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A Blockchain-Based Distributed Hybrid System for Tracking Power Distribution in Electrical Power Systems

By

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114848

A Thesis Submitted to the Faculty of Information Technology at Strathmore University in partial fulfilment of the requirements for the award of Master of Science in Information Technology.

Master of Science in Information Technology

Strathmore University

December 2021

Declaration and Approval

I Raphael L. Kimiti declare that this research has not been submitted to any other University for the award of a Degree in Information Technology.

Student Name: Raphael L. Kimiti

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Sign: ______________________ Date: 21st September 2021

Abstract

Power distribution systems carry power the last few miles from transmission or sub-transmission to consumers through wires either on poles or underground. These systems encounter perpetual issues of power losses, and they have little or no real-time monitoring of power flow. These challenges represent a significant challenge of electricity use. The aim of this research is to develop a blockchain-based distributed hybrid system for real-time tracking of power distribution in electrical power systems. The study devised a solution that can aid in power re-routing to end-users in the distribution grid in case of transformer failure. The solution consists of a blockchain-based platform to help re-route power in the cases of any power outage and blackout and relaying the relevant information regarding the cause of the disturbance to the utility center in real-time. The rapid application development methodology was used for this study because it offers a quick and flexible way to discover and validate the idea and facilitates easy incorporation of changes to the prototype. The results of this study show that continuous power availability to end-users is achieved through the application that has been developed using blockchain. The proposed solution can enable industries, residences, and other end-users to benefit from having reliable and uninterrupted power flow. In conclusion, it is expected that the proposed solution will improve grid access which in turn can eliminate unpredictable outages. By using the proposed solution, power distribution companies can easily monitor the grid and have quality supplies to end-users.

Keywords: Distribution, Blockchain, Power, Transmission

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List of Acronyms

P2P	Peer-to-Peer
PDP	Power Distribution Planning
PoW	Proof of Work
PoS	Proof of Stake
PoA	Proof of Authority
IoT	Internet of Things
RAD	Rapid Application Development
UML	Unified Modeling Language
SU-IERC	The Strathmore University Institutional Ethics Review Committee

Chapter 1: Introduction

1.1 Background

The electricity we consume globally comes mostly from massive electric plants that travel over long distances before the final consumer can use it. The lengthy distances, mainly on a single-way transmission, increases vulnerability to power loss. The power loss or disruptions bring exposure to power supply reliability. The leading cause of power outage is a system disturbance that occurs in the transmission lines and transformers. This has led to a desire to adopt distributed bidirectional transmission lines by modern electrical power systems to improve system efficiency, reliability, and power quality (Specht, 2020).

According to Paynter and Boydell (2011), the distribution grid refers to the electrical grid's final stage, which takes power to residences, industries, and any users at the end of the chain. In addition to distributing power to users in the system, it also revamps safety consumption among users. The consumption safety is achieved using step-down transformers that bring electricity voltage levels to safe use levels by the consumers. The power distribution system comprises transformers, power lines, protection circuits, and switching circuits that enable power distribution safety.

According to Sr (2013), the distribution grid is distinguished from the transmission grid by its voltage and network topology. The grids for distribution have a radial type of topology where power moves from a single way from the substation to the intended load. This is why they are called star networks. Other distribution grids have a circular topology that has double power movements between the substation and load.

Electric power systems worldwide are characterized by operating from a central system by relevant bodies. They are responsible for controlling electricity spread in grids. They manage delivery and electric yield schedules, which usually move in a single direction until they reach the final consumers. For this case, the final consumers have little control over the power use, and the operating system has depended on the generator's flexibility to deliver the power to the final consumers. Additionally, system operators have had minimal real-time information about the operation of the power grid, especially the equipment on the distribution grid closest to end users and the real-time usage of customer devices. This is a common phenomenon observed globally, but there have been changes in the past years that are promising (Livingston et al., 2018).

Over the year's power system reliability have been critical issues, the most crucial factor is interrupting power flow to the residential, industrial or any other end users (Kepka, 2015). Power reliability has been one of the significant challenges faced by the power distribution grid due to the electric grid's hierarchical structure. The electric grid's hierarchical nature can be redesigned to a flat design by applying blockchain technology.

