Blockchain for peer-to-peer energy trading

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BLOCKCHAIN FOR PEER-TO-PEER ENERGY TRADING

YANG JIAWEI

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

2020

Blockchain for Peer-to-Peer Energy Trading

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School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Master of Engineering

2020

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Date

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Assoc. Prof. H. B. Gooi

Authorship Attribution Statement

The thesis contains materials from one under revision journal paper and one published conference paper, where I was the first author.

Chapter 3 is published as: Jiawei Yang, Amrit Paudel, Hoay Beng Gooi, "Blockchain Framework for Peer-to-Peer Energy Trading with Credit Rating," 2019 IEEE Power and Energy Society General Meeting (PESGM), Atlanta, GA, USA, 2019.

The contributions of the co-authors are as follows:

- I have established the blockchain model and the P2P trading structure on MATLAB. I produced the results and finished the manuscript.
- Mr. Paudel assisted in revising the manuscript and taught me the method to collect data.
- Prof. Hoay Beng Gooi closely supervised the research work. He gave suggestions for the grammar and technical concept of the manuscript and reviewed the manuscript for the final submission.

Chapter 4 is resubmitted under the second-round review as: Jiawei Yang, Amrit Paudel, Hoay Beng Gooi, "Compensation for Power Loss by A Proof-of-Stake Consortium Blockchain Microgrid," for consideration of publication in *IEEE Transactions on Industrial Informatics*.

The contributions of the co-authors are as follows:

- I have proposed the idea and set up an experimental blockchain model for energy transactions. I did the coding; analysed the results and prepared the manuscript.

- Mr.Paudel helped me to estimate the power loss of the proposed model and assisted in editing the manuscript.
- Prof. Hoay Beng Gooi closely supervised the research work. He gave advice for the revision of the manuscript for submission and corrected the organization of the manuscript.

13/1/2020

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Abstract

This thesis presents the study of blockchain technology used in peer-to-peer energy trading. The proposed blockchain methodologies are applied in the transactions happening between prosumers, who are equipped with PV panels. The blockchain studies are focused on how smart contracts and mining process could help and support transactions from microgrids. The protocols of the proposed blockchain are Proof-of-State and Proof-of-Work. The main goal of these studies is to explore the potential capability and how deep the blockchain technology could operate technically in the power system.

Increasing penetration of renewable-based distributed generations (DGs) and the presence of distributed energy resources (DERs) encourage a direct energy trading among prosumers, which is called P2P energy trading. P2P energy trading is the flexible trading among the peers, where excess energy from many small-scale DERs is traded locally. But it cannot be applied without a software platform, which enables the information exchange among peers, and also assists the system operators to monitor and control the distribution network. Also, different trading rules defined by the platform also have significant influences on the decisions made by peers when trading with other peers. Therefore, blockchain technology that works as the platform, is introduced in the energy trading field to support P2P transactions.

The proposed approaches aim to apply a blockchain based P2P market platform where all members of a network could enter directly into energy exchanges with

any other members without restrictions or oversight from a centralized authority. The blockchain based P2P market enables the energy trading through smart contracts in which energy transactions are immediate, automated, and flexible. Blockchain applications in a P2P energy market also help to reduce corruption; increase transparency; provide payment platform for energy trading; and support seamless integration of multiple microgrids; etc. The prosumers possess specific load profiles and power generation profiles with a specific cost function and generation capability margins. The price of electricity is dependent on the grid selling and buying prices and the marginal costs of the controllable generators. The energy-trading algorithm should decide the market clearing prices for considering the welfare maximization of the prosumers.

Work is oriented towards the technical operations of power systems, including compensating for power loss and developing a generic integrated blockchain-supported decentralized market platform. This can facilitate the secure and transparent electrical energy trading, which can be adapted to country-specific restrictions in terms of infrastructure and regulatory framework. Decentralized clients of a market platform can use smart contracts based on bidding algorithms and schedule individual power flows according to the transactions. Methods to regulate market participants' behaviours such as credit rating or mining-rewarding mechanism are designed to support the blockchain based P2P energy trading model.

The blockchain framework is built on the Ethereum platform by using Geth (one of the Ethereum's functions). The content of the smart contracts are written in Solidity language. The experimental case studies for the proposed P2P energy trading market are carefully designed and simulated using the MATLAB. The proposed blockchain methodologies are compared with those of some existing works. The results validate the feasibility of the proposed blockchain methods and show that these methods could be implemented to support the P2P trading effectively.

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Abbreviations and Symbols

Abbreviations

BESS	battery energy storage system
CEMS	community energy management system
CRPs	credit rating points
Dapp	decentralised application
DERs	distributed energy resources
DGs	distributed generators
DSOs	distribution system operators
ELC	elecoin
ESS	energy storage system
FIT	feed-in-tariff
ID	identity
Joul	Joule
LAGs	load aggregators
MTM	microgrid-to-microgrid
OTC	Over-the-Counter Market
P2P	peer-to-peer
PoS	proof of stake
PoW	proof of work
PoW	proof-of-work
PTP	prosumer-to-prosumer

ABBREVIATIONS AND SYMBOLS
ABBREVIATIONS AND SYMBOLS

PV	photovoltaic
RESs	renewable energy sources
VPP	virtual power plant

Symbols

β	Power loss attribution coefficient
γ	Ratio value of TES and TEP
E	Generated energy
G	Generation energy
$Income$	Income of energy trading
K	Ratio value of active and reactive power
L	Load
NP	Net power
P_{buy}	Buying price
P_{ex}	Selling energy
P_{im}	Buying energy
P_{loss}	Power loss
P_{mine}	Energy consumption of mining
P_{sell}	Selling price
$Profit$	Profit of energy trading after mining
TEP	Total energy purchased
TES	Total energy sale
y	Rewarded value

Chapter 1

Introduction

1.1 Background

Heavy dependency on burning fossil fuel to produce energy causes huge damage to the environment (greenhouse gas, air pollution etc). How to make a full use of such renewable energy becomes a significant issue. Due to the stochastic characteristic of such renewable energy generation, energy storage technology is introduced to store this energy to fulfill consumers' demand. To improve the efficiency of energy utility and transactions, the peer-to-peer market offers a platform for all the participants who are equipped with PV panels and battery energy storage system (BESS) to trade their energy directly in a community without any intermediary agent. On the other hand, these participants are able to produce and consume energy, so they are defined as “prosumers” [1]. When a proper pricing mechanism is implemented, such a decentralized trading structure could enable its participants to save cost in every transaction as all the sellers can sell energy at a higher price and buyers can purchase energy at a lower price compared to the feed-in-tariff.

P2P energy trading cannot be applied without a software platform, which enables the information exchange among peers, and also assists the system operators to

monitor and control the distribution network. Also, different trading rules defined by the platform also have significant influences on the decisions made by peers when trading with other peers. The blockchain technology supports the energy trading by storing the information of transactions in blocks, verifying the validity of transactions by all the nodes in the network, and ensuring the security and privacy of transactions by encrypting them. The design of the assembled transactions and short-term balancing contracts based on smart contracts are necessary for energy trading via blockchain. As a result, a blockchain supported decentralized market platform allows all members of an electricity network to enter directly into the market and exchange energy with any other members without oversight from a centralized authority.

A blockchain framework is utilised into the P2P trading market to ensure the security and transparency of all the transactions. Only valid transactions can be grouped in blocks, which are maintained in the sequential time and stamped with different hashes to connect with each other. The advantage of this framework is that to overwrite a transaction, a peer has to change the hashes of all the blocks in this blockchain while showing the validity of the proof of work (PoW) or proof of stake (PoS) of every block and controlling more than 50 per cent of the peers in the network. This huge workload makes it infeasible, thereby protecting peers' personal information. It is noted that, with the functions of blockchain, a P2P market is provided using a software foundation which enables the information exchange among prosumers and helps to monitor and control the distribution network. However, there is still no effective method to prevent customers' cryptocurrency in digital wallets from stealing by cyber-attack, so real money is still the first choice to purchase energy for the prosumers in this paper. However, miners will still be rewarded according to PoW.

1.2 Peer-to-Peer Energy Trading

Currently, power systems are operated in a centralized market, but distributed generators will mushroom to the point where they will impact the distribution system significantly [2]. With the increase in the level of the distributed generation, there is a crucial need to introduce market structures which facilitate generation and consumption of the electricity locally. The local electricity market facilitates a local balance of energy supply and demand and reduces the need for further expensive grid expansion. In some countries, their electricity markets are established by the governments to enable more retailers and distributed energy resources owners to participate in the market. Without any authority agents, transactions can be executed directly between participants, thereby saving participants' time and money. This trading mode is defined as P2P energy trading. P2P trading is based on the structure of microgrids from the distribution system. Thus, it requires not only electrical wires between prosumers but also information exchanging between them. Figure 1.1 illustrates the structure of information and electrical wires in a microgrid. In this figure, there are five units (prosumers). The Intermediate Energy Trader transfers the transaction information among those units and the utility grid. Depending on the information offered by the Intermediate Energy Trader, units could purchase energy they need from the utility grid.

Nowadays, energy policies implemented by various countries aim to encourage the self-consumption of photovoltaic (PV) energy from the prosumers' perspective. Therefore, ideas for designing a market platform for energy trading have been investigated in several works. In [3] the authors propose a distributed approach to system design and a P2P based trading model. The authors in [4] propose a formulation for distributed energy resources (DERs) utilizing the knapsack auction scheme and the mechanism of market clearing from the prospective of sellers. The authors in [5] applied a 34-bus test radial distribution system to check the validity of the model and extensive tests are also performed for verifying the optimization. However, P2P energy trading cannot be applied without a software platform [6],

Figure 1.1: Information and electrical wires of a microgrid

which enables the information exchange among peers, and also assists the system operators to monitor and control the distribution networks. Also, different trading rules defined by the platform also have significant influences on the decisions made by peers when trading with other peers. Without the support from a proper software platform, the private information of customers and the process of transaction execution are extremely vulnerable to the cyber-attack. A P2P energy trading market needs a platform to ensure the security and transparent level of each trading process so that pricing mechanisms and regulation rules of a market can be secured and enforced.

1.2.1 Blockchain Technology

To solve this problem, we use blockchain technology as the platform to fully support P2P energy trading. Blockchain technology is a cryptography method of

1.2. Peer-to-Peer Energy Trading

information storage [7–9]. During each time slot, peers who want to trade should send the transactions willingness to other peers in the same network. After verifying these transactions by all the other peers, transactions will then be executed and terminated within this time slot. All the information of these transactions will be encrypted as a set of code and be stored in a new block. Finally, this new block will be added to the last block and therefore, a blockchain is set up by adding new blocks one after one. The set of code which represents the block is a hash number [10]. The process of calculating a hash number is called ‘mining’. Anyone in the world could compete mining a block as long as their computers are capable of mining, but usually, the one equipped with more computation power is more likely to win the opportunity to create a new block. In the Bitcoin or Ethereum platform, a certain number of crypto-currency will be earned by the block-creator as a reward of mining.

The blockchain technology can support the P2P energy trading by storing the information of transactions in blocks, verifying the validity of transactions by all the nodes in the network, ensuring the security and privacy of transactions by encrypting them [11]. Due to the high replication of transaction records, the blockchain based energy trading ensures stronger guarantees against tampering. These advantages of blockchain technology could support P2P trading more effectively. It reduces corruption; increases transparency; provides payment platform for energy trading; and supports seamless integration of multiple distributed generators, etc. Thus, with the assistance of Blockchain technology, a P2P transaction could be executed directly between peers without any third parties. However, blockchain technology is still a new invention to the public and its utilization still does not realise its full potential.

1.2.2 Smart Contract

To realize the advantages of blockchain technology fully, a smart contract is created to support the P2P trading. Usually, it is impossible to trade goods between two

peers who do not trust each other. To solve this problem, a smart contract written in code which is immutable is invented to support the transaction execution. A smart contract is a computer code [12] running on top of a blockchain containing a set of rules under which the parties involved in that smart contract agree to interact with each other. If and when the pre-defined rules or conditions are met, the agreement is automatically enforced. The smart contract code facilitates, verifies, and enforces the negotiation or performance of an agreement or transaction. It is the simplest form of decentralized automation.

