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A Blockchain-based Architecture for Stable and Trustworthy Smart Grid

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Abstract

Smart Grid represents an efficient power transmission, distribution and management system. However, solutions for Smart Grid have raised security and privacy problems. Moreover, with the introduction of renewable energy resources, such as rooftop solar panels and small biogas plants, more and more electricity consumers are involved in the energy generation system. This may cause the power system unstable and/or the waste of the energy. Blockchain is a promising technology for solving these problems in the future energy system on account of its distributed trust, anonymity, data integrity and availability. In this paper, we propose a Blockchain-based architecture for Smart Grid. By using the proposed architecture, electricity consumers can be fully involved in the energy system and tracing the details of the energy they have consumed or generated. At the same time, the stability of the energy system can be kept, reducing the waste of the energy and potential hazard to the electrical equipment.

Keywords: Smart Grid; Blockchain; Dynamic Electricity Price; Smart Contract

1. Introduction

Smart Grid represents in general an efficient power distribution and transmission system by making use

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effectively the existing power infrastructure. Smart Grids have been proven to be able to reduce costs concerning generation, outages, operational costs for transmission and distribution, and mitigate carbon dioxide (CO2) emissions [1].

However, solutions for Smart Grids have also raised various security problems which will be a growing concern. Physical attacks, cyber-attacks [2] or natural disasters are major notable forms of threats to smart grid deployment which could lead to infrastructural failure, customer privacy breach, blackouts, energy theft, endangered safety of operating personnel.

In addition, as technological advancements come to life, renewable energy resources have become possible, such as rooftop solar panels, small biogas plants etc. Thus, the traditional energy consumers are deeply involved in the energy system and market – they become energy prosumers (i.e., producers and consumers). Furthermore, the prosumers want to know and trace their energy generation and consumption in detail. Decentralized provision and consumption of energy, will revolutionized the energy system and market.

Hence, the energy system of the future will be decentralised and based on renewable energies. This puts forward new challenges in stabilizing the energy transmission and distribution system and satisfying the needs of users.

- As more and more energies are produced by households or small, private companies, both the energy distribution networks and the big, central energy producing plants are to be affected. How to maintain and optimize the grid stability is a big challenge to grid operators.
- Since customers are deeply involved in the energy system, new mechanism and models needs to be introduced to operate the grid in order to reduce the energy waste.
- New demands from energy consumers will emerge. For example, consumers may also want to use the green energy and be sure what energy they are using. How to keep the energy system transparent to the customers is of great importance.

Blockchain is a distributed ledger technology, providing distributed trust, anonymity, data integrity and availability [3][4]. Blockchain technology can benefit the energy system in two aspects fundamentally. One is it is distributed system in nature. The other is Blockchain has intrinsic security mechanisms by design. Hence, Blockchain can be a promising technology for meeting the requirements of future energy system.

Due to the intrinsic features of blockchain technology, it has been used in Internet of Things (IoT) [5][6][7][8] and Smart Grid [9][10] to solve the security problems. In [11], IoTChain, a blockchain security architecture for IoT is proposed. The architecture is a combination of the Object Security Architecture for IoT (OSCAR) and the ACE authorization framework, aiming at providing an E2E solution for the secure authorized access to IoT resources. In this architecture, the blockchain replaced the single ACE authorization server to handle authorization. The authorization servers, key servers, and clients act as blockchain nodes. Compared with this work, the trustworthy core network nodes with high capacity are used as blockchain nodes. We use blockchain to store and process privacy-sensitive information of anonymous users. The grid operation, in other words, electricity consumers get their electricity usage information, through the smart contract.

In [9], Smart homes constitute an overlay network together with service providers, cloud storages, and users' smartphones or personal computers. Nodes in the overlay are grouped into clusters and each cluster has a cluster head. The cluster heads maintain a public blockchain in conjunction with two key lists. The IoT devices in a smart home are identified by Device IDs. For each smart home, a smart home miner is a used to process centrally the incoming and outgoing transactions to and from the smart home. Compared with this work, we share the same idea of having a blockchain overlay. However, in our architecture, each user has its own public and private key pairs, and we do not rely on a central miner and cluster heads to maintain the keys. In addition, the transmission of the privacy insensitive data will not be affected in our architecture.

