system with one-way remote communication. And then, AMR had been developed to the Advanced Metering Management (AMM) system that adds, wireless communication module and centralized data management centers. Finally, the AMM had been enhanced and turned into AMI which has a complete measurement system and supports advanced two-way communications.

AMI has initially been used to collect data from the smart meters. To count the users' load information, the AMI acquires a variety of user-side measurement values periodically, such as electricity, electricity demand, voltage, current, etc. With the raise of the various aspects of demand, home power information measurement terminals and the mass power data mining functions are then added to the advanced measurement infrastructure [11]. AMI collects a huge amount of data, most of which are affixed real-time labels. AMI can take full advantage of the massive amounts of collected data, from which AMI can dig out the useful values, and then provide a scientific basis for the power supply company to lay down the power supply strategies, evaluate the equipment operation condition and plan the grid construction.

BC Hydro Company proposes the evolution of AMI infrastructure over the next 20 years, which is envisaged by the multi-level integration of communication facilities as the basis. They have carried out Smart Metering Infrastructure (SMI) project, and planed for the future AMI supports both smart meter infrastructure automatic meter reading function and the home user application connectivity, and supports power distribution automation, substation automation, mobile workforce management and other functions.

AMI architecture consists of three parts, referring to the master system, communication networks and smart meters [12]. Fig. 1 shows a basic smart grid AMI architecture diagram. The master system is deployed in the information center of the power company and physically constituted by the high-speed network, server groups, storage facilities, PKI and other facilities. The master system is mainly responsible for the AMI data collection, data storage, data analysis, and network management and security features [13]. Smart meters and master system are connected together via a communication network so that they can communicate with each other and collaborate on data collection. AMI develops toward comprehensive IPv6, using IPv6 protocol to set up a private network in LAN to replace traditional private forms of heterogeneous network [14]. Smart meters also add some new features to support IPv6 protocol that can achieve conducted LAN communication between meter and meter, and between meter and the collect router.