It is also a mechanism involving digital assets [13], and two or more parties, where some or all of the parties deposit assets into the smart contract and the assets automatically get redistributed among those parties according to a formula based on certain data, which is not known at the time of contract initiation. The content of a smart contract is written in a computer language named Solidity and realized on the Remix, which is an open platform to write and execute the content of smart contracts. Within the help of a smart contract, transactions in the P2P market can be triggered and executed automatically without any services from an intermediary agent.

A few pilot projects and research work are implemented in this field. From those studies, smart contracts definitely expand the applicability of blockchain technology. The authors in [14] use the smart contract to set up flexible and light weight trading. Flexibility is ensured by this decentralised application (Dapp) in requesting peer's identity (ID). In addition, deposits are paid by two sides while setting up the contract to improve the reliability. The authors in [15] propose a distributed energy transaction mechanism based on the smart contract, including bidding, auditing and clearing. But there is no specific pricing mechanism proposed and no example of implementing it in a real microgrid or electricity market. More seriously, as the smart contract is the core component of a blockchain. Although it is immutable theoretically, once it has been rewritten by malicious purpose,

1.3. Motivation

tremendous property loss will be caused. To prohibit this problem, the content needs to be written extremely carefully and so does the implementation.

1.2.3 Issues in the communication and data transmission

Existing distribution networks are not designed to operate with any advanced communication mechanism. An increasing number of communication mechanisms and techniques are being implemented in the existing distribution network for the smart grid applications. The implementation of those communication infrastructures and their relevant smart grid applications contribute to a rapid growth of the volume of data transmission in the distribution networks. Communication related issues, such as connection failures, data errors, transmission delays etc., are expected to become more and more critical.

1.3 Motivation

As explained in Section 1.1 peer-to-peer (P2P) energy trading is an emerging energy market platform in distribution networks for implementation of the energy sharing concept in a community. P2P energy trading helps to cope with the challenges posed by increasing penetration of renewable energy sources (RESs), decreasing feed-in-tariff (FIT) rates, and increasing retail prices. P2P energy trading has the potential to elevate the benefits of all the participants in the market using a transactive energy concept. It also assists in the local balance of the demand and intermittent generation from RESs, thus improving the health of the distribution network.

Prosumers are the prime stakeholder in the P2P energy market. They are always encouraged to generate green energy and share in the P2P market. Both the financial as well as non-financial factors motivate the prosumer to enter the P2P market. The financial factor is mainly the monetary benefit whereas social responsibility to alleviate the emissions can be taken as an example of non-financial

factors.

P2P energy trading cannot be applied without a software platform, which enables the information exchange among peers, and also assists the system operators to monitor and control the distribution network. In addition, different trading rules defined by the platform also have significant influences on the decisions made by peers when trading with other peers. Therefore, smart energy management services are required to enable the prosumers to make decisions on whether or not they want to deliver, to whom and when and at what price, while negotiating with other actors in the energy market. Development of a well-designed community energy management system (CEMS) to manage these complex energy transactions in the P2P energy trading platform considering the technical aspects of the network is the fundamental motivation behind this study.

1.4 Research Objectives

The main objective is to design a completed blockchain framework with a proper pricing mechanism to ensure cost savings for the participants. And then, realising the potential of the blockchain methods for technique operations (loss compensation) in microgrids.

1. The first objective is to propose a pricing mechanism: Distributed generation in a P2P market allows all prosumers to trade their energy, so the price of every unit of energy should be decided by the amount of every participant's generation according to the time slot when it is traded. This characteristic achieves the consensus with that of the blockchain technology, as the establishment of a new block needs to be approved by the majority of peers.
2. When it comes to the trading market, a proper regulation should be designed to ensure participants' legal behaviours. Any malicious operations should be punished. To achieve this purpose, two methods are introduced in this thesis.

1.5. Scope

One is the credit rating system to mark participants' trading behaviours: High credit rating points are blessed with more trading choices and privileges and those with low points are suffering more costly buying price. The other one is the mining-reward system, in which miners are pre-selected from the users to make compensation for the power loss and they could be rewarded by more values of crypto-currency. Unapproved operations could be punished by losing their stake according to the PoS protocols.

3. The last objective is to implement these above methods in the P2P market with the support of blockchain technology, as fraud issue can be completely eliminated by using a combination of these methods. These methods play different roles in the P2P market to achieve an optimal management and saving results for prosumers, therefore, this model is theoretically able to accommodate new modification by using any more advanced technologies instead of these methods.

Smart contract is utilised to take the place of intermediary agents to achieve a decentralised market structure. By applying the smart contract into this P2P energy trading model, the efficiency of transaction execution can be improved. As only simple algorithms could be executed in a smart contract, the pricing mechanism is simplified and written in Solidity language in the smart contract. The blockchain of this model is set up in the Ethereum platform. The final goal is to make this model more feasible and easier to be implemented in the OPAL-RT machine (a real-time simulation hardware) and the microgrid of NTU.

1.5 Scope

The proposed blockchain based P2P energy trading method may serve as a feasible and effective tool for transactions from the distribution system with the active participation of the prosumers and consumers in the energy market. Blockchain

based energy trading model may consider:

1. PV generation and load demand schedules of prosumers.
2. Power loss estimation caused by the microgrid energy transactions.
3. Whether PoW or PoS protocol used in the blockchain technology can support the P2P energy trading.
4. Smart contracts for the transaction execution and pricing calculation.
5. The cost or profit from the transaction mining or participation.

1.6 Thesis Structure

The remainder of this thesis is organized as follows:

Chapter 2 presents a comprehensive review on various topics, ideas and research related to this study. A brief introduction of peer-to-peer energy trading, blockchain technology concepts and smart contracts are presented. The basics of TE, its advantages and current status are also reviewed. The concept of energy trading and sharing with its framework is summarized. The P2P energy trading with its various aspects is discussed in detail. Existing trails on P2P energy trading arrangements are summarized and compared. A review of game theory and its applications in energy trading are also presented.

Chapter 3 presents a blockchain based two-level pricing P2P energy trading model with credit rating in the microgrid distribution system. In addition to the literature review in Chapter 2, the study of the smart contracts and mining process are further extended in the P2P energy trading model. The proposed blockchain based P2P trading model is simulated in an example environment to see its effectiveness.

Chapter 4 proposes a power loss compensation method depending on the mining mechanism form a PoS consortium blockchain. The goal of this proposed method is

1.6. Thesis Structure

to explore its technique operation potential in the PoS blockchain. Miners are pre-selected from the trading participants and making contribution to the power loss caused by the energy transactions. The implementation process of the proposed consortium blockchain approach for energy trading on the Ethereum platform is specifically presented.

Chapter 5 concludes this thesis with the future works related to the blockchain topics in the power system domain. The possible work plan of a future PhD study is also presented and publications are listed.

Chapter 2

Literature Review

2.1 P2P Model for Distributed Energy Trading

Nowadays, DERs and their energy storage systems become increasingly popular. Distributed system design and solutions to P2P electricity trading are urged emerging. A microgrid is an integrated system that comprises DERs and multiple electrical loads [3]. It is an autonomous grid where both grid-connected and isolated modes are supported [16].

A virtual entity is introduced in to the microgrid named microgrid trader [17] and it also has commercial agreements with prosumers as well as aggregators. In addition, the aggregator is an entity that aggregates the loads and generators who offer services to the wholesale market.

There are 5 commercial relations in this P2P trading model:

1. Commercial relations between the microgrid traders and their prosumers: trading between prosumers is performed via microgrid traders, which connect prosumers and energy purchase or sale among them.
2. Commercial relations between microgrid traders: as a microgrid may need to trade with other microgrids, microgrid traders play the role of a middle

man which exchanges the bids and offers.

3. Commercial relations between aggregators and microgrid traders: microgrid traders can have a contract with the aggregator to participate in the whole-sale market. And commercial agreements may also be set up between them to manage the load.
4. Commercial relations between distribution system operators (DSOs) and aggregators: aggregators will provide services to the DSO. To achieve this function, they can use prosumers' resources and microgrid traders.
5. Commercial relations between prosumers and aggregators: prosumers from a microgrid can also have contracts with the aggregators to join in the whole-sale market as sellers or buyers. Besides, they can offer services to their microgrid traders by having a commercial agreement with the aggregators.

From these relations it can be concluded that microgrid traders are the heart of the P2P trading model. A distributed trading mechanism was proposed in [18], in which microgrid traders interact with each other to determine an appropriate amount of energy to be traded and its price.

2.2 Blockchain for P2P Energy Exchange

Blockchain as a Bitcoin or Ethereum wallet service has emerged as an important factor in many areas. It allows the use of automated transactions and it is also likely to influence the energy sector. When prosumers want to trade their extra energy with others, blockchain technology can be an effective way to keep track of these transactions.

To maintain the responsibilities and rights of every prosumer or trader, and to have the necessary link to the wholesale market, the process of these transactions must be supervised by fair and neutral metering units, for example, the DSOs [19, 20]. In addition, a cryptography method is used to connect blocks and to protect the

2.2. Blockchain for P2P Energy Exchange

trading records from being changed. The records' function is traceability [21], which means that they are able to trace their origin.

The design of a blockchain for P2P trading should cover the functions of traceability, privacy and accuracy [22–25]. Accuracy has to be maintained to ensure that every block can be created correctly at each execution step of the market step accordingly.

Traceability is realized by two means in the blockchain design:

1. The transaction model: each generator that generates the electrical energy has to validate the amount of electricity that should be linked to a transaction. Generators confirm their electrical energy by sending it to the virtual power plant (VPP) [26] which aggregates the total generated energy. The VPP distributes the electrical energy by using a re-partition rule and signs this transaction off.
2. The consensus model: the aim of designing a consensus model is to avoid negative influences of malicious nodes. The mechanism of this model can be described as: All the new transactions are broadcast to all the time nodes. Every node makes a block to include all the valid transactions. At each time interval, a node is selected randomly and its block is then broadcast. Besides, other nodes are responsible for checking the validity of this block and that will increase their chains if they agree with it. This block can only be approved when most of the nodes agree with it.

These two means are designed to ensure the origin of the energy and fair transactions.

Privacy should be guaranteed for every individual, and this means that it is impossible to identify any customer's energy bill. What is approved in the community belongs only to this community. But in one microgrid or a community, all the participants know each other because transactions are the key identities of them.

A contractual agreement between all the participants is set up not to leak this information to the external parties. Anonymity is an effective way to protect participants' personal data [27] and the DSO system will also protect the data against cyber-attacks.

Overall, the adaption of the blockchain for energy trading in communities aims to provide a resilient and efficient method for energy transactions in a community and is to be accepted by the wholesale market.

2.2.1 Consensus Protocols of Blockchain

As a distributed and immutable ledger, the working mechanism of blockchain application is decided by its consensus protocol [28]. Enormous studies focus on finding an optimal consensus protocol to tolerate Byzantine fault [29] or creating a platform that could implement various consensus protocols.

Consensus works as a core part of the blockchain system and prevents the blockchain from being damaging. The main security issues include:

1. Double-spending attacks: Buyers spend the same money for multiple times. In other words, sellers have no ideas about the other transactions happened between those buyers and other sellers. To solve this problem, replicas of the transactions must be provided for every network user so that the transactions could be verified before their execution. The data of the transactions are distributed over the network.
2. Sybil attacks: Attackers could create a certain number of fake peers or users to validate their selfish transactions, which are supposed to be invalid. In case of bitcoin, this blockchain system applied 'proof-of-work', which requires solving cryptography problems to validate transactions. The high computation cost from this protocol makes it hard for the fake peers to compute and validate transactions.

2.2. Blockchain for P2P Energy Exchange

3. Byzantine generals problem: It is assumed that one-third of the network users might be malicious. The Paxos algorithm [30] is considered as one of the best solutions to it in the distributed system.