In [12], the function of the smart contract is to identify malicious usage of electrical power. Consumer data being manipulated maliciously on the smart grid network will trigger the smart contract to send an encrypted message to the smart meter and displayed on the screen of the smart meter of the consumer. Different from this work, we use the intrinsic mechanism of blockchain to provide security and transparency to users; in addition, we use smart contract to maintain the stability of the power system.

The rest of the paper will be organized as follows. We will describe the blockchain-based architecture for Smart Grid in section 2, including the mechanism for maintaining the stability of the power system. Then we will explain our prototype implementation in section 3, concentrating on the procedure of smart contract execution. Finally we will make conclusions and introduce our future work.

2. A Blockchain-based Architecture for Smart Grid

2.1. A Layered Architecture with Blockchain Overlay

Blockchain technology can benefit the management of the Smart Grid in that the privacy, transparency and security can be dealt by the blockchain network itself. This enables an easy and efficient way to provide transparent and trustworthy services to electricity users and keep the power transmission system secure and efficient. Figure 1 illustrates the management architecture for Smart Grid based on blockchain. It makes full use of the features provided by blockchain, and at the same time, uses the current well-accepted edge and cloud computing to obtain the efficiency and scalability of the whole system.

The architecture consists of four layers. The Grid Infrastructure Layer consists of equipment producing and/or consuming electricity power that needs to be managed and controlled, as well as the devices that measure and control the load of the power system. The Edge Computing Layer performs certain data storage and processing and provides some services and data related to local areas. The Cloud Computing Layer mains the grid level database and polities, and performs data analysis at the whole grid level. The Blockchain Network Layer is an overlay, consisting of the trustworthy nodes in the infrastructure, edge and cloud computing layer.

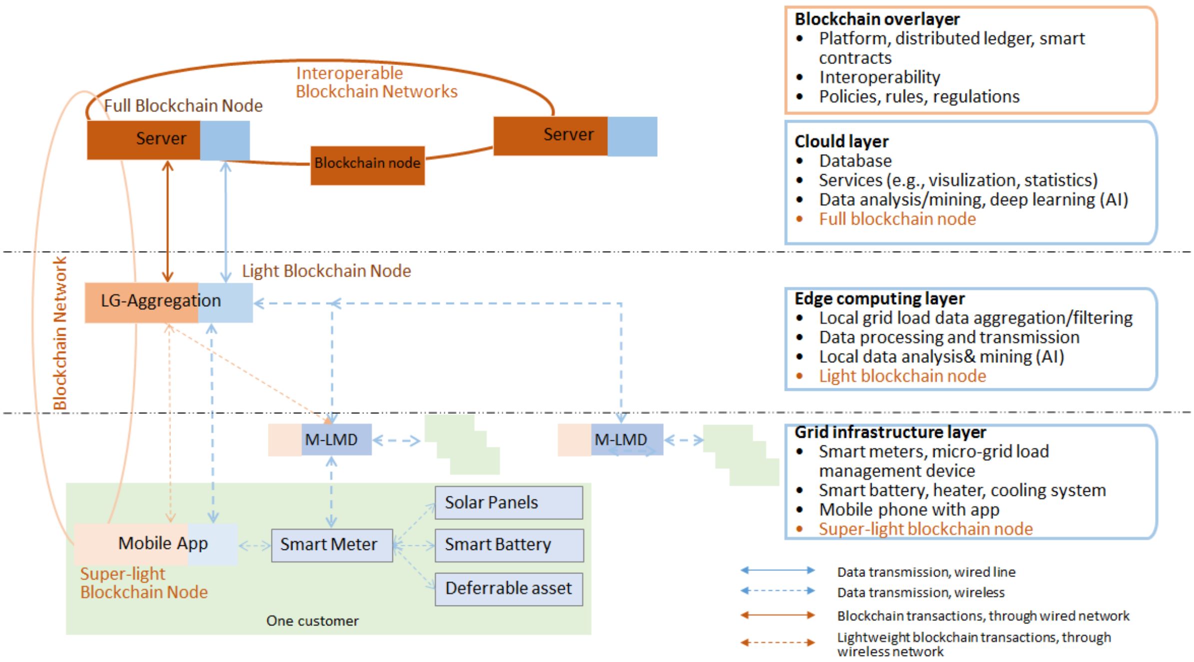

Fig.1. Blockchain-based architecture for Smart Grid

Grid Infrastructure Layer (GIL)

As mentioned above, the technical advancements have made it possible for electrical consumers to become also an electrical producers and be deeply involved in the Smart Grid as prosumers. The energy system of the future will be a decentralised system. Thus, the infrastructure layer consists of equipment producing and/or consuming electricity power, including those installed at users' locations, such as solar panels, smart batteries and deferrable assets. All the equipment must be well managed and controlled in order to maintain the stable of the whole grid system and reduce the waste of the "green" electricity produced by customers.