Blockchain is an in-depth system that incorporates many kinds of technologies. This system includes cryptography, distributed data store, consensus mechanism, and smart contracts. Blockchain is a new technology for redistribution, reckoning, and storage of data that is very well secured with consensus mechanisms (Münsing, Mather & Moura, 2017). For this, blockchain system has high maintenance, transparency, and decentralization. This helps coordinate energy consumption, production, and storage to increase usage needs (Zhu, 2019). Blockchain has shown strong capabilities of revamping centrally operated systems.

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1.2 Problem Statement

There are lots of challenging issues in power distribution systems. The most key ones are power quality, reliability, protection and grounding. Reliability in this context is frequent power outages and blackouts persistence and, whether the fault is with generation transmission or distribution, they represent a significant challenge for electricity expansion and use (Taneja, 2017).

According to Taneja (2017), the power distribution network, particularly at distribution levels, has little or no real-time monitoring to the point that it relies on customers calling to report a fault. Majority of utilities monitor the condition of high transmission lines while distribution lines often go unmonitored, and outages go unreported until unhappy customers contact the utility directly. Therefore, that consistent reliability of electricity remains a major problem. The few existing automated control systems also have very limited remote-control capabilities.

In this study, the focus is on solving this challenge of power reliability and monitoring of distributed grid. A blockchain enabled distributed hybrid distribution system is proposed to address the challenges. Blockchain technologies has a potential of solving this challenge since its application in power distribution system can create a self-healing grid by embedding grid devices with smart contracts. The smart contracts automatically enable real-time identification and resolution of anomalies in grid operations.

1.3 Aim

The aim of this research is to develop a blockchain-based distributed hybrid system for real-time identification and resolution of anomalies in power distribution grids.

1.4 Specific Objectives

i) To investigate the current challenges facing power reliability on distribution grid

ii) To analyze the existing techniques, models and approaches of guaranteeing reliability in power distribution

iii) To develop a distributed architecture for real-time identification and resolution of anomalies in power distribution grids.

iv) To test the proposed solution

1.5 Research Questions

i) What are the current challenges of power reliability in the distribution grid?

ii) What are the current techniques, models and approaches of power distribution?

iii) How can a distributed architecture for real-time identification and resolution of anomalies in power distribution grids be developed?

iv) To what extent does the proposed hybrid architecture improve power supply reliability?

1.6 Justification

One of the key causes of power outages is system disturbance in the transmission lines either within the distribution grid or transmission grid, this has a negative impact on power reliability within the grids. Creating a distributed grid using blockchain technology can help in countering the negative impact.

Majority of utility distributor's strategies are improving power supply quality and reliability, increasing grid access through a continued connectivity process, and sustained technical and non-technical energy losses. This study helps in adoption of blockchain technology in distribution grids which in turn improve the power supply reliability and eliminate unpredictable outages.

1.7 Scope and Limitation

This study acknowledges that there exist power transmission lines in both transmission grid and distribution grid for reliable power supply, its aim is to focus only on distribution grid. In the interest of time, the study focuses on creating a blockchain distributed hybrid distribution grid. This study only focuses on the smart contracts, distributed ledger, cryptographic aspect of blockchain technology.

Chapter 2: Literature Review

2.1 Introduction

Blockchain technologies have shown great potential to help the energy industry in planning, operation and numerous controls, planning. These technologies enable distributed-shared database which is safe, cheap, transparent, and autonomously enables the distribution of power. (Adeyemi et al., 2020).

2.2 Power Distribution Grid

The distribution grid links consumers and the significant sources of power (Donev et al., 2020). This is the last step in the grid that makes it possible for energy to reach residences, manufacturing plants, and other final consumers.

The beginning of the distribution grid is at the distribution substation supplied by single or numerous sub-transmission lines. At times the distribution substation receives high voltage directly from the power transmission lines. This changes with the company involved. Each distribution substation ensures one or more primary feeders receive power. In most instances, the feeders are radial, simply because of the presence of a single path for power to reach the end consumer from the substation (Kersting, 2017).