Consensus algorithms are agreements or methods for the decentralised network to make decisions. They ensure the quorum structure, regulation, integrity, byzantine fault tolerance and authentication [31]. Except for the ‘proof-of-work’ used by bitcoin, other concepts of consensus algorithms such as ‘proof-of-stake’, ‘proof-of-authority’ and ‘proof-of-existence’ are all widely used in the blockchain domain. Especially for the byzantine fault tolerance, a new consensus protocol named Stellar [32] is invented to solve this issue and maintain the low latency, flexible trust and asymptotic security of the blockchain system.

In addition, consensus protocols also help to validate transactions and avoid forking problems, which means different groups of miners mine their respective block of the same transactions. This issue is managed by the ‘longest chain rule’ [33]. Therefore, the protocols regulate the architecture of a blockchain.

2.2.2 Methodology of Blockchain Establishment

For different types of blockchain, various platforms are created to set up blockchain structures. They are:

1. Ethereum: Ethereum is designed as an upgraded version platform which could utilize the function of cypto-currency (Ether), providing various features such as on-blockchain payment platforms, smart contracts, gambling markets and its own programming language. Ethereum allows arbitrary contracts creation for any types of transactions [34].
2. Corda: Corda is a blockchain application which focuses on financial contracts and data records. Consensus of Corda combines values with smart contracts; validates transactions and ensures transaction uniqueness. This application

allows customers to check the validity of the code used in smart contracts as well as if contracts are working with the appropriate signatures, thereby maintaining error free execution and the validity of transactions.

3. Hyperledger Fabric: Hyperledger [35] aims at becoming a cross-industry platform for blockchains. Hyperledger Fabric is a distributed ledger platform for establishing blockchain models and running smart contracts. The protocol of the fabric distinguishes the network peers as validating peers and non-validating peers by recognizing whether the peers could execute transactions or not. Go language is used for implementation in this platform.

2.2.3 Current Blockchain Issues

1. Security issue: Except for the security issue mentioned in the previous section (Section 2.2.1), another issue is about the data security. Data protection such as privacy, access control, authentication, integrity and authorization should be maintained. Therefore, more sophisticated blockchain structure and consensus protocols need to be explored to solve the security issues.
2. Collaboration issues: Blockchain is a tool to store and secure information. Currently it has been used with other modern technologies like cloud computing [36], IoT [37] and so on. However, various cloud environments and the security issue of the data transmission of cloud technology itself has improve the difficulty of blockchain applications. The existing blockchain structure (public, private and consortium) should be redesigned for different projects.
3. Technical operation in the power system: Current blockchain cases used in power systems are only limited in transaction level. Because hardwares currently cannot be logically connected to the blockchain platform. How a blockchain system could help for the technical operation of power system such as reducing power losses [38] and solving demand response issues is a major field of studies.

Chapter 3

Peer-to-Peer Energy Trading with Credit Rating in Blockchain Framework

3.1 Introduction

Market operations and distribution networks become increasingly complex as the power industry moves towards decentralization, in which renewable energy plays a significant role. To improve the efficiency of energy trading, the peer-to-peer market offers a platform for all the participants who are equipped with PV panels to trade their energy in a community directly without any intermediary agent. These participants are able to produce and consume energy, so they are defined as “prosumers” [4]. When a proper pricing mechanism is implemented, such a decentralized trading structure could enable its participants to save cost and enjoy a more acceptable trading price in every transaction.

Under the Peer-to-Peer (P2P) trading of energy, “Prosumers” is a new term in the energy sector which refers to units that both consume and produce energy. In many countries, electricity is mainly offered by their utility grid and the price for

the energy is relatively higher than trading directly among prosumers. So, a proper trading price for each transaction is significant in the P2P energy market. The electricity market of Singapore has been established by the authority and is open to the public. With tremendous participants engaging in the market, a reasonable pricing mechanism could help the market terminate transactions and motivate prosumers to engage in the P2P trading. More importantly, according to the structure of the microgrid and distribution system, the pricing mechanism could also help to provide the pricing service for transactions among different microgrids. Such a feature will reduce the trading cost of distributed energy resources (DERs) and any other participants.

3.2 Related Works

Previous studies have proposed several options in improving the efficiency of the distributed applications and expanding the field of blockchain technology utility. Reference [39] explores the use of blockchain by implementing it on Predix as a case of green certificates, proving it a promising technology for monitoring energy related assets. The authors in [40] study an energy sharing model for a microgrid and implement an internal pricing mechanism for prosumers. In [41], the authors propose a P2P electricity trading model by using plug-in hybrid electric vehicles to shift peak load. In addition, it also introduces blockchain technology to support this vehicle-to-vehicle transaction and eliminate its reliance on a third party. Similarly, the authors in [42] propose a coalition formation algorithm and use blockchain technology to ensure the execution of this algorithm. Except for the energy transaction, the use of blockchain in the grid operations considering the energy losses is discussed in [43]. The authors in [44] study an adaption of the blockchain technology to make it accepted by the wholesale electricity market. All of these previous studies show the robustness, transparency and decentralization of the blockchain. But the blockchain framework still needs to collaborate with

3.3. Major Contributions

optimization methods to enhance the social welfare of the community. This in turn will motivate more prosumers to engage in the P2P energy trading market, which are not shown clearly in those aforementioned studies. Furthermore, the regulation of a fair market should prevent malicious operation in each transaction.

In this thesis, we apply a blockchain framework on the P2P trading market to ensure the security and transparency of all the transactions. Only valid transactions can be grouped in blocks, which are maintained in the sequential time and stamped with different hashes (codes) to connect with each other. The advantage of the blockchain is that to overwrite a transaction, a peer has to:

1. Change the hashes of all the blocks in this blockchain.
2. Show the validity of the proof of work of every block.
3. Control more than 50 percent of the peers in the network.

The above three steps cannot be achieved theoretically, thereby forbidding any attempts to overwrite. With the functions of blockchain, a P2P market is provided with a software foundation to enable the information exchange among prosumers and help to monitor and control the microgrid.

3.3 Major Contributions

The contributions of this thesis are:

1. A P2P energy trading model is proposed with a proper pricing mechanism to minimize the cost of participants. The first objective is to propose a pricing mechanism. Distributed generation in a P2P market allows prosumers to trade their energy, so the price of every unit of energy should be decided by the amount of every participant's generation according to the time slot [41]. This characteristic achieves the consensus with that of the blockchain technology, as the establishment of a new block needs to be approved by the

majority of peers.

2. A credit rating system [45] is designed to prevent malicious operations. As for the trading market, the prosumers who used to have records of deregulation should be punished by assigning a lower priority in the market. To achieve this goal, a credit rating system is applied to reward prosumers' good behaviors and improve the market quality. A credit rating system can be implemented in this P2P market with the support of blockchain technology to completely eliminate fraud issue.
3. A blockchain framework is applied to safeguard the transparency and security of participants. These methods play different roles in the P2P market to achieve an optimal management and savings for prosumers. This model is able to accommodate theoretically new modification by using more advanced technologies instead of these methods.

3.4 System Model

3.4.1 Blockchain Framework

Every block of a blockchain records the information of trading among participants in a P2P market, where a prosumer announces its transaction to other prosumers in this market. The announcement is then acknowledged and recorded by every prosumer in the market. Once a transaction satisfies certain basic condition, the transaction will be processed under the condition of the smart contract, which aims to operate this transaction automatically and reach the consensus among traders. A smart contract is a set of code made by multiple peers in the blockchain and it is immutable once it has been set up. No one could overwrite the content inside a smart contract and break it during the transaction. After the trade, the information related to this transaction will be stored in a new block before being added to the blockchain.

3.4. System Model

A blockchain is a chain of sequential blocks and every block is a collection of valid transactions, smart contracts and hashes. The contents of one block are used to calculate the hash (the code used to represent the respective block), the following block will take this hash as an entry to connect to it. A change in the block content will cause unpredictable change in the hash, and all the following blocks will reflect this change and become invalid. Figure 3.1 shows the structure of a blockchain. A transaction needs to be approved by the majority of the prosumers

Figure 3.1: The illustration of the structure and contents of the blockchain

in one microgrid so that it can be labeled as a valid transaction. This framework of the blockchain improves the security level of the transaction data. And malicious operations could be prevented.

3.4.2 Block Creation

A blockchain is made by a chain of blocks. A block is represented by a set of code, which means the code is the DNA and expresses all the contents of this block. One of the computing methods called ‘Sha256’ [46] is utilised in the blockchain technology to translate these transactions into this unique set of code. This computation process is defined as ‘Hashing’ [47], and the DNA code is defined as a hash number. Every number and letter of a hash number are created depending on the information of the transactions in a certain time slot.

Usually in a certain time slot, more than one transaction are executed in the market, so the hashing process is more complicated. Steps of creating a new block

are as follows:

1. Every transaction will be hashed to form a unique hash number of its own.
2. Every two hash numbers are grouped randomly and then, they will be hashed again to form a new hash number which represents these two hash numbers.
3. Repeating Step 2, until there is a hash number which could represent the whole transactions in this time slot.
4. The hash number from Step 3 will be hashed again with the hash number of the last block to form the final hash number of this block.

At last, the final hash number is the DNA of the new block. The reason behind Step 4 is that, by hashing these two hash numbers, the connection between the new block and its last block is established, which means the chain of these two blocks is set up.

From this aforementioned hashing process, tremendous transactions are represented by a line of code (hash number). The structure of this encryption process is called a merkle tree [48]. Figure 3.2 illustrates the structure of a merkle tree if there are 8 transactions which are A to H in a time slot. In this figure, the transactions in a pair are grouped and hashed. Their codes are grouped and hashed again until the final code (Root) is hashed out to represent these eight transactions.

With the support of blockchain technology, the pricing mechanism implemented in this P2P model could work effectively without any third parties. A trading token is introduced into the P2P market. In this study, a type of crypto-currency named Ether is used because we used Ethereum as the basic platform to establish the blockchain, and the unit of Ether is wei. When a prosumer announces its trading requirement (buy or sell) and sends this information to other participants, a certain amount of trading tokens from this prosumer is passed around all the peers, who validate them (trading tokens) simultaneously. These tokens will finally

3.4. System Model

Figure 3.2: The structure of a merkle tree

be received by the prosumers who are able to deal with the sender.

Figure 3.3 shows a process of the two-direction ring-based algorithm to express the way prosumers passing the tokens around. Two identical tokens are sent by prosumer A and go around the network circle in opposite direction. This transaction is approved when each peer receives the tokens and decides whether to deal with the token sender. After that, tokens are passed to the following peers who will do the same work and send them back to the sender. Then, the token sender collects all responses from other peers and selects peers to trade. At the end, when this approved transaction is terminated, the information of the trading process is stored in a new block which is added to the blockchain of the microgrid.

The whole transactions are all operated in the aforementioned way by the smart contract automatically. When the condition of ‘prosumer A receives m amount of energy from prosumer C’ is fulfilled, the execution of ‘transfer M number of dollars from C to A’ will be triggered immediately to ensure the completion of this transaction. In this time slot, if the token sender cannot find any responses from others, the condition of triggering the smart contract therefore is not met and no block will be created. The working process of the blockchain framework

Figure 3.3: The Token-passing process inside a microgrid

applied in the multi-microgrid system is nearly the same as that applied within each microgrid.

However, due to the weather condition, the amount of generated energy from the solar PV system is limited. So participants in the network would need to obey some basic rules, and our proposed model could work only under these circumstances:

1. The renewable energy output of prosumers is usually smaller than the electricity usage of consumers. The power station would fill in the unavailable gap and balance the grid system.
2. The smart meters are reliable agents for users. They would honestly record electricity consumption or generation, and post the information to the blockchain.
3. The smart contracts would not be responsible for grid control, but only for digital settlement. This also indicates that users cannot switch energy sources dynamically.
4. The real-time price of electricity is calculated by smart contracts, varying dynamically with supply and demand. This means that participants cannot propose personal bidding privately without going through the blockchain

3.4. System Model

system.

