CONTROL AND AUTHENTICATION OF A FULLY DECENTRALIZED PAY-PER-USE ENERGY TRADING PLATFORM

BY

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ABSTRACT

This research aims to solve some problems related to blockchain peer-to-peer energy trading, which are purchased energy under consumption and transaction authentication and demand response control, which still rely on centralized schemes. The purpose of this thesis is to control and authenticate a fully Decentralized pay-per-use energy trading platform. It presents a blockchain-based peer-to-peer (P2P) energy trading platform where prosumers can trade energy autonomously and without interference from a central authority. Multiple prosumers can collaborate on energy generation to form a single supplier. Customers' electricity consumption is monitored via a smart meter connected to an IoT node connected to a private blockchain network. Smart contracts invoked on the blockchain enable autonomous trading interactions between parties and govern the behavior of accounts within the Ethereum state. The decentralized P2P trading platform uses autonomous usage-based billing and energy routing monitored by a smart contract. A Deep Learning-based Gated Recurrent Unit (GRU) model predicts future consumption based on past data collected on the blockchain. The predictions are then used to set Time of Use (ToU) ranges using the K-means cluster. The data used to train the GRU model is shared among all parties within the network, making the predictions transparent and verifiable. By implementing K-Mean clustering in a smart contract on the blockchain, the set of ToU is independent and unchallengeable. To ensure the validity of the data uploaded to the blockchain, a consensus algorithm is proposed to detect fraudulent nodes, along with a Proof of Location (PoL) to ensure that the data is uploaded by the expected nodes. To address the conflict of interest between prosumers and distribution system operators (DSOs) in decentralized P2P energy trading platforms, where prosumers seek to maximize their profit on the one hand, while DSOs seek optimal power flow (OPF) on the other hand, a novel fully decentralized architecture is proposed for an OPF-based demand response management system that uses smart contracts to force generators into compliance without the need for a central authority or hardware. The study details the proposed platform architecture, operation, and implementation. The results are presented mainly in terms of gas consumption of smart contracts and transaction latency for different loads. The work presented in the thesis is relevant in the sense that we have attempted to address a popular and important contemporary research issue related to blockchain technology. The research work holds great potential for industrial use. In the future era of renewable energy, decentralization of energy trading is a necessity for the future society.

خلاصة البحث

يهدف هذا البحث إلى حل بعض المشكلات المتعلقة بتداول الطاقة من نظير إلى نظير (P2P) على البلوكشين (blockchain)، والتي تتمثل في عدم الاستهلاك الكلي للطاقة التي تم شراؤها، ومصادقة المعاملات والتحكم في استجابة الطلب، والتي لا تزال تعتمد على طرق مركزية. الغرض من هذه الأطروحة هو التحكم والمصادقة على منصة تداول الطاقة اللامركزية بالكامل للدفع على حسب الاستخدام. إنه يقدم منصة تداول الطاقة من نظير إلى نظير القائمة على بلوكشين حيث يمكن للمستهلكين تداول الطاقة بشكل مستقل ودون تدخل من اي سلطة مركزية. يمكن للمستهلكين المتعددين التعاون في توليد الطاقة لتشكيل مزود واحد. تتم مراقبة استهلاك الكهرباء للعملاء عبر عداد ذكي متصل بعقدة إنترنت الأشياء المتصلة بشبكة بلوكشين خاصة. تتيح العقود الذكية والتي يتم استدعاؤها على بلوكشين تفاعلات تجارية مستقلة بين الأطراف وتحكم سلوك الحسابات داخل حالة ايثيريوم (Ethereum) .تستخدم منصة التداول اللامركزية P2P الفوترة المستندة إلى الاستخدام المستقل وتوجيه الطاقة الذي يتم مراقبته بواسطة عقد ذكي. يتنبأ نموذج الوحدة المتواترة (GRU) القائم على التعلم العميق بالاستهلاك المستقبلي بناءً على البيانات السابقة التي تم جمعها على البلوكشين .تُستخدم التنبؤات بعد ذلك لتعيين نطاقات وقت الاستخدام (ToU) باستخدام تجميع .K-mean تتم مشاركة البيانات المستخدمة لتدريب نموذج GRUبين جميع الأطراف داخل الشبكة، مما يجعل التنبؤات شفافة ويمكن التحقق منها. من خلال تنفيذ تجميع K-Mean في عقد ذكي على بلوكشين، تكون مجموعة ToU مستقلة وغير قابلة للطعن. لضمان صحة البيانات التي تم تحميلها على بلوكشين، تم اقتراح خوارزمية إجماع للكشف عن العقد الاحتيالية، إلى جانب إثبات الموقع (PoL) لضمان تحميل البيانات بواسطة العقد المتوقعة. لمعالجة تضارب المصالح بين المستهلكين ومشغلي أنظمة التوزيع (DSOs) في منصات تداول الطاقة اللامركزية P2P ، حيث يسعى المستهلكون إلى تعظيم أرباحهم من ناحية ، بينما يسعى DSOs للحصول على تدفق الطاقة الأمثل (OPF) من ناحية أخرى ، لهذا تم اقتراح بنية لا مركزية بالكامل لنظام إدارة استجابة الطلب المستند إلى OPF الذي يستخدم العقود الذكية لإجبار المولدات على الامتثال دون الحاجة إلى سلطة أو أجهزة مركزية. توضح الدراسة تفاصيل بنية المنصة المقترحة وتشغيلها وتنفيذها. يتم عرض النتائج بشكل رئيسي من حيث استهلاك الغاز للعقود الذكية وزمن انتقال المعاملات للأحمال المختلفة.