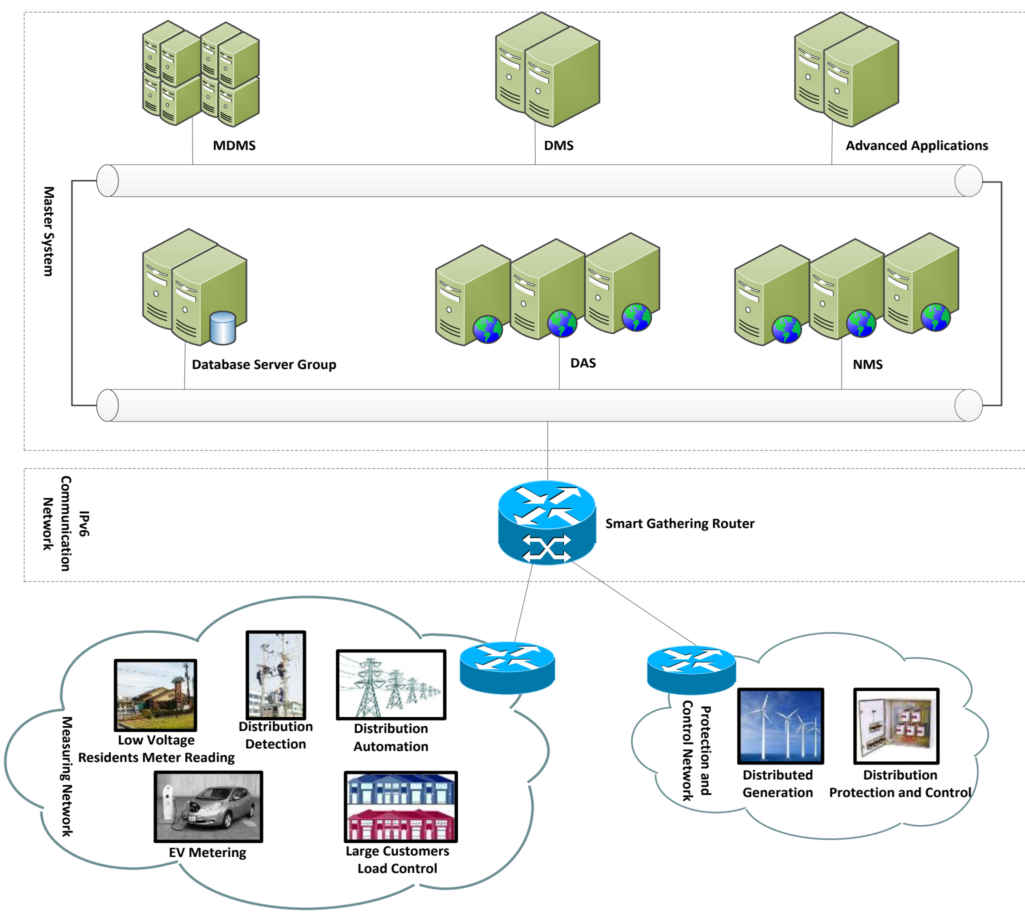

Figure 1: A basic architecture of smart grid AMI diagram

Although there are a lot of researches on AMI architecture, most studies are based on macroscopic analysis with all parts of the AMI architecture, for example, Yan Y et al[1] analyzed the compositions of the smart grid. Some researches only design some local functions for AMI architecture, for example, Yu K et al [15] gave a solution according to the flow demand for AMI; Bhatia R K et al [16] designed AMI architecture for wireless security attacks.

III. THE ANALYSIS OF SMART GRID SENSING BASED ON AMI

AMI is composed of three parts, including the main system, smart meters and communication networks. With the development of smart grid, besides smart meters, more new terminal devices sensed by AMI have appeared, including electric cars, intelligent household electric appliance [17]. The traditional way of billing is that electricity meter counts the electricity consumption of one unit. However, smart grid sensing technology based on AMI can sense each terminal when it accesses in and gets out. Moreover, it can collect the detailed information of devices and the terminal energy consumption. Through sensing terminal devices to get their information, AMI can judge the security of the terminal devices, and calculate the interval between the devices access in and get out, which is particularly significant for those electricity devices accessing in temporarily. We respectively introduce the three parts of AMI, and discuss the challenges which smart grid sensing based on AMI is facing.

a. The master system

Smart grid master system is composed of Data Measuring Management System (MDMS), Distribution Management System (DMS), and Network Management System (NMS) etc. The master system monitors voltage and current within the smart grid, and counts users' electricity consumption based on the measured data collected from smart meters, and then carries out distribution automation management and communication network management.

b. Smart meters

The development of smart meters for AMI is important. Smart meters collect the user's electricity consumption, which determines the accuracy and real-time measurement of AMI [18]. Statistics and analysis of users' electricity consumption are important for the electricity company to calculate the power consumption of the users, optimize circuit parameters, calculate the line loss and accurately predict loads. However, traditional meters had presented many drawbacks, such as the huge consumption of human source, large meter reading errors and poor real-time performance, so that it cannot meet the AMI requirements for the smart meters and have been replaced by electronic meters, which have high accuracy, stable performance, low power consumption, small size and light weight. In addition, the electronic meters also have some other features, such as multi-rate measurement, maximum demand measurement, the power factor measurement, active and reactive energy record, load curve record, the voltage passing rate measurement etc.

To solve the difficulty in smart grid heterogeneous network communication, smart grid has to turn into IP network. Considering the huge number of smart meters, smart grid communication network is bound to select the IPv6 protocol. IPv6 could provide an address for each smart meter. Due to the development of the smart grid communication network, the support for the IPv6 protocol is added to the smart meters, which originally support serial communication, ZigBee, power line carrier communications. In addition, due to the simple construction, flexible topology and easy maintenance, the wireless mode becomes a new trend in the development of smart meters. But with the power constraints, embedded smart meters use wireless 6LoWPAN protocol, which is based on the IPv6 low-loss wireless personal-area network protocol. In the 6LoWPAN protocol, IPv6 protocol is compressed to suit the embedded devices with limited processing ability, low power consumption, and small storage space [19]. Smart meters using 6LoWPAN protocol are able to connect directly with the IPv6 Internet, which provides a great convenience for the development of smart grid communication networks [20].