Energy transactions without going through the blockchain would incur unpleasant problems in a post-paid system. As all users share the same group of electricity contributors, an identical purchasing price is just fair to all users.

Blockchain technology can be used in this P2P model properly because the setup of a new block needs to be approved by other peers and the price in different time slots also relies on all the peers' load demand and power generation. Therefore, the advantages of blockchain technology such as high level of security, decentralization and traceability can be realized successfully.

3.4.3 Smart Contract and Creation

A smart contract in the blockchain technology plays a significant role. The design of assembled transactions and short-term balancing contracts based on smart contracts are necessary for energy trading via blockchain. By evaluating available blockchain concepts and restrictions regarding computational power as well as communication infrastructure, a concept featuring frugal requirements and sufficient security is elaborated. Data on transactions is trustworthily encrypted in a blockchain, and cash flows are exchanged in crypto-currency. Decentralized clients of a market platform negotiate contracts based on bidding algorithms and schedule individual power flows according to the transactions. In the case of spontaneous deviations, short-term contracts are negotiated, or the balancing group manager ensures adequate provision of power. By collaborating with the pricing mechanism, both consumers, operators of electric cars and grid operators/utilities achieve savings. Energy auctions may be implemented as smart contracts according to the transparent rules and visible to all the participants in energy trading. The smart contracts are written in Solidity (a language used in writing smart contract) and executed on blockchain. It takes the place of any intermediary parties to execute transactions and it also enables decentralized computation for distributed

applications. Once the pay-and-take condition of a smart contract is fulfilled, the transaction will be executed automatically so that no intermediary party is needed for the execution of the energy transactions.

The blockchain based P2P market enables energy trading through smart contracts in which energy transactions are immediate, automated, and flexible.

As the regulations of mechanisms are highly defended by this cryptography method (blockchain), the pricing mechanisms and credit rating system can work in the blockchain framework through smart contracts.

When it comes to the procedure of energy transaction in the blockchain platform, Figure 3.4 illustrates the process of executing a transaction by the smart contract. After the verification of a transaction in the network, consumers use their crypto-currency bought from the Over-the-Counter Market (OTC) (a platform for selling crypto-currency) to purchase electrical energy to fulfill their load demand. In this study, Ethereum is used as the platform to set up a blockchain, so, the crypto-currency is offered from this platform called Ether. The unit measurement of Ether is wei.

If and only if all the conditions of the smart contract are satisfied, then a transaction can be executed. The ‘Payment Sent’ and ‘Goods Received’ are therefore the conditions satisfied when the smart contract receives the correct amount of money from the consumer and the information about the correct amount of the transferred energy from the smart meters. Finally, the money and energy can be exchanged by the smart contract. In this manner, the smart contract facilitates the execution of energy transactions.

After all the conditions of the smart contract are satisfied, the trading parties (prosumers, consumers, EVs or batteries) send requests to the energy control center via smart contracts of the blockchain to satisfy the actual energy requirement using the physical network. The actual energy flow occurs only if the transac-

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Figure 3.4: The working process of smart contract

tion is technically feasible. The structure of the P2P energy trading market using blockchain is shown in Figure 3.5.

In each time slot, after broadcasting trading requirement from the buyers to the P2P network, sellers could respond to each initial participant by providing their energy size and price when they received the trading tokens. Meanwhile, the CRP values of the market participants will be verified by all the peers in the network depending on the criteria of the credit rating system. When the optimal sellers and buyers are selected, transactions can be operated and terminated between traders. Therefore, the new condition of the smart contract to trigger the transaction is that ‘the CRP values are verified by all peers and buyer A receives m amount of energy from seller B’, after which, the next step ‘transfer M number of dollars from A to B’ can be triggered automatically.

When verified transactions are done, the information of the whole transactions in each time slot is grouped and stored in a new block. This new block is then received by all peers in the network and added to the blockchain. As there is only

Figure 3.5: Blockchain used in P2P trading

one new block established in each time slot on each trading level (PTP and MTM), it is impossible for the blockchain to have any branches (forking problem) in the same time slot. Another advantage of applying blockchain technology in this P2P trading structure is that all transactions in the blockchain are terminated when they are done. So, buyers are not able to spend the same money for multiple times (double-spending) while sellers also cannot exhibit their offers when their energy has already been sold out.

On the smart contract interface, we write the pricing mechanism (algorithm) in the platform of smart contract. The tool utilised to write the Solidity language is called Remix, which is a platform to write and execute smart contract. To

3.4. System Model

demonstrate functions of the smart contract, the load demand and generation profile of one of the prosumers are taken for example.

In this blockchain, the duration of each time slot is reduced to 15 minutes because in the Ethereum platform, every new block is restricted to be set up in 15 minutes. Therefore, the time slot is adjusted to achieve the consensus with the Blockchain technology. After establishing the blockchain and smart contract of this P2P energy trading market, all the transactions can be simulated on this blockchain framework. Figure 3.6 demonstrates the interface of some participants in the P2P trading market.

```
-----
Event name: SettleEvent
*****
seqnum: 18

node type:      Power Station
account:        0x315599B43a2297dC8C4Caa897EcEB7AbF966173a
consumption:    0 Joul
electricity output: 6 Joul
expense:        -6000

node type:      Prosumer
account:        0x77de319279188DAF072ba59EaA53F44E869A0945
consumption:    0 Joul
electricity output: 46 Joul
expense:        -36800

node type:      Consumer
account:        0xDe17ecE263e4462B043f2b8daB6983f1F04E15A5
consumption:    52 Joul
electricity output: 0 Joul
expense:        42796
```

Figure 3.6: Information of participants in blockchain

This figure shows each participant's identity (Power station, Prosumer or Consumer), their account number and their transactions information in a certain time slot. The unit of energy is Joule (Joul). The price and expenditure of the energy is translated into the crpto-currency 'wei' from the Ethereum platform. In the process of executing a transaction, details are shown in this interface dynamically. From this figure, another advantage of blockchain technology is shown: every participant's account name is anonymous but the details of transactions is clear. This

means that the security and privacy of customer are seriously protected while the transparency of each transaction is still ensured. Based on this feature, blockchain technology is a reliable support for the P2P energy trading.

Figure 3.7 provides the details of the process of transactions in a time slot. This interface not only demonstrates the aforementioned contents, but also shows the trading price and participants' energy consumption (load demand) and production (generation power). In this study, the BESS is not taken into consideration, so all the contents for the battery station are zero or 'the battery station did nothing'.

```

node /usr/local...port 8545 -b 1 ...ain/smart-contract -- -bash Python power_station.py
-----
Event name: PriceEvent
-----
seqnum: 33
consumption price: 893 wei/Joul

sale price (prosumers): 800 wei/Joul
sale price (battery station): 855 wei/Joul
sale price (power station): 1000 wei/Joul
-----
Event name: SettleEvent
-----
seqnum: 33

node type:      Power Station
account:        0xf8c845305f576492Aa9A3BE779771587A950D89
consumption:    0 Joul
electricity output: 121 Joul
expense:        -121000

node type:      Battery Station
account:        0x94C4378EacCE5E5F854c71CEE5EcaBC9b17d1aB
consumption:    0 Joul
electricity output: 0 Joul
expense:        0

node type:      Prosumer
account:        0xb5768A17a5997a13058A4e9BC963A738A92CbD86
consumption:    0 Joul
electricity output: 138 Joul
expense:        -110400

node type:      Consumer
account:        0x74A69a7DdAC434825a680241bA99Aa642A8BCfb3
consumption:    259 Joul
electricity output: 0 Joul
expense:        231287
-----

interface -- Python consumer.py -- 87x16
~/LocalGit/FogChain/interface -- Python consumer.py

22:28:14 05/17/18 +08 Calling smart contract
-----
Sequential Number: 32
Consumer: 0x74A69a7DdAC434825a680241bA99Aa642A8BCfb3
Consumption: 259 Joul
-----

22:28:25 05/17/18 +08 Calling smart contract
-----
Sequential Number: 33
Consumer: 0x74A69a7DdAC434825a680241bA99Aa642A8BCfb3
Consumption: 259 Joul
-----

interface -- Python prosumer.py -- 87x9
~/LocalGit/FogChain/interface -- Python prosumer.py

22:28:24 05/17/18 +08 Calling smart contract
-----
Sequential Number: 33
Prosumer: 0xb5768A17a5997a13058A4e9BC963A738A92CbD86
Production: 138 Joul
-----

interface -- Python battery_station.py -- 87x9
~/LocalGit/FogChain/interface -- Python battery_station.py

22:28:25 05/17/18 +08 Calling smart contract
-----
Sequential Number: 33
Battery Station: 0x94C4378EacCE5E5F854c71CEE5EcaBC9b17d1aB
The battery station did nothing
-----

```

Figure 3.7: Transaction execution in blockchain

Blockchain technology in this study is a framework to secure participants' privacy and security and to demonstrate transparency of transactions. And thus, it cannot effect the results of the two-level pricing mechanism. The purpose of applying blockchain technology is to support and defend P2P energy trading.

3.4.4 A Two-Level Pricing Mechanism

To support the transaction execution in the P2P market fully, a two-level pricing mechanism is introduced to address the pricing problem [49]. All the prosumers in

3.4. System Model

a microgrid are equipped with PV panels, and several microgrids are connected to each other to create a multi-microgrid system. The pricing mechanism which has two levels for trading in a P2P market is presented. The first level is designed for the prosumers within the microgrid and the second one is designed for different microgrids in the system.

To achieve a better outcome with the blockchain technology, any agents or parties who play a role as a middleman are eliminated in this study, so that a decentralised structure can be realised with the support of the pricing mechanism and blockchain technology.

3.4.5 Prosumer to Prosumer

This section aims to provide a feasible P2P market for prosumers rather than trading with the utility grid.

The load (L) and generated energy (E) is of participants in a microgrid during each time period are defined as:

$$L_i = [L_i^1, L_i^2, L_i^3, \dots, L_i^T] \quad i \in [1, 2, 3, \dots, n] \quad (3.1)$$

$$E_i = [E_i^1, E_i^2, E_i^3, \dots, E_i^T] \quad i \in [1, 2, 3, \dots, n] \quad (3.2)$$

where n is the total number of peers in each microgrid. T is the number of time slots.

For prosumer i , the amount of energy it needs to sell or buy can be calculated as:

$$P_{im,i} = L_i - \min(L_i, E_i) \quad (3.3)$$

$$P_{ex,i} = E_i^t - \min(L_i, E_i) \quad (3.4)$$

The net power (NP), total energy sale (TES) and the total energy purchased (TEP) at time slot t are defined as:

$$NP_i^t = L_i^t - E_i^t \quad t \in [1, 2, 3, \dots, T] \quad (3.5)$$

$$TES^t = -\sum_{i=1}^n (L_i^t - E_i^t), \quad NP_i^t < 0 \quad (3.6)$$

$$TEP^t = \sum_{i=1}^n (L_i^t - E_i^t), \quad NP_i^t \geq 0 \quad (3.7)$$

According to the rationale explained in [17] and with constraints of the feed-in-tariff, the trading price in every transaction can be described as:

$$\gamma^t = \frac{TES^t}{TEP^t} \quad (3.8)$$

$$P_{sell}^t = \begin{cases} \frac{P_{usell} \cdot P_{ubuy}}{(P_{ubuy} - P_{usell}) \cdot \gamma^t + P_{usell}} & 0 \leq \gamma^t \leq 1 \\ P_{usell} & \gamma^t > 1 \end{cases} \quad (3.9)$$

$$P_{buy}^t = \begin{cases} P_{sell}^t \cdot \gamma^t + P_{ubuy} \cdot (1 - \gamma^t) & 0 \leq \gamma^t \leq 1 \\ P_{usell} & \gamma^t > 1 \end{cases} \quad (3.10)$$

where γ is the ratio value of the TES and TEP . P_{usell} and P_{ubuy} are the selling and buying prices for the transaction between prosumer and the utility grid.

To encourage prosumers to engage in the P2P market platform in the very beginning, the assumption is that the first priority of prosumers in each time slot is to trade their excess power to those who lack energy in order to satisfy their load demand.