Moreover, an intelligent meter will be installed at each prosumer (including the institutions and companies). It can measure the amount of energy (e.g, in kilowatt hour) each prosumer has consumed and produced, and can also control the electrical equipment, producing or consuming electricity according to the specified mode.

In addition, micro load management devices (M-LMDs) belong also to the infrastructure layer. M-LMDs are dynamic and intelligent circuit breakers controlled by programmed load management parameters. It can send instructions to the meters at each prosumer to control the local equipment. M-LMDs will be installed in the junctions of the low voltage electrical transmission line covering a local area. The M-LMDs communicates each other and with intelligent meters over wireless transmission. M-LMDs are also capable for demand response and fault detection and recovery.

Electrical users can download a mobile applications to communicate with intelligent meters and M-LMDs, and visit the blockchain network, tracing the usage of the electricity. It can also control electrical equipment through intelligent meters.

Edge Computing Layer (ECL)

The Edge Computing Layer is responsible for certain data storage and processing, and providing services by analysing locally obtained data. As shown in Fig. 1, a local grid aggregator (LG-Aggregator) will aggregate data from several M-LMDs and perform certain computations. It will store, process and analyse the data sent from M-LMDs, and send data to the server in the cloud periodically according to the strategy provided by the cloud. In addition, the edge computer maintains also certain dynamic states information of the whole energy grid from the cloud. Since the edge computer is physically close to M-LMDs and customers' equipment where data are collected, the edge computer can response the M-LMDs quickly due to the short data transmission delay, which will control the local equipment with the help of intelligent meters accordingly. Therefore, and data obtained from the grid through cloud, and is responsible for control the stability of the local grid level.

Cloud Computing Layer (CCL)

Cloud computing can process data very efficiently due to the high capability of cloud computers and the various information from the whole grid system. As shown in Fig. 1, LG-Aggregators connect to a server in the cloud. Thus, the server will have the dynamic data of the whole grid. Further performance evaluation of the grid, as well as data mining, deep learning will be done by at the cloud level by using the data from the whole grid. In addition, the whole system and the data will be visualized, which will benefit the analysis and decision of the whole energy management system.

Blockchain Overlay Layer (BOL)

The blockchain network is an overlay built on top of the GIL, ECL and CCL. It is a virtual network consists of nodes in the GIL, ECL and CCL, which can act as the blockchain nodes (in Fig.1, orange colour denotes nodes or transactions belonging to the blockchain overlay). Using overlay ensures that the existing data communication protocols, services and data exchanges without privacy-protecting and security requirements will not be affected.

Smart contracts are programs executing in blockchain driven by events. They work similar to contracts in the real world: when all the prescribed terms are fulfilled, certain actions will be executed. Therefore, by introducing the Blockchain Overlay, certain secure services related with agreements between grid operators and users can be realized in the form of smart contracts. This can reduce the overhead of time and monetary cost, and can also eliminate the mistakes and misbehaviors from human beings, increasing the reliability of the services.

In our architecture, the blocks (ledgers) will store, in a tamper proof manner, the energy production and consumption related data collected from intelligent meters. The self-enforcing smart contracts define programmatically the expected energy flexibility at the level of each producer and consumer, and thus, establish the rules for balancing the energy demand with the energy production at grid level, keeping the grid system stable. Through this way, blockchain will provide a trustworthy and transparent means for encouraging green energy usage and reducing energy waste in a flexible and controllable way. For example, since the blockchain can trace all the transactions in the network and therefore knows the origin of every unit of electricity, a consumer can choose what type energy he wants to use, e.g., from which generating plants or household he wants to purchase his electricity.

By introducing the blockchain overlay, the privacy-sensitive data, such as the value of meters, the type of each user's electrical equipment, and its geographical location, is encrypted and/or replaced by a public key, and will be stored, processed and exchanged through the blockchain overlay. In addition, the transactions of each user, i.e., the amount and type of electricity power a user consumed or produced can be well traced.