The construction of AMI has attracted widespread attention in worldwide, which is used for electricity demand adjustment and load control. A lot of countries support the replacement of smart meters for constructing the AMI. China plans to install 300 million smart meters until the end of 2015; France plans to improve the family smart meters penetration rate to 80% by 2020, which means 35 million smart meters will be installed; Spain plans to change all the electromechanical meters to smart meters before 2018; the United States is expected to reach 50% penetration rate of smart meters at the end of 2015; Japan claims that the government will install smart meters for all proposed users after 2020.

As shown in Fig.2, smart meters consist of five modules: power signal conditioning module, power signal metering module, microprocessor module, remote control module and communication module [21].

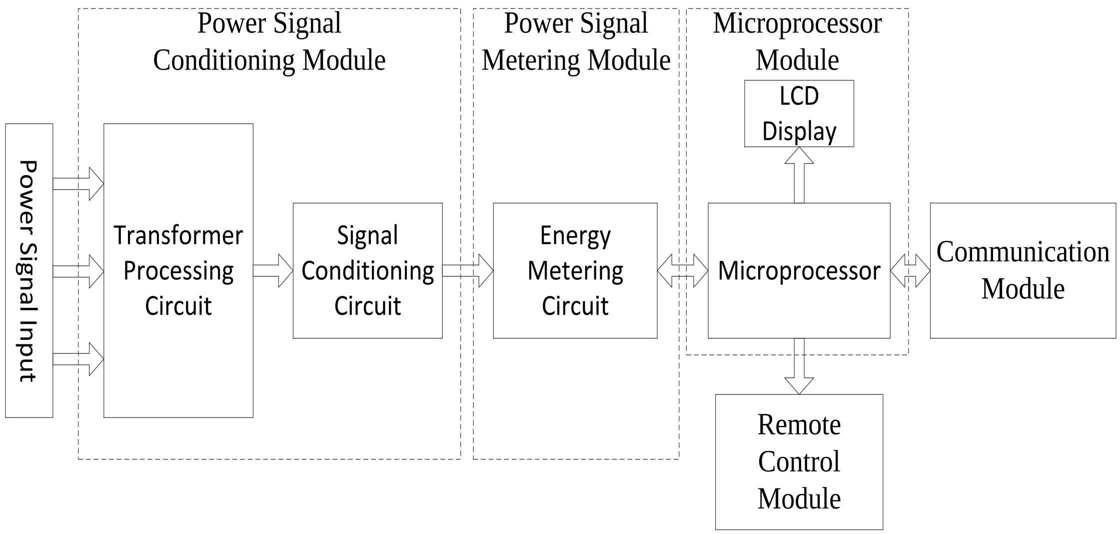

Figure 2: Hardware system schematic diagram of a smart meter

Power signal conditioning module is composed of transformer processing circuits and signal conditioning circuits. The input power signal passes the voltage transformers and the current transformers at the first place, through which the grid voltage is converted into current in milliampere. Then, the signal conditioning circuits filter the high frequency components of the converted voltage and current and adjust the voltage signal into the range of -0.5V ~ + 0.5V, so that it is easy for further processing by electric energy metering module.

Energy metering chip is the core of the electric power signal metering module. It can complete the A/D sampling of analog voltage and current signal with phase calibration. Those signals are conditioned by power signal conditioning module. Energy metering chip can capture the voltage and current signals, calculate the voltage rms, current rms, and then get active power, reactive power and apparent power, and provide storage space for storing measurement data.