3.4.6 Microgrid to Microgrid

On the second level, transactions are carried out among the microgrids. We assume that these microgrids are near to each other in their locality, thereby ignoring the power loss during power delivery. The load demand and energy generation of microgrid j equals to the total amount of load and generation of its prosumers. The calculation of the total energy sale ($TESm$) and the total energy purchased ($TEPm$) at time slot t is same as that in the first level.

$$TESm^t = -\sum_{j=1}^n (L_j^t - E_j^t), \quad NP_j^t < 0 \quad (3.11)$$

3.4. System Model

$$TEP_m^t = \sum_{j=1}^n (L_j^t - E_j^t), \quad NP_j^t \geq 0 \quad (3.12)$$

So, the trading price (P_{msell}^t and P_{mbuy}^t) between microgrids in this community can be defined as:

$$\gamma_m^t = \frac{TESm^t}{TEP_m^t} \quad (3.13)$$

$$P_{msell}^t = \begin{cases} \frac{P_{sell}^t \cdot P_{buy}^t}{(P_{buy}^t - P_{sell}^t) \cdot \gamma_m^t + P_{sell}^t} & 0 \leq \gamma_m^t \leq 1 \\ P_{sell}^t & \gamma_m^t > 1 \end{cases} \quad (3.14)$$

$$P_{mbuy}^t = \begin{cases} P_{msell}^t \cdot \gamma_m^t + P_{buy}^t \cdot (1 - \gamma_m^t) & 0 \leq \gamma_m^t \leq 1 \\ P_{sell}^t & \gamma_m^t > 1 \end{cases} \quad (3.15)$$

In this two-level pricing mechanism, prosumers' first priority is to trade their energy within each microgrid. If its prosumers' load demand or extra generation cannot be addressed thoroughly within this microgrid, then, they are able to trade with the prosumers from another microgrid by using the second level pricing mechanism. This pricing mechanism lowers the participants' trading cost because the trading price could not be higher than the price offered by the utility grid.

In this thesis, we introduce six microgrids in one community. Microgrids 1 to 6 have 5, 3, 4, 3, 6 and 6 prosumers respectively. Their power generation and load demand in each time slot are shown in the Appendix. To participate in this P2P trading market, prosumers need to reveal its extra energy or energy deficit. The amount of energy each prosumer can trade and the trading price for each transaction can be calculated according to the aforementioned algorithms. Figure 3.9 illustrates the trading price of PTP and MTM.

3.4.7 Contributions for Decentralization

An interesting part of this pricing mechanism is narrated below. As the amount of power generation from PV panels is uncontrollable, the selling price of the prosumers is influenced by the load demand. Therefore, the prosumers could

change the trading price by making plans to meet their energy consumption. When the amount of generation energy is too high, the value of γ will increase which leads to the decrease of the selling price. Therefore, prosumers are more likely to generate less energy because the excess energy cannot be sold at a good price. Adversely, extremely low amount of generation energy will lead to a high selling price which motivates prosumers to generate more to improve their profits. This is a simple demand response behind this two-level pricing mechanism which adjusts the load demand and PV profile.

This pricing mechanism always ensures that the price of renewable energy is cheaper than that trading with the utility grid. This feature prevents peers from being arbitragers. If the price of conventional energy is cheaper than the price of renewable energy, one can keep storing and reselling electricity later, claiming the electricity is renewable.

In addition, the price of electricity in each time slot is decided by the generation profile and load demand of all participants. This feature achieves the consensus with the blockchain technology, as every transaction needs to be validated by all the nodes in the network before the creation of a new block. As a result, with the support of blockchain technology, this two-level pricing mechanism could work effectively in a decentralised P2P market.

3.5 Credit Rating in P2P Market

In the process of trading, a credit rating system plays a significant role because the rating points influence participants' choice directly: Prosumers with higher rating points have more trading choice in transactions. Those with lesser rating points may have no access to trade with those of better offers/bids. It means that a transaction cannot simply be established on the basis of an agreement on a price between buyers and sellers. This system determines the number of offers or bids a

3.5. Credit Rating in P2P Market

prosumer can collect when it joins the market. Good behaviors of traders can help increase their credit rating points (CRPs), but their bad behaviors could decrease their CRPs.

In the P2P market, it is important to select the optimal object for traders according to the CRPs results, which are given by assumption. The values of CRP are divided in 1, 2, 3 and 4 points. These four value standards [50] allow prosumers up to 50 percent, 75 percent, 90 percent and 100 percent access to all the offers and bids respectively. If there are only a few participants engaging in the market, traders with a lower CRP value can subsequently accept the bids or offers left behind by those with a higher CRP value. For sellers, those with the highest CRPs must be at the top list which means their offers must be considered by buyers first. Those with lower CRPs could lose the chance to engage in the market at this time slot if the buyer's CRPs are too low to trade with them. When sellers have the same CRP value, the one with the lowest price is obviously at an advantageous position. For buyers, their CRPs could limit their choice of sellers depending on sellers' offer price. Buyers with the lowest CRPs can only choose the most expensive price left behind in the market.

Energy trading between different microgrids is the same as the above mentioned procedures. By using the two-level pricing mechanism, each microgrid plays a role as a trader. In each time slot, we set the CRP value of each microgrid equals to the average CRPs of its prosumers. The energy purchased by a microgrid will then be distributed to its prosumers at the decreasing order of their respective CRP values and the price is also paid by them depending on the amount of energy they accepted. These transactions are actually operated among different groups of prosumers. The process of transactions is demonstrated in Figure 3.8.

This credit rating system keeps the execution order in the P2P energy trading market on both the prosumer-to-prosumer (PTP) and microgrid-to-microgrid (MTM) levels. Traders with lower CRPs suffer a higher trading cost and limited choices to

Figure 3.8: The process of trading for buyers

complete their transactions. So, the legal behaviors of traders can be successfully secured by this system. This leads to an improvement in the market quality. Furthermore, this system also dictates the order of operating transactions, i.e. traders with high CRPs could enjoy the trading energy in the market first.

To demonstrate how the two-level pricing mechanism could work with the credit rating system in this P2P energy trading model, the aforementioned 6-microgrid structure is still utilised in the simulation and implementation process.

In this report, taking the 16th hour for example, all transactions recorded in blocks and secured by the blockchain framework are verified by all the participants in this P2P trading network. By using this blockchain based credit rating methods in this 16th hour-time slot, these prosumers' CRPs and the transaction data of the six microgrids as well as the total cost of different microgrids after the two-level transactions is shown in Table 3.1 and Table 3.2 respectively. '+' is for the prosumers' income and the values of their extra energy and selling price. '-'

3.5. Credit Rating in P2P Market

Figure 3.9: (a) The buying price of PTP (b) The selling price of PTP (c) The buying price of MTM (d) The selling price of MTM

represents prosumers' cost and the values of their energy deficit and buying price.

Table 3.1: Conditions of transactions in the microgrid-community before the 16th hour

Participant	Energy(kW)	Price(cents/kW)	CRP	Prosumers' CRPs
MG1	+71.4991	+8	3	(4,4,1,3,3)
MG2	-271.6902	-20.3000	3.3	(3,3,4)
MG3	+189.4559	+8.2448	2.5	(1,3,2,4)
MG4	+4.5971	+11.0160	3.7	(4,4,3)
MG5	+114.1669	+8	2.8	(2,4,4,3,1,3)
MG6	-19.7418	-8.6245	3.2	(4,3,2,4,2,4)

Table 3.2: Cost of microgrids comparing with peer-to-grid

Participant	Unmet Energy(kW)	Cost (cents/kW)	Final Cost	Peer-to-Grid cost
MG1	0	+571.99	+571.99	+571.99
MG2	0	-5515.31	-5515.31	-5515.31
MG3	+88.2872	+1114.47	+1820.77	+1515.66
MG4	0	+50.64	+50.64	+36.78
MG5	0	+913.34	+913.34	+913.34
MG6]	0	-170.3	-170.3	-400.8

For the prosumers, Table 3.3 provides the information of their costs after using the first-level pricing mechanism, and their final cost after the second-level one.

3.6 Discussion

From these tables it can be concluded that in this P2P energy trading model, all the prosumers can save cost and even make some profits by trading with each other when compared to trading with the utility grid. But not all the requirements of traders are satisfied after trading, because prosumers with low CRPs due to their bad historical records will be punished by buying at a higher purchasing cost and limited trading choices.

This study utilizes the above methods to improve the market quality. The CRP value is a significant index to determine the transaction priority of traders and stipulate the order of transactions in the market of each time slot. The pricing mechanism allows prosumers to save their cost or maximize their income after

3.7. Summary

Table 3.3: Cost or income of prosumers

Participant	Unmet Energy(kW)	Cost (cents/kW)	Final Cost
P11	0	+456.399	+456.399
P12	0	-451.6852	-451.6852
P13	0	+421.6095	+421.6095
P14	+48.6320	-841.3951	-1828.6247
P15	0	+84.5171	+84.5171
P21	+158.229	0	-3212.0627
P22	+200.764	0	-4075.5265
P23	+153.793	0	-3212.0007
P31	+77.575	0	-1574.7894
P32	+24.5055	-1101.677	-1599.138
P33	+6.42543	0	-130.4364
P34	0	+812.1297	+812.1297
P41	0	-70.1518	-70.1518
P42	0	+680.0382	+680.0382
P43	+36.4460	-848.6534	-1588.5702
P51	+64.5539	-87.8285	-1398.272
P52	0	+461.7836	+461.7836
P53	0	-1010.3068	-1010.3068
P54	0	-169.0951	-169.0951
P55	0	+597.3453	+597.3453
P56	0	-179.1546	-179.1546
P61	+117.821	0	-2391.7699
P62	+159.572	0	-3239.3250
P63	+48.7702	0	-990.0354
P64	+129.595	0	-2630.7894
P65	+39.9052	0	-810.0769
P66	+32.8015	0	-665.8723

accomplishing every transaction. The transparency of each transaction process and the security of traders' private information are protected by the blockchain framework.

3.7 Summary

This thesis proposes a P2P energy trading model comprising a two-level pricing mechanism, a credit rating system and a blockchain framework. The main function of these methods is financial incentives. A pricing mechanism makes it possible for prosumers to achieve maximum cost saving or income. The credit rating sys-

tem encourages them to improve their reputation so that higher priorities over other competitors can be enjoyed during transactions. Then, the advantages of blockchain technology are utilized to support this model. In this case study, six different microgrids are observed. In conclusion, this proposed model could not only improve the quality of a P2P market, but also provide some flexibility for the market operators to apply more advanced technology into the market.

This study also presents the application of the smart contract in the P2P energy trading field. Instead of a third party, the smart contract executes transactions and algorithms for participants in the network (microgrid). When conditions of the smart contract are satisfied, transactions will be triggered automatically. The content of a smart contract is immutable, and thus, it is reliable for prosumers and consumers to trade with each other. Only validated transactions can be executed and added to the blockchain. From the interface of the smart contract and blockchain, customers' private information is protected and encrypted, and at the same time, the transparency level of transactions is ensured

In the blockchain framework, 'miner' and 'participant' are two different concepts. Participants are those who engage in the P2P trading and transact with others as prosumers. Miners are block creators who mine new blocks for the blockchain. As a result, with the support from both of them, this decentralised application (blockchain) could work effectively in the decentralised market and improve the quality of P2P energy trading.

Chapter 4

A Proof-of-State Consortium Blockchain for Power Loss Compensation

4.1 Introduction

With the rapid development of photovoltaic (PV) power generation and the open of local electricity markets in many countries, peer-to-peer (P2P) energy trading [4] becomes increasingly popular as it reduces participants' cost as well as the power loss in the distribution system. To ensure the security level and transparency of P2P transactions, blockchain technology is widely applied in the microgrid to support P2P energy trading in the distribution system. Transactive energy [51] becomes a new topic flourishing in the energy trading field. Relevant crypto-currency such as Bitcoin is invented as the payment can be executed without the need of any third parties.