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APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole or any part of for any other degrees at IIUM or other institutions.

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Indeed, all praise is due to Allah, we praise Him, we seek His aid, and we ask for His forgiveness. We seek refuge in Allah from the evil of our actions and from the evil consequences of our actions. Whom Allah guides, no one can misguide, and whom Allah misguides, no one can guide. I bear witness that there is no god worthy of worship except Allah, and I bear witness that Muhammad is the servant and messenger of Allah.

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LIST OF ABBREVIATIONS

Aps	Access Points.
BG	Byzantine Generals.
CRNs	Cognitive Radio Networks.
DER	Distributed Energy Resources.
DLT	Distributed Ledger Technology.
DPoS	Delegated Proof of Stake.
DSO	Distribution System Operator.
ERD	Entity Relationship Diagram.
ETH	Ethers.
FBA	Federated Byzantine Agreement.
GPS	Global Positioning System.
GRU	Gated Recurrent Unit.
HR	Hash Rate.
IDE	Integrated Development Environment.
IoT	Internet of Things.
LBS	Location Based Services.
LP	Location Proof.
MAPE	Mean Absolute Percentage Error.
NEM	National Electricity Market.

NIST	National Institute of Standards and Technology.
OPF	Optimal Power Flow.
P2P	Peer-to-Peer.
PBFT	Practical Byzantine Fault Tolerance.
PL	Proof of Location.
PoB	Proof of Burn.
PoET	Proof of Elapsed Time.
PoI	Proof of Importance.
PoL	Proof of Location.
PoS	Proof of Stake.
PoW	Proof of Work.
PQC	Post-Quantum Cryptography.
RSA	Rivest-Shamir-Adleman.
RSSI	Received Signal Strength Indication.
SCP	Stellar Consensus Protocol.
SHA 256	Secure Hash Algorithm 256-bit.
T&D	Transmission and Distribution.
TEE	Trusted execution environment.
ToU	Time of Use.
UTXO	Unspent Transaction Output.

LIST OF SYMBOLS

CN_i	Consumer node i.
I_i	Current at node i.
K_j^{Pr}	Node j private key.
P_{G_i}	Active power injected at bus i.
P_{L_i}	Power load demand at bus i.
P_{ij}	Active power flowing in transmission line between nodes i and j.
Pl_0	Path-loss at a reference distance of $1m$.
Pl_T	Wi-Fi signal power transition.
$Pol\_Req_{i \to j}$	Target node i requests location proof from anchor node j.
Q_{G_i}	Reactive power injected at bus i.
Q_{ij}	Reactive power flowing in transmission line between nodes i and j.
R_{cst_i}	Independent constant in linear equation.
S_i	Net power injected at bus i.
$S_{i,j}$	Power flow between nodes i and j in a power network.
V_i	Voltage at node i.
W_c	Block mining power consumption.
X_{ij}	Reactance of transmission line between nodes i and j.
δ	Standard deviation (Section 2.1.2 in Chapter 3).
δ_i	Phase voltage angle.

γ	Path-loss exponent (Section 2.1.2 in Chapter 3).
λ	Lagrangian coefficients for different constraint functions (Section 2.1.3 In Chapter 3).
λ	Wave length of the emitted signal (Section 2.1.2 in Chapter 3).
a_i	Bus i generation cost quadratic function coefficients.
b_{ij}	Suceptance of transmission line between nodes i and j.
y_{ij}	Admittance of transmission line between nodes i and j.
y_{sh_i}	Shunt suceptance at bus i.
B	Bus suceptence matrix.
D	Current Mining Difficulty..
Gw	Gigawatt..
L	Lagrange function.
ND	Number of Devices used to mine a block..
P	Wattage of the mining device used.
TAv	Block average mining time.
Y	Bus admittance matrix.