Not only does the distribution grid supply power to consumers, but also it decreases the voltage to secure consumer-usable levels. In this scenario, the step-down transformers reduce the electric voltage to safe levels, usually between 100 and 400 volts. The distribution grid comprises poles, transformers, lines, and protection and switching circuits vital to the supply of secure power. Figure 2.1 shows a typical distribution grid component, flowing from left to right (Galloway & Gill, 2017).

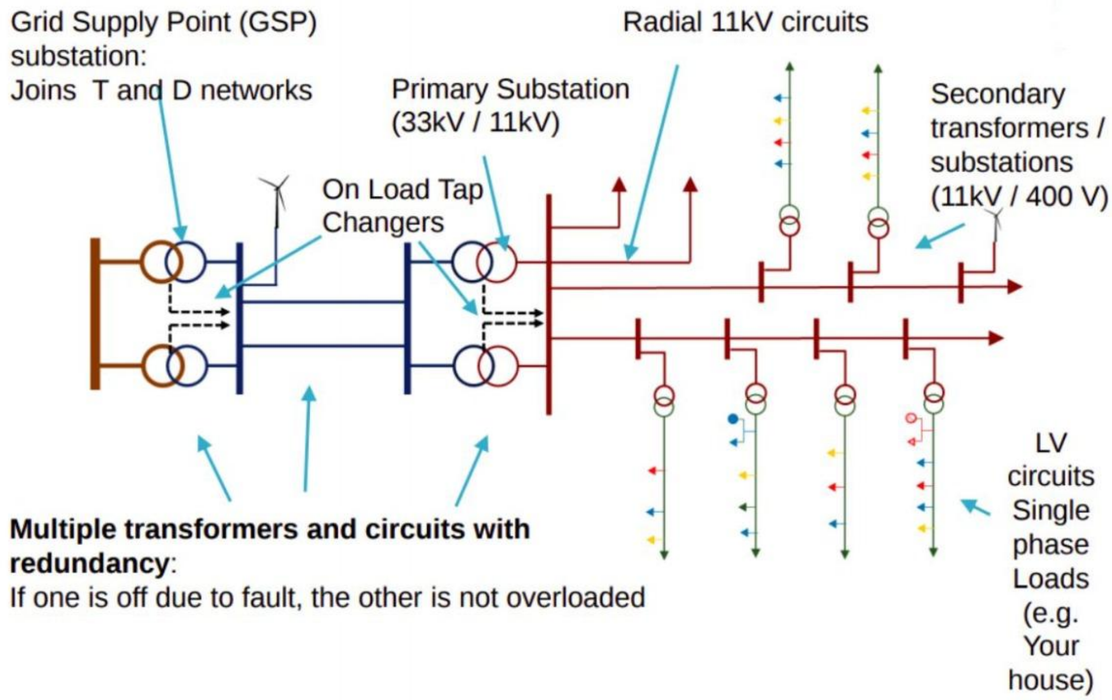

Figure 2.1: Distribution Grid (Galloway & Gill, 2017).

2.2.1 Power Distribution Substation

Substations are found everywhere in the power grid, starting from the power plants to the distribution grid. Those close to the power production have step-up transformers that increase the electric voltage and, in the process lower the loss of electricity while being distributed. The step-down transformers reduce electric voltage to enable safe connection with sub-transmission lines to the lines for distribution while approaching the distribution station. The distribution transformers receive the stepped-down voltage through the feeder conductors. Hence substation serves one or more radial distribution feeders (Daware, 2017).