The mechanism of Bitcoin working in a network is introduced in [33]. Trading by exchanging crypto-currency from digital wallets saves time of money transfer [52]. Such crypto-currency like Bitcoin is published mainly by mining. According to

the proof-of-work (PoW) protocol [53], miners who mine a block successfully could be rewarded with some Bitcoins. However, the main drawbacks of this protocol are that, the mining process is extremely energy consuming. In addition, once the highest computation power of a miner exceeds 50% of the whole network, it can take over the mining work as a monopoly role. This consequence could be easily achieved when the number of miners is small. To solve this problem, another consensus protocol named proof-of-stake (PoS) is created [54]. The probability of winning a mining competition is determined by miners' respective stake. Nowadays, blockchain technology is divided into three types:

1. Private chain: the chain is ruled by a centralized entity.
2. Consortium chain: some pre-selected miners maintain the distributed ledger.
3. Public chain: anyone in the world with different levels of computation power could engage in the mining pool and mine blocks.

Compared with the other two blockchain techniques, consortium blockchain is preferred because of its modest cost, better scalability and shorter delay [55].

4.2 Related Works

Several works related to the consortium blockchain have been done. The authors in [56] propose a PoS based consortium blockchain concept and demonstrate a distributed system model to introduce the components of the blockchain: 1) users; 2) miners; and 3) verifiers. Both miners and clients with mobile devices could be verifiers. The pre-selected miners could also be chosen from the users. In [57], the authors use consortium blockchain to enable localized P2P energy trading among plug-in hybrid electric vehicles. But load aggregators (LAGs) are defined as the only pre-selected miners, creating a non-flexible mining environment, as the identity of LAGs is constant and cannot be switched to another groups. In addition, the energy consumption of mining which cannot be ignored is not described in

4.2. Related Works

this paper. The authors in [58] use the same blockchain structure to secure energy trading with the help of internet of things. They define a credit bank as a trusted bank node with enough energy coins. This bank could provide energy coins loans for transaction participants according to their credit values, which offers a way to publish the crypto-currency. However, this credit bank as a virtual third-party entity shows no advantage compared to the services provided by the practical bank. Customers could still use traditional on-line payment platform rather than paying by energy coins. It is significant to realise the benefit and potential of crypto-currency trading.

In many microgrids studies, power loss is usually neglected because the energy is transmitted in the distribution system [59] without long-distance transmission. But without considering power losses, the power flows of P2P energy trading cannot match the physical situation. For the power losses allocation in the distribution system, the authors in [60] proposes a multi-phase branch current decomposition method to fairly allocate the losses to the end-users. But a different method in [61] based on the injected active and reactive power requires that the losses should be allocated to the loads and generators depending on their loss contribution. To provide a better solution for the loss allocation, the study in [62] uses a game-theory methodology to allocate power losses among all the network users. In conclusion, except for the amount of energy needed from buyers, some members of the microgrid have to deliver more energy to compensate for the power losses. To provide a feasible P2P energy trading model, it is necessary to take the power loss into consideration. A technical approach in [49] proposes a method to calculate the power loss and store this information in the blockchain. It proves that blockchain can be used for technical operations in microgrids, such as the issue of power losses tracking and attribution.

Unfortunately, most papers about energy trading do not demonstrate or focus on the detailed process of blockchain implementation [49, 58, 63–65]. These studies

provide specific demonstration about their own ideas or proposed optimization methods, but with little introduction of blockchain technology. They assume that their ideas could be implemented in the blockchain framework successfully without experiments. Moreover, smart contracts cannot execute complicated computation, let alone those pricing schemes which consider complex optimization and iteration algorithms [40]. These factors make their ideas unfeasible.

4.2.1 Major Contributions

In this part of the thesis, the establishment of blockchain and its process of implementation are demonstrated. The idea of this paper focuses on motivating prosumers with extra energy traded to meet consumers' load demand while contributing to power losses during energy delivery. The contributor (prosumer) and its mining opportunity are both determined by the PoS protocol. The rewarded crypto-currency is named 'elecoin' in this chapter. The objective is to create a P2P energy trading model where elecoin (ELC) becomes the only currency of energy trading and incentivizes prosumers to fulfill the power losses.

In this context, the main contribution of this chapter is threefolds:

1. A PoS based consortium blockchain: we propose a PoS blockchain under the consortium condition not only to improve the security level of transactions and reduce the energy of mining, but also to publish elecoins to reward the prosumers who compensate the power losses. In this model, the energy consumed by mining is taken into consideration.
2. An elecoin-payment based P2P energy trading model: We introduce a power distribution model to estimate the power losses and suggest an optimal solution to increase the incomes of miners.
3. A feasible implementation of blockchain technology: The setup process and implementation of blockchain are specifically demonstrated. Through the

4.3. System Model

above study and proposed technique, implementing blockchain in the energy trading model becomes practical.

Numerical results show that our PoS consortium blockchain is an effective and efficient way to motivate prosumers to maximize traders' income or cost savings and motivate prosumers to fill up the gap caused by power losses.

4.3 System Model

4.3.1 Pricing Scheme for P2P Energy Trading

Before applying a consortium blockchain into a microgrid, the P2P energy trading market needs a pricing scheme to realize its superiority, i.e. customers could trade their energy at a more acceptable price than trading with the utility grid. In this thesis, prosumers are assumed to be equipped with solar PV panels. Modern technologies are currently unable to support every prosumer with an energy storage system (ESS), due to its high cost of capital investment, the installation and maintenance of batteries. Not all the prosumers could be equipped with ESS. To simplify the trading model in this section, all the prosumers are assumed to be not equipped with ESS. Their generated energy should be consumed or traded at once.

The load demand and generated energy of prosumers in a microgrid during every time slot are defined as:

$$L_i = [L_i^1, L_i^2, L_i^3, \dots, L_i^T] \quad i \in [1, 2, 3, \dots, n] \quad (4.1)$$

$$G_i = [G_i^1, G_i^2, G_i^3, \dots, G_i^T] \quad i \in [1, 2, 3, \dots, n] \quad (4.2)$$

where n is the total number of peers in each microgrid. T is the number of time slots.

For prosumer i , the amount of excess energy it needs to export or that of unmet energy it should import can be calculated as:

$$P_{im,i} = L_i - \min(L_i, G_i) \quad (4.3)$$

$$P_{ex,i} = G_i^t - \min(L_i, G_i) \quad (4.4)$$

The total energy sale (TES) and the total energy purchased (TEP) at time slot t are defined as:

$$TES^t = \sum_{i=1}^n P_{ex,i}^t \quad (4.5)$$

$$TEP^t = \sum_{i=1}^n P_{im,i}^t \quad (4.6)$$

The pricing scheme of this P2P model is established on the basis of crypto-currency payment. The ‘elecoin’ (ELC) is thereby utilized to measure the value of energy. According to the rationale explained in [40] and with constraints of the electricity price proposed by the utility grid, we simplified the method in [40]. The trading price in each transaction can be described as:

$$\gamma^t = \frac{TES^t}{TEP^t} \quad (4.7)$$

$$ELC_{sell}^t = \begin{cases} \frac{ELC_{usell} \cdot ELC_{ubuy}}{(ELC_{ubuy} - ELC_{usell}) \cdot \gamma^t + ELC_{usell}} & 0 \leq \gamma^t \leq 1 \\ ELC_{usell} & \gamma^t > 1 \end{cases} \quad (4.8)$$

$$ELC_{buy}^t = \begin{cases} ELC_{sell}^t \cdot \gamma^t + ELC_{ubuy} \cdot (1 - \gamma^t) & 0 \leq \gamma^t \leq 1 \\ ELC_{usell} & \gamma^t > 1 \end{cases} \quad (4.9)$$

where γ are the ratio value of the TES and TEP , ELC_{usell} and ELC_{ubuy} are selling and buying price for the transaction between the prosumer and the utility grid. The value of energy is transferred into ‘elecoin’, so ELC is used to represent the price of energy.

An advantage of this pricing scheme is as follows: Although the amount of generated energy from PV panels is uncontrollable, the selling price of the prosumers is influenced by their controllable load demand. Therefore, prosumers could change the trading price by planning to alter their energy consumption. In the peak generation slots, the high value of γ^t could lead to a relatively cheap ELC_{sell}^t price,

4.3. System Model

which encourages prosumers to increase their load demand. An increase of the energy consumption will adversely decrease the value of γ^t and create a higher ELC_{sell}^t price.

With the support from the smart contract of the consortium blockchain explained in Section 4.4, prosumers can trade their energy directly at the price of the proposed pricing scheme, without the help from any practical or virtual third-party entities (such as Energy Sharing Provider). Although smart contracts are not able to operate complicated calculations, the equations above are simple enough to be executed.

4.3.2 Power Loss Estimation

In a feasible P2P energy trading strategy, the transactions should match the losses of the distribution system on top of the transactive energy. To achieve this objective, power losses during energy delivery should be taken in to consideration. The calculated value of power losses is stored in the blockchain. Figure 4.1 illustrates the basic structure of a microgrid.

Figure 4.1: Electrical wires of a microgrid

According to the structure of the energy delivery within a microgrid, different transactions in the same time slot may cause a superposition of the power flows between prosumers and consumers. Although these transactions cause non-linear coupling of power flows on the same branch from different prosumers, we can still estimate the power losses by the following calculation method. Firstly, in this P2P energy trading network, the energy flow among the prosumers will pass the branch A. So except for the energy trading between the utility grid and prosumers, the distribution system can be reduced to a simpler structure, which is shown in Figure 4.2.

Figure 4.2: A simple structure of the distribution system

Then, it has been proved in [38] that the value of power losses can be expressed as the function of the active and reactive power of node A with its series resistance R_A as well as its sending bus voltage V_A :

$$P_{loss} = \frac{R_A}{V_A^2} (P_A^2 + Q_A^2) \quad (4.10)$$

The coefficient β_{Pi} is introduced for the attribution of the power losses from Prosumer i (P_i) at node A. If there are n prosumers connect to branch A, the power

4.4. Blockchain for P2P Transactions

loss attribution equations can be defined as:

$$P_A = \beta_{P1}.P_A + \beta_{P2}.P_A + \dots + \beta_{Pn}.P_A \quad (4.11)$$

where $1 = \beta_{P1} + \beta_{P2} + \dots + \beta_{Pn}$.

The ratio of P_A to Q_A is defined as K :

$$\frac{P_A}{Q_A} = K \quad (4.12)$$

Using (4.12), (4.11) can be written as:

$$K.Q_A = K.\beta_{P1}.Q_A + K.\beta_{P2}.Q_A + \dots + K.\beta_{Pn}.Q_A \quad (4.13)$$

Therefore, the attribution of the power losses for the reactive power can be defined as:

$$Q_A = \beta_{P1}.Q_A + \beta_{P2}.Q_A + \dots + \beta_{Pn}.Q_A \quad (4.14)$$

Using (4.11) and (4.14), (4.10) can be redefined as:

$$P_{loss} = \frac{R_A}{v_A^2} [(P_A^2 + Q_A^2) \sum_{i=1}^n \beta_{Pi}^2 + 2(P_A^2 + Q_A^2) \sum_{i,j=1}^n \beta_{Pi}\beta_{Pj}] \quad (4.15)$$

$$P_{loss} = P_{loss} \sum_{i=1}^n \beta_{Pi}^2 + 2P_{loss} \sum_{i,j=1}^n \beta_{Pi}\beta_{Pj} \quad (4.16)$$

From the above equations, it can be concluded that the total power losses in a time slot can be calculated as the sum of every power loss caused by respective transactions. In this section, these equations outline the method to estimate the value of power losses of a microgrid, before implementing the whole blockchain model.

4.4 Blockchain for P2P Transactions

The blockchain framework is an effective method to defend the security of transactions. The related concepts have been explained in Chapter 3. Every block's hash code is connected to each other, so that a slight change in anyone of it will cause a Domino effect that all the hash codes will reflect to this change and become invalid [66]. Figure 4.3 shows the structure of a blockchain made by the hash function. In this figure, $H(x)$ represents the block no. x and $H(x-1)$ because $H(x)$

is hashed from them. To overwrite a blockchain, a malicious node need to control most of the nodes in the network and overwrite all the content of the previous block, while surpassing the mining speed of all the honest nodes.