The microprocessor module consists of a microprocessor core chip, microprocessor peripheral circuits, power management circuits and LCD display circuits. The main functions of the microprocessor chip are the display of the measurement data stored in the energy metering module, and remote upload via the communication module. The microprocessor module plays a role as sending control signals to remote control module.

The communication module is a circuit supporting standard interfaces such as SPI, I2C and other communication chip interfaces. Recently, smart meters have used wireless communication chips frequently, which support wireless technologies such as ZigBee, Wi-Fi and 6LoWPAN protocol. Function of the communication module is controlled by the microprocessor chip. The module could provide two-way communication between the microprocessor and the master system. With the help of communication module, smart meters can both regularly upload the measured data, and receive the control commands from the master system.

Remote control module contains a relay driver circuit to take off power in case of the user arrears or in need of power repair. Remote control module also can restore the electricity service after the user pays the fee or when the electrical maintenance finishes.

c. Communication networks

AMI communication networks can be divided into two types, namely wired networks and wireless networks. In wired communication networks, PLC, which has a long history, has been widely used in Europe countries since as long as there are wires PLC technology has been fused with IP technology [22]. G3-PLC standard uses 6LoWPAN protocol in its adaptation layer, and use compressed IPv6 addresses in low power lose network to remove unnecessarily overhead [23, 24, 25]. AMI backbones mainly use optical communication techniques, because of the high transmission rate, low noise, and high throughput.

In addition, since the wireless networks are easily structure and show high flexibility, AMI also has gradually been transiting to a wireless network. Mobile wireless technologies, such as 3G, LTE, can support AMI network communications without substantial additional facilities, because their infrastructures are consummate. Security mechanism of mobile networks is mature and strong. While the high rent causes the increasing of cost. In the HAN, the formations of smart meter network or the smart appliances network usually use ZigBee, Wi-Fi [26] and RF Mesh [27]. ZigBee, whose data rate is between 20kbps to 250kbps, uses the low power technology. Therefore it is suitable for low power consumption embedded devices. Wi-Fi is based on the IEEE 802.11, working at 2.4 GHz, 3.6 GHz and 5 GHz. Its advantages are high data rate and bandwidth, however, the power consumption of Wi-Fi is large, so that it is not easy to bear for embedded devices with limited battery capacity. RF Mesh, whose center frequency is 900MHz, supports multiple-hop network mode. Nodes in RF Mesh network can relay messages to the destination, enhancing the flexibility of the smart meter networks; therefore RF Mesh networks are very suitable for AMI [28]. However, RF Mesh still exists many security problems and needs further improvements.

d. The challenges of smart grid sensing based on AMI

One of the initial purposes on which AMI collects electricity consumption accurately is to grasp the users' electricity consumption, including electricity consumption of both utilities' and users' electricity appliances, so as to formulate a reasonable period of the peak level time and the price range. Smart grid can strengthen the interactivity between users and the power grid and provide a wealth of value-added services, but at the same time increase the possibility of violating the user privacy. Smart grid may disclose user privacy from the following three aspects [29, 30, 31].

(1) Users' electricity situation will present the user's habits, work and other time schedule etc. AMI has recorded a large amount of household electricity usage data, which can be analyzed to obtain the timetable of when the users get up, sleep, go out, go home and other personal privacy.

(2) Users' home appliances will be exposed by the electricity consumption data. Future AMI will carefully monitor the electricity consumption of different home appliances, which may expose the brands and models of these home appliances, the habits of electrical appliances usage in daily life and other preferences.

(3) Electric car battery charging will expose the geographic location information. The future electric cars connected to the grid for temporary charge need to register in the AMI of network management system and complete the authentication process. In this process, a unique ID and geographic location information of the electric vehicles are the essential information to be submitted. Therefore, users may leak their geographical location information in the electric vehicle temporary charging access.