Figure 2.2 shows a more comprehensive substation layout. This substation has double load-tap changing transformers, serves four distribution feeders, and is fed from two sub-transmission lines. Under normal conditions, the circuit breakers (CB) are in the following positions:

Circuit breakers closed: X, Y, 1,3,4,6

Circuit breakers open: Z, 2,5

The arrangement of breakers ensures that transformers can receive power from divergent sub-transmission lines and double feeders. By any chance, if one sub-transmission line becomes faulty, then breaker Z will shut, and X or Y will open. This way, one sub-transmission line can serve two transformers. “The transformers are sized such that each transformer can supply all four feeders under an emergency operating condition. For example, if Transformer T-1 is out of service, then breakers X, 1, and 4 are opened, and breakers 2 and 5 are closed. With that breaker arrangement, all four feeders are served by transformer T-2. The low-voltage bus arrangement is a “breaker-and-a-half scheme” since three breakers are required to fill two feeders” (Kersting, 2017).

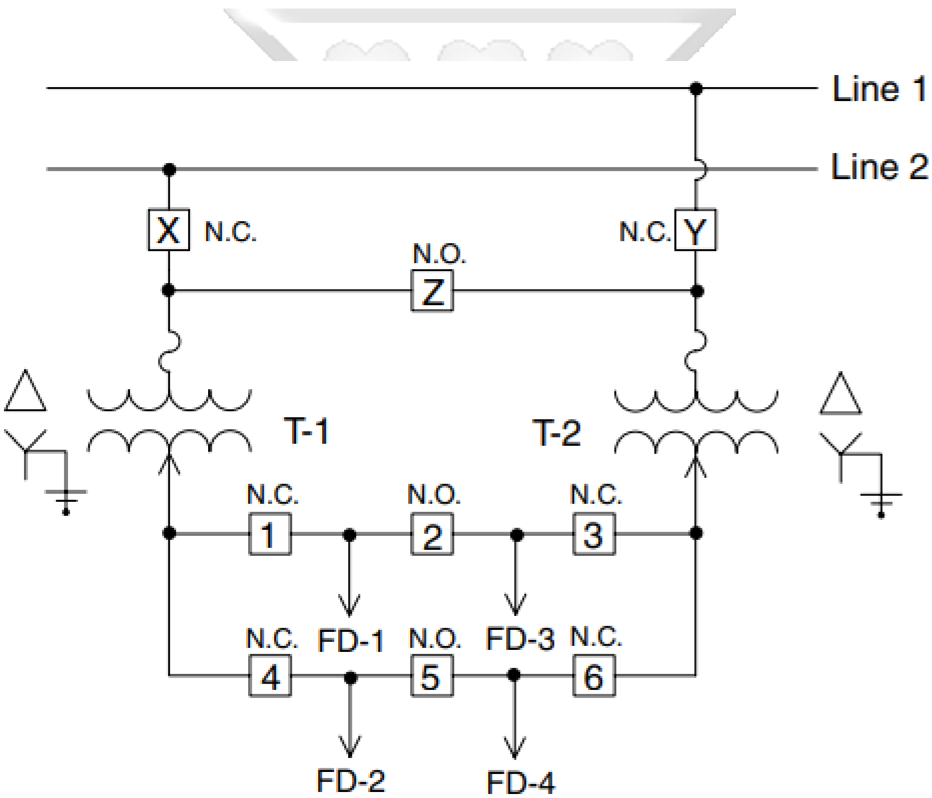

Figure 2.2: Two-transformer substation (Kersting, 2017)

2.2.2 Power Distribution Feeders

According to Csanyi (2018), “a feeder is a conductor that connects the substation to the area where power is distributed. They are referred to as radial feeders since they are characterized by having only one energy path to flow from the source: distribution substation to each customer.”

Generally, no tapings are removed from the feeder, making the current stable all through (Kersting, 2017).

The loading of a distribution feeder is inherently unbalanced because of the large number of unequal single-phase loads that must be served. An additional unbalance is introduced by the nonequilateral conductor spacings of three-phase overhead and underground line segments (Kersting, 2017). Figure 2.3 illustrates the major components of a distribution feeder. The connecting points of the features will be referred to as "nodes."