Note that not all the nodes in the blockchain overlay have full function of a blockchain. Servers at the CCL can maintain a full copy of the blocks and work as miners. Since the blockchain nodes can see all the transactions happened in the blockchain, only the trustworthy nodes can work as this type of nodes. For example, some of the routers with high computing power in the core network, or servers from the grid operator can be authorized to act as this type of nodes. The LG-aggregator at the ECL are light blockchain nodes, it is trustworthy and can only store a copy of the blocks in the local areas. In practice, the definition and size of the area depend on the deployment of the architecture. The users' mobile devices are super-light blockchain node in that they can only exchange transactions with the grid, without storing blocks or being as miners.

2.2. Dynamic Electricity Price and Grid Stability

The participant of users' equipment in generating power to the Smart Grid can generally reduce the cost for each customer and is environment friendly. However, this may either cause the whole grid unstable, or potentially waste the electricity produced by each customer due to the limitations of weather and equipment of customers. In order to keep the stability of the Smart Grid, a dynamic electricity price mechanism is used in the architecture. The more each type of electricity is generated to the grid, the lower the price, and vice versa. In addition, each customer can also specify his preference of energy types in his contract (i.e., offline) with the grid management, which will be programmed in the smart contract after the user has been registered in the blockchain. Based on electricity price and users' preference, a smart contract can be created between each user and the Smart Grid operator.

Thus, being a super-light blockchain node, each user maintains an "energy wallet", and deals with the Smart Grid operator by exchanging transactions on the blockchain and executing the smart contract in the blockchain automatically. In this way, the information of each unit (kwh) of electricity consumed or produced by a user is transparent to users - every unit of electricity can be traced down to where it is produced - whether it is renewable energy or whether it originates from a nuclear power plant for instance. The electricity customers can choose from which generation plant they want to be supplied. Customer preferences are noted in a smart contract and thereafter executed on automatically to guarantee supply with electrical energy from the preferred energy generation plant. The delivery is verified by transferring the coded kilowatt hour to the customer's "energy wallet". For example, when a neighbour's solar panels make excess energy, the smart contract automatically redistribute it to a customer nearby who is willing to buy local and clean energy generated from the sun. This enables the buying and selling of the renewable energy generated in the local grids and among neighbouring customer groups.

2.3. Storage and Load Aggregation

In practice, the dynamic price and grid stability can also be achieved through the smart storage and load aggregation. In time of high generation and thus low prices, individual smart batteries can store energy motivated by the payments (i.e., gains) over the blockchain in their private prosumer "energy wallet". Therefore, the load on the grid will be reduced. Similarly, in time of high demand and high prices, electricity will be supplied from the individual batteries. Through the flexible prices and prosumer payments based on pre-programmed user preferences set in smart contracts, the grid will be automatically stabilized. The battery solution is intended for multi-family houses with or without a photovoltaic system and shall communicate seamlessly with smart energy meters in the same low voltage system.

In addition, the stability can also be achieved by controlling the usage of deferrable assets through the dynamic price. Deferrable assets, such as water heaters or cooling systems, can be switched on when the overall demand is low and can be switched off when the overall electricity demand is high. By controlling and aggregating different types of electrical equipment dynamically with the help of dynamic electricity prize and smart contract, a balance in the demand and supply can be achieved and the load stability of the Smart Grid can be maintained.

3. Prototype Implementation

We have implemented a simple prototype of the architecture based on Ethereum [] platform. A server is configured as a full blockchain node at the cloud layer and another server is configured as blockchain node but without miner function, acting as a LG-aggregator. A DApp (distributed application) software is developed for mobile phones, allowing users to join the blockchain. Through the DApp, users can check the balance of their "energy wallet" after selling his power to the grid or buying power from the grid. User can also trace their usage of the energy by checking all the exchanged transactions with the Smart Grid.