IV. Analysis of AMI network critical safety factors by using AHP

a. Introduction of AHP

1970s, Professor TL.Saaty in University of Pittsburgh proposed a hierarchical decision analysis weighting method in the study "Power Distribution of different industrial sectors according to their contribution to national welfare" for United States Department of Defense. And the weighting method is called the Analytic Hierarchy Process (AHP). Analytic Hierarchy Process refers to a complex multi-objective decision problem as a system, and decomposes the target into multiple targets or guidelines, and then divides them into a number of multi-level indicators. After calculating the single-level sorting and total-level sorting through qualitative fuzzy index quantization method, AHP can provide the basis of a systematic approach to choose the best option. Using AHP, generally according to the following four steps:

(1) Analyze the relationship between the various factors in the system, and create a system of hierarchical structure;

(2) The same level of importance of each element on the previous level in a pair wise comparison criteria, construct pair wise comparison judgment matrix;

(3) Calculate the relative weights of the element by judgment matrix, and test the consistency of the matrix.

(4) Calculate the total sorting weight of each level in the system, and sort them. And finally get the total rent of each program.

When using AHP to analyze the decision making problem, first of all, the problem should be structured and hierarchical, and a hierarchical structure model should be constructed. Under this model, complex problem is broken down into component elements, and these elements form a number of levels according to their attributes and relationships. Elements of upper levels perform as a dominant criterion for the elements of lower levels. These levels can be divided into three categories:

(1) The highest level (target level): Only one element is generally intended target or desired results to analyze problems;

(2) The middle layer (Layer Guidelines): Included involved to achieve the objectives of intermediate links, which can consist of several levels of composition, criteria include the need to consider the sub-criteria;

(3) The lowest level (program level): includes various measures to achieve the goal of alternative decision-making programs.

The complexity of the problem class delivery times and the number of hierarchical structures and the need to analyze in detail the extent relevant, in general, the number of levels is unlimited. Elements in each level of each element is dominant for generally not more than 9, this is because the elements will dominate the excessive pair wise comparisons difficult. A good hierarchy to solve the problem is extremely important, if indecisive on the relations of domination and determine levels of hierarchical division between the elements, you should re-analyze the problem and clarify the relationship between the elements in order to ensure a rational hierarchy. AHP hierarchical structure is the simplest and most practical form of hierarchy. When a complex problem with a hierarchical structure is difficult to express, you can extend the use of more complex forms, such as hierarchical structure of internal interdependence, feedback hierarchical structure.

After the establishment of hierarchical structure, affiliation between the upper and lower elements was determined. The next step is to determine the weight of heavy elements at all levels. For most social and economic issues, especially the more complex problems, weight is not easy right elements directly, and then you need to export their weights by appropriate methods, AHP judgment matrix gives decision makers using methods derived weights. The next level of the elements in mind the criteria of Element C is dominated by, U_1, U_2, ⋯, U_n . For criterion C, decision-makers to compare two elements U_i and U_j that one is more important, the formation of judgment matrix $A=(a_{ij})_{nxn}$. In the matrix, a_{ij} is a U_i element and U_j relative importance of the criteria C, the ratio of the scale.

b. Analysis of AMI network critical safety factors

TOPSIS method is a sequential selection technology. In the analysis of grid communication network security, TOPSIS can be used to calculate the “distance” between the evaluation target and ideal solution，and sort the related factors. According to the "distance" value， related factors are sorted. And then according to the sorted result, we can get the guidance of the security work model. For example, the safety analysis algorithm proposed in this paper sorts the terminal security and network security ordered respectively.

According to the analysis of the affecting factors for AMI network security, those factors affecting the index system can be gotten by using AHP analysis. The index system includes metering devices and the network structure of metering devices, as shown in Figure 3 and Figure 4 respectively.