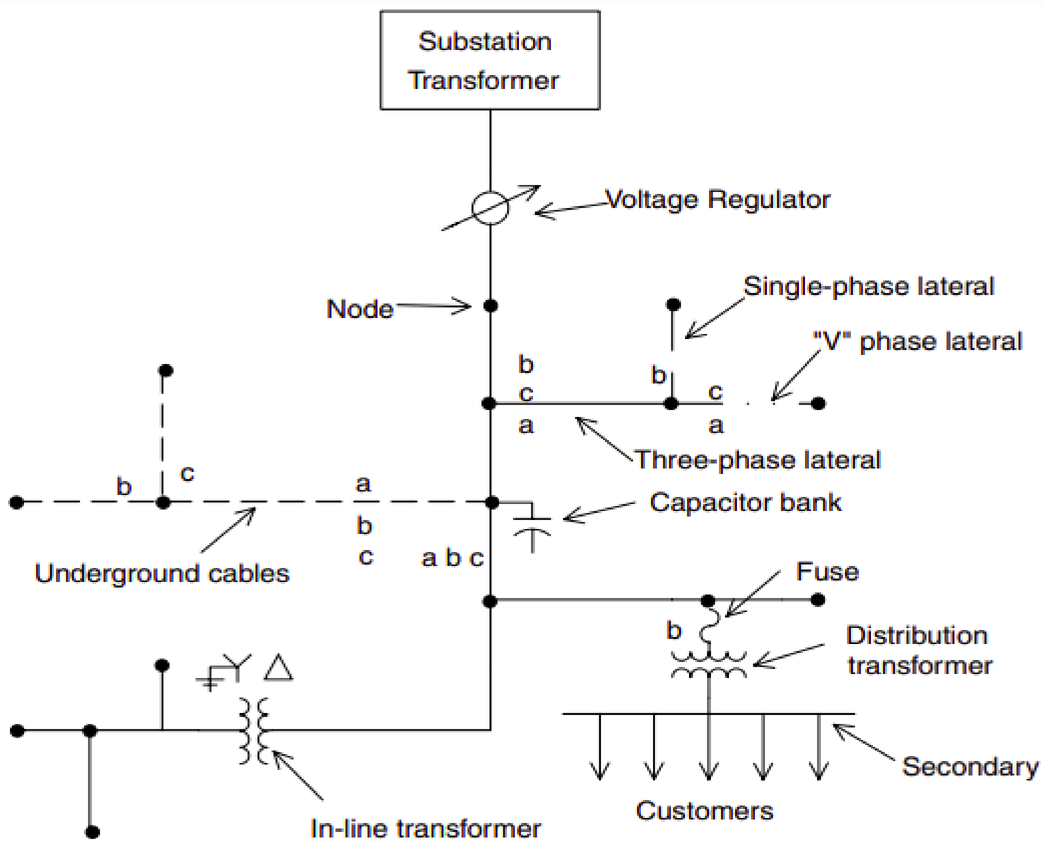

Figure 2.3: Distribution Feeder (Kersting, 2017)

2.2.3 Power Distribution Transformer

The distribution transformer is a step-down 3-phase transformer, which pumps power through the system up to the end users. It steps down the voltage to 400Y/230 volts. Here it means, voltage between any one phase and the neutral is 230 volts and phase-to-phase voltage is 400 volts (Daware, 2018).

2.4 Power Distribution Models

Distribution systems should operate at their maximum capacity. “This is because most of the distribution power demands are domestic, industrial, or commercial loads. The power consumed by these loads may vary according to voltage or frequency deviations from their rated values" (Kersting, 2017). The load of the distribution network is constantly changing due to the variations of consumer demands. This makes limitations quite challenging to model in relation to load changes and variations in the days or seasons. Thus, it is crucial to precisely make and analyze systems for distribution. The main classifications of loads are in static and dynamic models.

2.4.1 Static Model

A static load model expresses the active and reactive powers as a function of the voltage (magnitude and/or frequency) (Lindén & Segerqvist, 1992). The load model could be a stationary or quasi-stationary representation of the load. The model is not dependent on time, it describes the relationship of the active and reactive power at all times to the voltage and/or frequency. This model express loads as a voltage magnitude function and considers only voltage – depended characteristic.