Figure 4.3: The structure of a blockchain

The variable x for the hash function ($H(x)$) are users, transactions, time, smart contracts and the hash code of the last block.

$$Hashcode = H(t, User, Trans, Contract, H(t - 1)) \quad (4.17)$$

4.4.1 Consortium Blockchain for the Power Loss Compensation

In this consortium blockchain, only some of the nodes are selected to be the miners. To motivate energy sellers to deliver more energy to make up for the power losses, they are qualified to serve as miners so that they could be rewarded. This means that in every time slot, the miners are chosen from the sellers. According to the PoS protocol, miners are obliged to deposit their stake to compete for the right to mine. The stake is the elecoins whose value equals to prosumers' excess energy in their respective digital wallet, which is calculated by (4.4). The one who owns most crypto-currency has the biggest chance to mine. If the miners' generation surplus is insufficient for the loss compensation, the prosumers with the second largest stake should then be selected. They are added to the mining pool until the total generation surplus is enough to compensate the power losses. The rewards

4.4. Blockchain for P2P Transactions

will be proportional to their respective contribution. When the total amount of the generation surplus from the microgrid is still not enough, utility grid will take the place of miners. The one who owns most crypto-currency has the lightest chance to mine. The trading price of electricity in this paper is assumed to be ELC_{sell}^t and ELC_{buy}^t per kilowatt which is described in the pricing scheme.

When a prosumer wins the opportunity to mine a block, part of its stake will be paid to compensate for the total power losses in the microgrid in the time slot. Considering the energy consumption of mining in each time slot (P_{mine}^t), the value of the energy a miner consumes should be less than the value of the rewarded y ELCs:

$$\sum_{i=1}^n P_{loss}^t + P_{mine}^t < \frac{y^t}{ELC_{buy}^t} \quad (4.18)$$

This equation informs us that the value of the rewarded ELCs could purchase more energy from the utility grid than it sacrifices for the compensation.

However, in a PoS blockchain, if the miner behaves maliciously during the mining period, the block will not be validated and he will also be punished by losing all of its stake. To prevent miners from such illegal behaviours, all nodes in the network ensure that the value of rewarded coins is less than the miner's stake. Therefore, malicious operations could cost more than they earned from the rewards. With the above constraints, the value of the rewarded elecoins should be limited as follows:

$$\sum_{i=1}^n P_{loss}^t + P_{mine}^t < \frac{y^t}{ELC_{buy}^t} < G_i^t - L_i^t \quad (4.19)$$

Another advantage of these constraints is about the financial balance of the market. If the value of the rewarded elecoins is too high, the market could not provide enough products (i.e. electrical energy) to support the value of the crypto-currency. Finally, the elecoins become valueless.

Miners could also engage in trading its energy if there is surplus energy after

mining. So the income of energy trading in a time slot can be calculated as:

$$Income = ELC_{sell}^t \cdot (G_i^t - L_i^t - \sum_{i=1}^n P_{loss}^t - P_{mine}^t) \quad (4.20)$$

At last, for the seller who mines block, its profit in the time slot is calculated as:

$$Profit = y^t - ELC_{buy}^t \cdot (\sum_{i=1}^n P_{loss}^t + P_{mine}^t) + Income \quad (4.21)$$

For those who do not win the right of mining, their profit value is the same as their incomes.

$$Profit = Income = ELC_{sell}^t \cdot (G_i^t - L_i^t) \quad (4.22)$$

From these algorithms and constraints, the seller who wins to mine could earn more than other sellers. This financial incentive strives sellers to compete for the mining right and the opportunity to compensate for the power losses in the proposed consortium blockchain. This model connects mining mechanism with power loss compensation, which provides a better match between transactions and power flows.

Another advantage of this proposed consortium blockchain is the flexibility of the role of miners. At different time slots, the amount of prosumers' respective energy generation and load could also be different. Some prosumers might become consumers if their generated energy cannot meet the load, and thus, they lose the chance to compete for the miners. Conversely, consumers can also become prosumers (miners) if they have extra energy in a time slot. In summary, every prosumer in the microgrid have the chance to be the miner. The group of miners is not constant.

To achieve the financial balance of the P2P energy trading market, the quantity of the elecoins should be limited. The value of total elecoins rolling in the market should not exceed the elecoin value of the total generated energy, which can be expressed as:

4.4. Blockchain for P2P Transactions

$$ELC_{total} < \sum_{t=0}^{24} (ELC_{buy}^t \cdot \sum_{i=1}^n G_i^t) \quad (4.23)$$

It should be noted that, the elecoin value at the right side of this constraint is not a constant value. It has a positive proportional relation with the number of prosumers in the network. This feature encourages more prosumers to participate in the P2P energy trading market, so that more elecoins could be published by mining. As long as there are electrical wires to connect them and ensure the energy delivery, even prosumers from different microgrids can also join this consortium blockchain model. The trading model of transactions among different microgrids is described in [17]. At last, all the above information will be stored and secured by the blockchain. The value of elecoins mined out by each miner is determined by the average value of its maximum and minimum. Because enormous published elecoins will decrease its own value in the market, while a little rewarded elecoins value will depress miners' motivation of mining:

$$y^t = \frac{(y_{max}^t + y_{min}^t)}{2} \quad (4.24)$$

The whole working process of the consortium blockchain is shown in the Algorithm 1 below:

In this algorithm, every participant (user) in the blockchain network owns a private key and a public key. Traders use their private key to decrypt their proposed transaction and broadcast it to the network. The other users from this network will check this proposed transaction and verify it by using their public key, which cannot change the content of the transaction. If the transaction is legal or it is approved by the other users, a new block will be encrypted and added to the blockchain.

There is also a demand response factor behind this model. As the number and the stake of competitors for mining is enormous in peak generation periods but few in the off-peak, it motivates prosumers to increase energy consumption in the

Algorithm 1 The procedures of a working blockchain

```

1: for each  $trader_i \in [microgrid]$  do
2:   initialize a broadcast of new transactions to the microgrid;
3:   other users in the microgrid collect and verify the new block for the new
   transactions;
4: end for
5: if all transactions are valid and not already executed then
6:   users express their acceptance of the block;
7: else transactions are not allowed;
8: end if;
9: for  $miner_i \in [prosumers]$  do
10:  deposit its stake;
11:  mine the accepted block:
12:   $Hashcode_i = H(block, Hashcode_{i-1})$ ;
13:  receive rewarded coins
14: end for
15: if block is mined legally then
16:  receive the deposit back;
17: else lose its deposit;
18: end if

```

peak generation periods, and reduce their load demand during the off-peak period to preserve their PV generation. This benefit could alleviate the damage of the ‘duck curve’ caused by PV generation.

Although the transparency of transactions is open to users, traders’ personal information such as their real names is inaccessible. Because their privacy is highly defended by anonymity, which is another advantage of blockchain technology. Miners also have no access during mining [63]. Figure 4.4 illustrates the interface of mining, where no private content is shown. In this figure, two blocks were successfully mined.

```

INFO [07-17|16:10:32.254] □□□block reached canonical chain
INFO [07-17|16:10:32.260] □□□mined potential block
INFO [07-17|16:10:32.265] Commit new mining work
fees=0 elapsed=12.965ms
> miner.sINFO [07-17|16:10:32.718] Successfully sealed new block
...8ddea0 elapsed=464.757ms
INFO [07-17|16:10:32.724] □□□block reached canonical chain
INFO [07-17|16:10:32.731] □□□mined potential block
INFO [07-17|16:10:32.740] Commit new mining work
fees=0 elapsed=15.956ms
INFO [07-17|16:10:32.958] Successfully sealed new block
...8ddea0 elapsed=464.757ms

number=504 hash=ab319...fec73e
number=511 hash=edad5...697fbc
number=512 sealhash=64904a...4a80f3 uncles=0 txs=0 gas=(
number=512 sealhash=64904a...4a80f3 hash=05291c
number=505 hash=45179...dc9a9f
number=512 hash=05291...8ddea0
number=513 sealhash=5f5bbb...17388d uncles=0 txs=0 gas=(
number=513 sealhash=5f5bbb...17388d hash=cf4864...bc2400

```

Figure 4.4: The mining interface of the blockchain

To sum up, the functions of the proposed consortium blockchain realized in this

4.5. Case Study and Results

thesis are: 1) tamper-proof to cyber-attack; 2) issuance of crypto-currency; 3) compensation for the power loss; and 4) security for privacy.

4.4.2 Smart Contract Creation

In the consortium blockchain, smart contract is responsible for the execution of trading [67]. Transactions could be executed by the immutable smart contracts as follows:

Algorithm 2 Transaction execution of smart contract

```
1: for each  $smartcontract_i \in [block_i]$  do
2:   receive money from the seller;
3:   receive electricity from the buyer;
4: end for
5: if the value of money and electricity is fair then
6:   execute this transaction;
7: elsereturn money and electricity to the traders
8: end if;
```

4.5 Case Study and Results

In this section, the general structure of the methodology is explained in Figure 4.5. We establish the proposed consortium blockchain by using the Geth (a software used to link to the Ethereum platform). The content of smart contract is written in Solidity language on the Remix, which is an IDE (Integrated Development Environment) provided by Ethereum. Other software packages such as Truffle and Web3 are also required. The crypto-currency is written depending on the ERC20 standard proposed by the Ethereum company. The tools above are used to set up the proposed blockchain which is shown at the left side of Figure. 4.5. MATLAB within Opal-RT is used to program the role of microgrids and their prosumers' respective energy generation and load demand, which referred to the content of Figure. 4.5 at the right side.

We also introduce three different microgrids with respective numbers of users (prosumers). Each prosumer is equipped with PV panels to generate energy.

Figure 4.5: The structure of the methodology

Their transactive energy profiles are shown in Figure 4.6, Figure 4.7 and Figure 4.8. In these figures, the amount of power below 0 is defined as the excess power P_{ex}^t , and the power above 0 is the unmet load demand P_{im}^t .

Figure 4.6: The amount of transactive energy within microgrid(a)

4.5.1 Pricing Scheme Implementation

These three microgrids (a, b, c) include 3, 6, 9 prosumers respectively. Because of the dependence on the Ethereum platform, the value of one unit of elecoin in this

4.5. Case Study and Results

Figure 4.7: The amount of transactive energy within microgrid(b)

Figure 4.8: The amount of transactive energy within microgrid(c)

chapter is defined as:

$$1ELC = 1 \times 10^{-5} Ether \quad (4.25)$$

According to the load demand and energy generation of these prosumers and the pricing scheme introduced in 4.3.1, the trading price within each microgrid can be calculated as shown in Figure 4.9, Figure 4.10 and Figure 4.11 respectively.

Figure 4.9: The internal trading price of microgrid(a)

Figure 4.10: The internal trading price of microgrid(b)

Figure 4.11: The internal trading price of microgrid(c)

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During the peak generation time, the price of each microgrid is different, because the amounts of load demand and energy generation of each prosumer are different from those of others.

4.5.2 Consortium Blockchain Implementation

To implement the proposed consortium blockchain, the genesis block (the first block of a blockchain) is created to set up the difficulty of mining and store the PoS protocol. Then, depending on the amounts of load demand and energy generation of each prosumer, the PoS protocol pre-selects the miner based on their extra energy (stake) deposited in the smart contract. The interface of miner-selection is shown in Figure 4.12. The first line of the code is the command of pre-selection and the address code in green colour is the account of the pre-selected miner.

```
> miner.setEtherbase(eth.accounts[1])
true
> eth.coinbase
"0x20aee1eb7a4b1d552248fa1fb9fa2f35255fca26"
```

Figure 4.12: The interface of miner-selection

Figure 4.13: The transaction execution interface of the smart contract

And then, prosumers as nodes in the blockchain network are connected. A smart

contract is written to execute transactions which have been verified by all of the prosumers. Taking 12:00 pm in Figure 4.7 for example, Prosumer P26 of the microgrid (b) owns most extra energy (about 170 kW) at that time slot, thereby becoming the miner. Meanwhile prosumer P23 needs 20kW energy to fulfill its load demand. Therefore, the transaction happens between these two prosumers. This transaction is then executed by the smart contract automatically once it receives the required conditions of energy and money. Figure 4.13 demonstrates the interface of transaction execution by the smart contract. *post_cons* and *post_prod* refer to the prosumers who need to purchase energy and sell energy respectively. In this time slot, only one transaction is announced in the microgrid, so the value of the *portion* is 1 (100 percent). The amount of the traded energy proposed by the buyer is less than that of the seller, because this seller is also a miner, so it needs to sacrifice an extra energy to compensate for the power loss aforementioned.