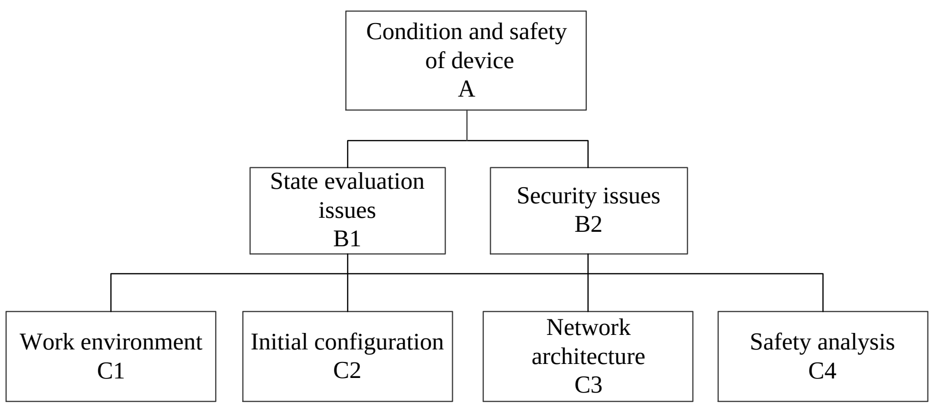

Figure 3: The index system of metering devices

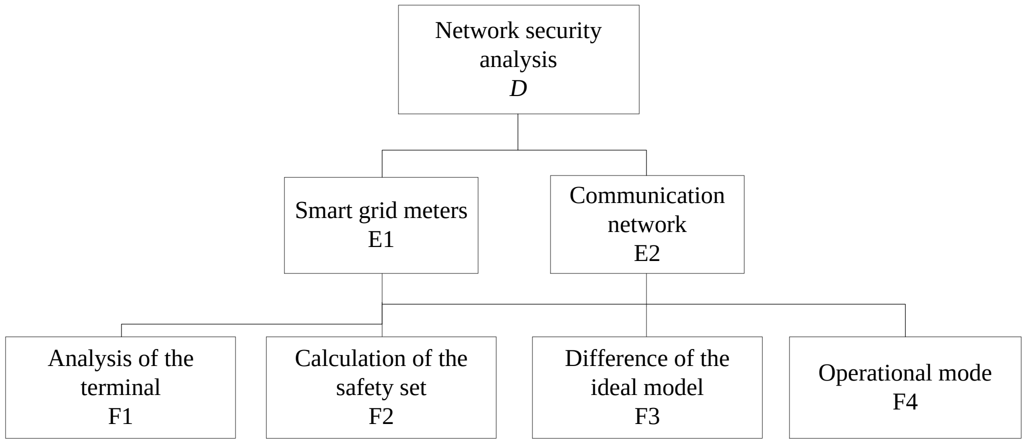

Figure 4: The index system of the network structure of metering devices

To construct the decision matrix in TOPSIS, those descriptive indexes of the actual state of network security with different scopes must be turned into quantitative digital indicators. Therefore, the key is to establish a unified parameter conversion standard.

A comparison discriminated matrix of an IPv6 electric energy meter network security is given by

	C1	C2	C3	C4	WB1
C1	1	3	7	2	WB1,1
C2	1/3	1	5	1/2	WB1,2
C3	1/7	1/5	1	1/6	WB1,3
C4	1/2	2	6	1	WB1,4

Furthermore, the weight matrix can be calculated through the model and the calculation results. WB = (WB1, WB2). And then we can get the order of the C level. WC = WB*WA = $(0.425, 0.217, 0.063, 0.296)^T$.