CHAPTER ONE

INTRODUCTION

1.1 Background

Blockchain is the underlying technology of the most potential applications which has been gaining traction in recent times (Salimitari et al., 2020), (Bouraga, 2021), (J. Zhang et al., 2020). Blockchain network is a decentralized, distributed ledger technology where all nodes must agree on the validity of the ledger they are sharing, to ensure that any data included are perfectly valid; then, hence, after being committed to the blockchain, it is impossible to delete, deny or tamper with (Nofer et al., 2017). Blockchain is a transformation of the Byzantine Generals (BG) Problem, where at least two third of the network should be willing to maintain the integrity of the network so that impact of malicious parties can be nullified (Lamport et al., 2019). In order to agree on the new data (blocks to be added to the chain) and ensure trust in the system, the nodes must rely upon a consensus protocol. These algorithms are the backbone of blockchain, which in several ways determine the performance that such a system can achieve. Up to now, increasing attention has been paid with regard to many consensus protocols, and different cryptocurrencies implemented different protocols. Consensus algorithms in blockchain have been subjected to numerous research studies and are still opened to new ones. Despite the fact that the proposed algorithms endeavored to strengthen some of the existing weaknesses, they will witness new constraints. Some consensus protocols are intensively robust, while others will also lead towards centralization and trust issues whilst blockchain was created to avoid it (Monrat et al., 2019).

In a world where energy technologies and battery storage systems are rapidly improving, and the sharing economy seems to be disrupting every industry, many consumers are asking, why can't we trade energy? Peer-to-peer (P2P) energy trading looks to address just that question by enabling people to buy and sell energy to each other directly.

One of the main hurdles that prevents small-scale producers (prosumers) of renewable energy from engaging in exchange is regulation from the National Electricity Market (NEM).NEM requires that vendors on their market have a generator larger than 5 megawatts, which is equivalent to 5,000 5kW solar systems. If the cost of a 5kW system is approximately USD 10,000, then the cost of a system large enough to meet the NEM's minimum would be USD 50 million. This is significantly more than the vast majority of households can afford, creating a huge barrier to entry for homeowners with a small array of solar panels. However, with P2P energy trading, everyone from a 1.5kW solar system homeowner to the biggest coal-fired power plant can engage in peer-to-peer energy exchange.

On top of lowering the barrier to entry for many consumers, P2P energy trading would allow users to purchase energy from specific sources. This means that it would be possible to buy solar energy or energy produced specifically by your neighbor. By enabling P2P commerce, prosumers will be able to generate revenue on their excess energy and consumers will be able to obtain transparently-sourced, reliable energy. The hope is that by cutting out the middleman, prices will go down and more people may be incentivized to install solar panels and other types of renewable energy generators. Blockchain in P2P energy trading is illustrated in Figure 1.1 (Saxena, 2019)

There are three main options for P2P energy trading:

- Trading through the power grid: in this option, a consumer remains associated with a central power grid and administer price and volume risk in an independent fashion, by selling or buying energy directly to other parties. The main benefits are the low upfront investment required by the P2P trader, the savings in subscription premiums billed by an energy retailer, the mindfulness and control of the consumption profile (peak shaving), the 100% certainty of purchasing green energy, and finally, the reduced vulnerability to market fluctuations as seen in the fall of 2021.
- Partially independent microgrid: In this constellation, participants build a microgrid that manages part of the total energy demand, but remains connected to the central grid for a remaining portion of the required capacity. An example of this is the Schoonschip Amsterdam microgrid. In this community-managed microgrid, electricity is traded among residents while the community remains connected to the grid for redundancy.

This encourages participants to balance each other's profiles and reduces the need for centralized grid investment. The investment cost for the parties involved is higher than trading over the grid, but the savings are also much higher. One trend is that partially independent microgrids are emerging in industrial clusters. For example, P2P platforms have been established in shipping ports around the world, such as the Port of Rotterdam and the Port of San Diego.

- Fully independent microgrid: In this constellation, multiple participants create a private, fully self-sufficient power grid that is not connected to the central power grid, and the parties transact through a P2P platform. In this case, the investment for the participants in the initiative, as well as the associated savings, are higher than in the other two concepts. However, given the current cost of energy storage and the maturity of microgrid technology, it is unlikely that this concept will catch on. It is more likely that consumers will first explore grid trading and partial independence from the electric grid in the coming years until the technology matures enough for this concept to become mainstream. The industry of P2P trading platforms is quite young but some players have already reached substantial communities of peers. An example of a P2P energy trading platform that can enable the three set-ups is *ENTRNCE* (2019). The platform was introduced in 2017 and currently handles transactions for over 10.000 peers on a daily basis. *ENTRNCE* (2019) facilitates all three set-ups and is an independent and fully automated (electricity) transaction platform for direct transactions between producers and