The content at the right side of Figure 4.13 is the structure of the transaction's block introduced in 4.4. The value of the power loss (kW) is calculated by the estimation algorithms from 4.4.1, which is shown in Table 4.1

Table 4.1: The value of power loss (kW) in each time slots

Time	Microgrid(a)	Microgrid(b)	Microgrid(c)
6	0	0	0
7	0	2.3397	1.0679
8	0	9.2015	1.4342
9	0	7.3794	10.9778
10	0	9.1406	16.6839
11	0	4.1659	7.1826
12	0.4824	3.5556	5.5727
13	0.5523	5.9423	4.5809
14	1.1146	3.1638	4.9941
15	0.1309	5.2775	3.5652
16	0	6.7643	12.8743
17	0	6.0683	4.0097
18	0	0	0

In some time slots, there is no transaction proposed by prosumers, thereby no

4.5. Case Study and Results

power loss.

According to the rationale of crypto-currency mining [68, 69], the value of P_{mine}^t is in proportion to the difficulty level of mining set in the genesis block as well as the amount of mined crypto-currency. In the Bitcoin mining pool, every bitcoin requires 968kW energy to mine. Thus, in this model, the value of P_{mine}^t can be calculated as:

$$P_{mine}^t = \frac{968 \cdot y^t \cdot D}{BD} \quad (4.26)$$

where D and BD refer to the difficulty level of mining elecoin (D) and bitcoin (BD) respectively.

The incentive for the miners is that the value of rewarded elecoins is more than the value of power losses and mining energy. The profit earned by a miner in a certain time slot is:

$$Profit_{mine} = y^t - ELC_{buy}^t \cdot \left(\sum_{i=1}^n P_{loss}^t + P_{mine}^t \right) \quad (4.27)$$

The difficulty level of mining is set between 130000 to 160000 in this model. According to the data for the energy generation and load demand of prosumers, the profit (ELCs) a miner can receive in different time slots after mining blocks is shown in Table 4.2.

In the second row (time slot 6) of the table, due to less prosumers in the micro-grid(a) and when their self-generation has already fulfilled their demand, there would be no trading between prosumers, thereby no profit made by miners in that time slots. Another feature should be noted that the pre-selected miner can be another prosumers in different time slots. This proposed model relies on the consensus algorithm of PoS to select the miner. The one that owns the most amount of excess energy is most likely to become a miner. The number of blocks of these three respective microgrids is also related to number of transactions. This is illustrated in Figure 4.14. The blockchain with more blocks could provide a more

Table 4.2: The profit (ELCs) of miners in each time slot

Time	Microgrid(a)	Micriogrid(b)	Microgrid(c)
6	0	0	0
7	0	959.3934	474.2076
8	0	3214.9347	636.6539
9	0	2556.4690	4527.8515
10	0	2287.4234	2914.4002
11	0	683.3547	800.2239
12	240.1728	583.2346	1254.6894
13	274.4017	1853.2602	973.4606
14	548.1407	518.9738	872.3897
15	65.5593	865.6897	622.7957
16	0	1109.5657	2565.1595
17	0	1779.3155	1754.4747
18	0	0	0

tamper-proof environment to secure transactions.

Figure 4.14: The increasing number of blocks of the three microgrids

In a microgrid, the total number of elecoins mined out during one day is correlated to the number of prosumers as well as their energy generation and load demand. Figure 4.15 illustrates this correlation between these factors.

From this figure, the number of mined elecoins roughly presents a positive relation with the number of prosumers in one microgrid. The difference exists in the microgrid(b) with six prosumers, due to the higher amount of energy transaction

4.6. Discussions

Figure 4.15: The correlation between the number of mined elecoins and that of prosumers

demand of these six prosumers, thereby increasing the number of transactions leading to a huge number of mined crypto-currency.

4.6 Discussions

In the proposed consortium blockchain, elecoins published by mining are utilized to reward miners, motivating them to make compensation for the power losses. The amount of elecoins a miner can mine out depends on the difficulty of mining. The value of difficulty is set from 130000 to 160000, which is much less than that of bitcoin mining (about $7 * 10^{12}$). In a full public chain like the Bitcoin, blockchain designers should improve the mining difficulty to an extremely high level to depress the mining speed. Because the amount of crypto-currency is limited but the number of miners is uncontrollable. Therefore, it requires a certain period of time to create a block. But in this consortium blockchain, only pre-selected miners have the right to mine and they are also users within a microgrid. Thus, the difficulty can set at a proper value so that the time duration for mining a block can be completed in seconds. In other words, transactions can be completed almost immediately. It is possible that a miner could mine its own transactions, but the

content of Figure 4.4 proves that miners cannot recognize their own transactions and any malicious operations will be punished by confiscating their deposited stake.

Before all the ELCs have been mined out, the number of rewarded (published) ELCs is related to its amount of extra energy (y_{max}) in the corresponding time slot (in Eq. (4.19)), which is a method to maintain the value of this crypto-currency. As it is a consortium blockchain in which the difficulty of mining is not as high as that of the public chain, the crypto-currency will be mined out sooner to ensure a constant number of ELCs rolling in the market. Once all the ELCs are mined out, miners can still be rewarded with elecoins (from the *gas – price* and *gas – limit* mechanism like *Ether* [34]) as this blockchain model is set up based on the Ethereum platform. In other word, the proposed model ensures a relatively consistent and stable monetary system.

In addition, because of the lower mining difficulty, the cost of electricity consumed in mining is also reduced. One mined elecoin requires only 1.8×10^{-5} kW compared to 968 kW for a mined bitcoin. Although the value of an elecoin equals to 1×10^{-5} ether currently, its value relies directly on the price of electricity. This means that its value is more stable than the other types of crypto-currency published by public chains.

When this proposed blockchain is compared to the private chain, it is more flexible in miner selection. The miner’s role can be replaced in any time slots. More importantly, a private chain requires a central agent to implement it. But in the consortium blockchain, the advantage of decentralization is still kept. Transactions are verified by all nodes in the microgrid and the PoS consensus algorithm facilitates the P2P trading mode in the electricity market. With the support of blockchain technology, any third entities such as banks or energy providers [40] could be eliminated.

From the simulation results in the case study, it has been proved that this blockchain

4.7. Summary

model is able to support the microgrid with a higher number of prosumers. When more prosumers participate in the P2P trading model, more elecoins can be mined out and traded within the microgrid. This feature shows the ability of expansion of the proposed consortium blockchain model.

4.7 Summary

This thesis proposes a consortium blockchain model to secure the P2P energy trading. It is restricted by the PoS consensus algorithm. The natural advantages of the blockchain technology such as security of users' privacy, transaction transparency and shorter delay are fully realized. The case study proves that the proposed blockchain model could help not only in saving users' trading cost, but also in executing the technical operation of the microgrid, such as compensation for the power losses in the electrical cables.

Furthermore, the specific procedures of establishing a blockchain and its smart contract are demonstrated in this thesis. The restriction on the crypto-currency publication is also provided. The proposed blockchain model provides a more flexible trading and mining environment for participants as miners can be switched in various time slots. The simulation results prove that proposed consortium blockchain provides an efficient and effective way in implementing the pricing scheme and ensuring miners' profit after compensating for the power loss.

Chapter 5

Conclusions and Future Works

5.1 Conclusions

The rapid growth of PV generation and blockchain technology allows peer-to-peer energy trading to be developed. In the distribution system, commercial relations and technical operations among different units should be taken into consideration. Blockchain technology provides a transparency and highly secured platform for the P2P trading model. For different P2P trading styles, corresponding consensus protocols are designed to fully support their blockchain framework which ensures the decentralised control, low execution latency, flexible trust and asymptotic security.

Methods of blockchain establishment are also introduced in this thesis. In the proposed models, the blockchain is established on the Ethereum platform and smart contracts are written in Solidity programming language.

This thesis firstly introduces a blockchain framework to support P2P energy trading market. Inside this framework, transactions are verified and recorded by peers from the microgrid (network). Blocks of transaction are mined by miners using the ‘SHA256’ hashing method. A two-level pricing scheme is designed for the P2P energy trading market to help save participants’ costs or increase their prof-

its, compared with those of the direct transactions between the utility grid and them. This pricing scheme relies on the ratio correlation between the amount of selling energy and buying energy, providing a flexible monetary system for the market. In addition, this blockchain based P2P energy trading model is also able to collaborate with the credit rating system, which regulates participants' trading behaviours.

Depending on the two-level pricing scheme, a Proof-of-Stake based consortium blockchain model is set up. This blockchain based P2P energy trading model allows the pre-selected miners to compensate for the power loss caused within the microgrid. The proposed mining-rewarding algorithms and the PoS consensus protocols ensure miners benefit from their legal mining behaviours. Moreover, the process of smart contract creation is specifically demonstrated. Simulation results prove the effectiveness of this consortium blockchain implementation and the power loss compensation mechanism is feasible for the P2P energy trading market.

In conclusion, the main contributions of the proposed works are:

1. The design of a proper pricing scheme to support P2P energy trading market.
2. The creation of rewarding mechanism and consensus protocols to ensure legal behaviours of peers.
3. The implementation and demonstration of the proposed blockchain models and smart contracts.

5.2 Future Works

Other than the discussed work, the application of blockchain as a disruptive technology has huge potentials in various future extension for the P2P energy trading:

1. Blockchain applications currently are mostly developed for transaction pay-

5.2. Future Works

ments. The potentials of participating in the technical operations of micro-grids such as power loss distribution and compensation will be progressively explored in the future work. More specific research will be conducted on the power system structure and energy storage system such as battery technology will also be considered to make the whole model more practical.

2. With the development of blockchain technology and P2P energy trading market, more advanced consensus protocols will be created to provide a lower latency, more byzantine fault tolerant and more secured blockchain framework. Therefore, future work will focus on applying or even inventing new and optimal consensus protocols into the blockchain based P2P energy trading.
3. As the purpose of the P2P energy trading is to increase the welfare of the market participants, future studies will research on corresponding concepts of economics and apply them into the blockchain based P2P market. These future applications will improve the efficiency of the transaction execution and achieve the modest operation cost as well as better scalability.

Appendix

The Power Generation and Load of 27 Prosumers from the 6-Microgrid Community

The specific information of each prosumer in the corresponding microgrid are shown in the figures below:

Figure 5.1: The data for the first three microgrids

Figure 5.2: The data for the last three microgrids

List of Publications

The Author's contribution in this M.Eng thesis are summarised in the following publications:

Journal Publications:

1. **Y. Jiawei**, A. Paudel, and H. B. Gooi, "Compensation for Power Loss by A Proof-of-Stake Consortium Blockchain Microgrid" *IEEE Transactions on Industrial Informatics (Under Second Round Review)*

Conference Publications:

1. **Y. Jiawei**, A. Paudel and H. B. Gooi, "Blockchain Framework for Peer-to-Peer Energy Trading with Credit Rating" *IEEE Power and Energy Society General Meeting 2019*, Atlanta, GA, USA, Aug. 4-8, 2019.
2. A. Paudel, **Y. Jiawei** and H. B. Gooi, "Peer-to-Peer Energy Trading in Smart Grids Considering Network Utilization Fees," *IEEE Power and Energy Society General Meeting (PESGM)*, Montreal, Ontario Canada, Aug. 2-6, 2020.

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