The evaluation objects are 15 IPv6 metering devices with different environment and network state. The safety parameters are shown in table 1

Table 1. Security contestant indexes

Number of smart grid meter	Environmental impact indexes				Safety indexes			
	*C*1	*C*2	*C*3	*C*4	*F*1	*F*2	*F*3	*F*4
1	7	3	9	6	7	4	1	6
2	2	8	3	3	3	4	2	4

3	2	1	3	3	3	4	2	4
4	7	3	9	6	7	4	7	6
5	7	3	9	2	7	4	7	6
6	6	3	8	6	7	4	2	6
7	6	4	9	5	6	4	2	6
8	3	5	8	6	4	4	1	6
9	7	4	4	6	5	3	2	5
10	8	2	3	4	6	4	2	5
11	9	4	5	3	6	4	1	4
12	7	4	9	6	5	3	2	5
13	8	2	3	4	6	4	1	4
14	9	2	5	3	5	3	2	5
15	7	3	6	5	5	4	3	5

From table 1, the index values of F2 calculated by AHP are basically the same. The reason is that the way those electricity meters work and connect are nearly the same. The environmental factor can be adjusted based on the actual needs, or other factors, which does not affect the overall workflow of the model.

The environmental impact decision-making matrix $U_A = (u_{ij})_{15\times4}$ and the security model decision matrix $U_D=(u_{ij})_{15\times4}$ are constructed respectively. And the environmental impact vector and the network security domain vector can be calculated:

$$C_A = (0.6039, 0.5147, 0.1066, 0.6039, 0.4710, 0.5031, 0.6039, 0.6530, 0.1231, 0.4871, 0.1854, 0.4671, 0.6510, 0.1345, 0.5244) \quad (1)$$

$$C_D = (0.2728, 0.1542, 0.1542, 1.0000, 1.0000, 0.2822, 0.1542, 0.2822, 0.1542, 1.0000, 0.2820, 0.1560, 1.0000, 0.2276, 1.0000) \quad (2)$$

Finally with C_A and C_D, calculate network value assessment of the state of each device in the collection. The network value assessment is

$$H = C_A^T \times C_D = (\mathrm{h}_1, \mathrm{h}_2, \cdots, \mathrm{h}_m) \quad (3)$$

$$H = (0.1647, 0.0794, 0.0164, 0.6039, 0.4710, 0.3024, 0.0819, 0.1354, 0.0198, 0.4781, 0.0279, 0.0195, 0.6510, 0.0546, 0.5244) \quad (4)$$

For the convenience of use, h transforms into $v = (1 - h)$. And then according to the scope of v, states are classified as follows:

0.5 is the normal judgment threshold. A device with the value of v above 0.5 will be judged as in a good/normal condition. According to the normal distribution, a device is in a normal condition when its value of v is between 0.5 and 0.7. When a device's value of v is above 0.7, its condition is good.

A device with the value of v less than 0.5 will be judged as note/exception. According to the normal distribution, a device needs to be noticed when its value of v is between 0.2 and 0.5. When a device's value of v is less than 0.2, its condition is exceptional.

From the analysis, we can come to a conclusion that the main security threats is from the network. Therefore, we design a more reliable, suitable AMI architecture, for a wide range of smart grid devices.

V. THE DESIGN OF AMI SENSING ARCHITECTURE

In this section, the designed scheme of AMI sensing architecture is proposed based on IPv6. Smart meters and home area network (HAN) [32] are particularly emphasized in the sensor network. Figure 5 is the design of overall architecture. In this scheme, the wireless sensors in smart grid adopt 6LoWPAN protocol to transmit data. Local area network (LAN) uses the unified network mode, which is easy to connect to the transmission network using IPv6 protocol [33].