Fig. 2 illustrates the electricity usage control procedure for prosumers based on the dynamic electricity price and smart contract in the prototype. Note that in Fig. 2, orange lines denotes the transactions within blockchain overlay, while the blue lines denotes the data exchanges between the entities.

a) First, the Smart Grid operator, as the manager of the grid, register the smart contract (i.e., EM, electricity management) in the blockchain network, containing the usage preferences of each user.
b) A user registers in the blockchain, and becomes a user in the grid system. His electricity usage preferences will be created as an instance of the smart contract EM.
c) M-LMD collects the values periodically from the intelligent meters at each user, and send them to the LG-Aggregator, which will be recorded in the blockchain.
d) M-LMD will also measure the load of the micro area, and send them to LG-Aggregator. LG-Aggregator will store the data for later use (i.e., further analyses and mining locally), and send the data to the cloud server. After getting data from relevant LG-Aggregators, the dynamic electricity price will be calculated and write into the blockchain.
e) The value of the dynamic price trigger the execution of the smart contract. According to the load of the grid and the user's preference parameter, control information will be sent to I-meter, which will further control the various equipment in the user.

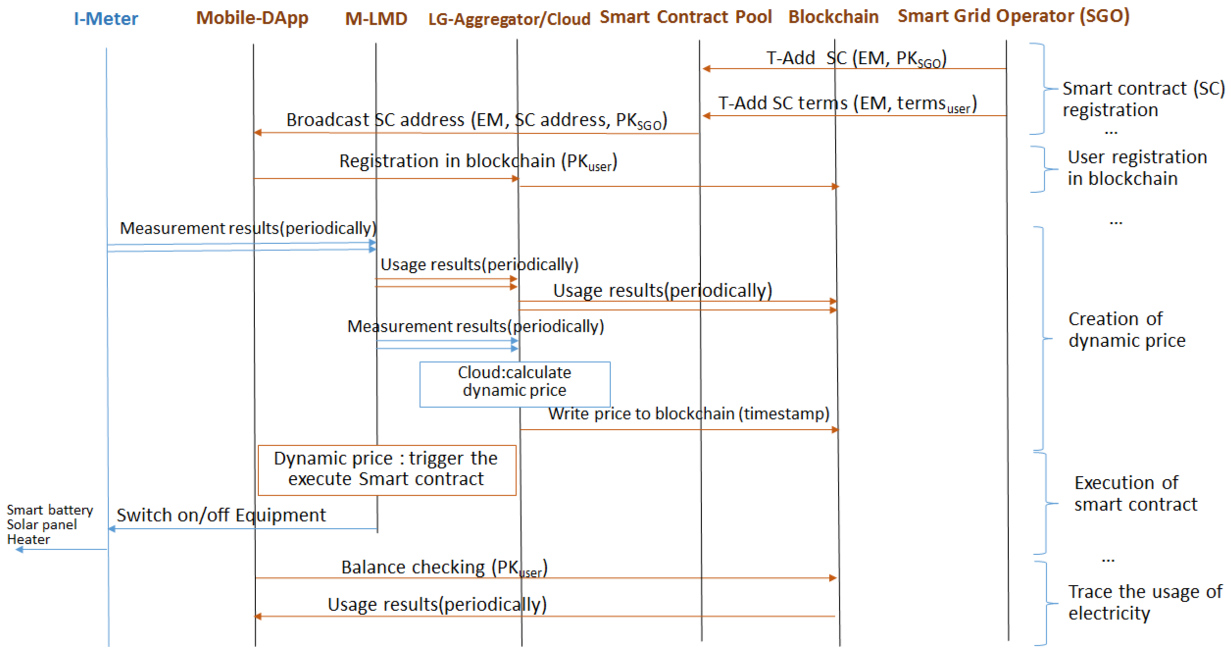

Fig.2. Electricity usage control procedure based on the dynamic electricity price and smart contract

To prove the concept of our architecture, in our prototype, we set 3 M-LMDs, and each M-LMD is connected to 10 intelligent meters. One LG-Aggregator and one cloud server is used. And random values for the measurement and usages are generated.

4. Conclusions and Future Work

In this paper, we proposed a blockchain-based architecture for the future Smart Grid, where new and renewable energy resources are expected to be used. Edge and cloud computing nodes are introduced to obtain the load state data in the grid, and perform data analysis and mining, and potentially quick response and control of users' equipment. A blockchain overlay is formed on top of the Smart Grid infrastructure and the edge and cloud computing nodes. It uses the dynamic price and smart contract to keep the stability of the Smart Grid, at the same time, users can trace the detail of their energy production and consumption. A simple prototype has been implemented to prove the proposed architecture.

For the moment we use only a very simple method to calculate the dynamic price in the smart contract. We are now working on a new algorithm to define the price of the electricity by analyzing the load data of various electricity types. In addition, we will also implement the M-LMD by improving the current product and realize the architecture in field trial.

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