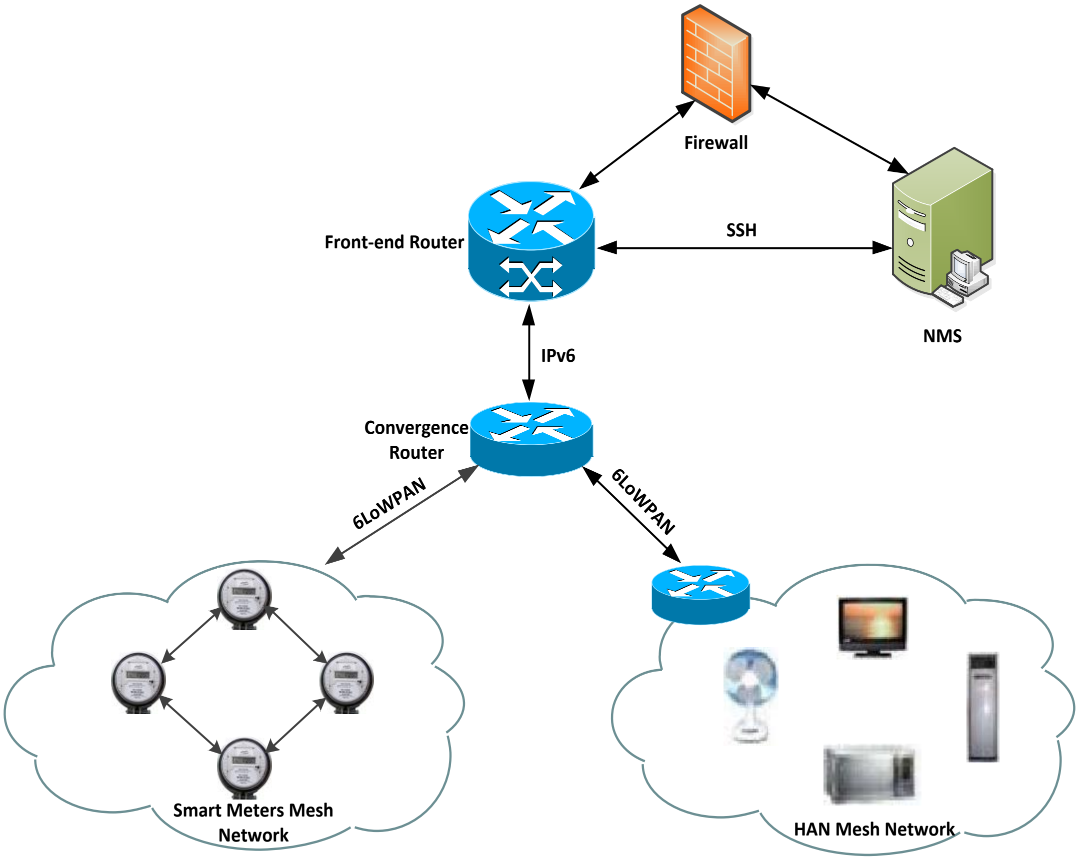

Figure 5: The diagram of the overall architecture design

The design of data acquisition layer avoids the formation of heterogeneous networks, which helps to improve the universality and expansibility of AMI. The Mesh technology is used in smart sensors network. Intelligent sensor networks can choose different Mesh network mode, such as single hop and multiple-hop networks. In smart meter networks, multiple-hops network mode is used. It indicates that network of smart meters, can be used as other meters' relay, and the message will be automatically forwarded to routing. By this way, our scheme plans to cancel the concentrator among meters, so that the meters can dock with the convergence router directly. The real application scenario for applying this way is: smart meters located in the same residential building relay each other through the Mesh technology, and every residential building installs a convergence router to gather the data of the whole building.

In HAN, the network mode is single hop network. Each family has a centralized router, every intelligent home appliances and the centralized router are connected directly. Mesh technology can make it more flexible and convenient for intelligent home appliance to join or leave HAN.

VI. CONCLUSION

AMI is an important part in Smart Grids. Based on AMI and computer networking, we proposed a novel sensing and control architecture for Smart Grids, especially for metering and load control. We firstly analysis AMI and network communications and the issues met in very large scale monitoring to millions of smart meters. The development status of smart meters and the function structures of the smart meters are also illustrated. The AMI security requirements and the existing threats, especially i security and privacy protection are analyzed. A security-enhanced mechanism is proposed based on IPv6 in this paper. The new architecture and a new network protocol are designed to support wide area monitoring. The test bed and experiments show that our new architecture could perform very well.

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