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2.4.2 Dynamic Model

The dynamic load model describes the time dependence as well as the voltage dependence of the load (Lindén & Segerqvist, 1992). The load model varies with time, it expresses the relationship of the active and reactive power at any instant of time as a function of the past history of voltage and/or frequency. These models represent variation of the load with the frequency and considers both voltage-dependent and frequency dependent characteristics.

These two main classifications are mainly described as Wye and Delta connected loads. Wye systems utilize a star configuration, with all three hot wires connected at a single neutral point. One neutral wire and one ground wire make for a total of five wires in 3-phase Wye systems.

The Delta configuration has the three phases connected like a triangle. Delta systems have four wires total: three hot wires and one ground wire. Each of these loads can be represented as being connected phase-to-neutral or phase-to-phase in a four-wire Wye system or phase-to-phase in a three-wire delta system (Radwan et al., 2020). The loads can be three-phase, two-phase, or single-phase with any degree of unbalance, and can be modelled as:

i. **Constant Power Load Model (Constant P)**

At this model there are no variations of power with changes in the voltage magnitude. The reactive and active forces are self-supporting from the changes in the volume of the voltage. The energy used by the load is unproportionally to the changes in voltage. It is also known as the constant real and reactive power (Constant PQ) model.

ii. **Constant Current Load Model (Constant I)**

In this model, power use is directly proportional to the magnitude of the voltage. That is, the reactive and active capabilities vary proportionally with the magnitude of the voltage. The internal resistance of the load varies to bring about a continuous flow of the current.

iii. **Constant Impedance Load Model (Constant Z)**

In this model, the power used is proportional to the magnitude of the voltage squared. The method has undergone to identify and locate faults around the distribution system. There are two types of methods that have been used, namely: artificial intelligence and conventional techniques. The methods can be divided into two categories, traditional and synthetic intelligence techniques. The model is also called the constant admittance load model.

2.5 Power Distribution Techniques

The primary goal of power distribution techniques is to design a distribution system that meets energy demand in the most reliable, economical, and safer way within a short time. There are two main categories of methods used in the power distribution grid: numerical techniques and heuristic techniques discussed in Table 2.1 and Table 2.2.

2.5.1 Numerical (Traditional) Techniques

Table 2.1: **Numerical Methods (Daiva et al., 2017)**

Numerical method	Specific features of the methods
Mixed Integer Linear Programming, (MILP)	A multi-level problem for the development of power distribution is presented as a problem of mixed integer linear programming, which is addressed through the branch-and-bound algorithm and (or) standard commercial programs. Integrated programming methodology for primary and secondary distribution systems is formulated and the related problems are solved by means of the MILP. MILP is also used for spatial energy distribution programming and solution of the related problems [7].
Nonlinear Programming (NLP)	The power distribution scheduling based on the mixed-integer NLP (MINLP) is performed through Benders decomposition. The dynamic power distribution is scheduled under two interrelated models whose solution is accordingly based on MILP and NLP methods [7]. Weaknesses of the method are that it is difficult for some complex industrial systems to create a nonlinear mathematical model, to handle "qualitative" and/or "incomplete" information and knowledge.
Dynamic Programming (DP)	DP helps solve multi-stage and multiple power distribution scheduling problems [7]. The method is advantageous, because it may be adapted to different types of tasks and can help jointly address deterministic and stochastic problems. However, it is disadvantageous, because it is not always easy to notice the option for the application of this method, and it is not suitable for solving large problems.
Ordinal Optimization (OO)	This optimization method allows to simultaneously optimizing power distribution scheduling and programming of charging stations for electric vehicles [7].
Direct Solution (DS)	The route of optimal power line is selected through the direct method, depending only on the determination of radial trajectories and calculation of appropriate costs [7].
Mixed Integer Nonlinear Programming, (MINLP)	In 2005, El-Khattam *et al.* proposed an integrated model to solve the problem of distribution systems by implementing a distributed generation as an attractive choice in the selected areas. All the objective function uses the formulation of a supply chain model. It is aimed at reducing investment and operating costs of distributed generation, costs for purchasing additional power required by the distribution network and companies, the total system loss compensation costs incurred during the scheduling period and other costs according to other likely scenarios. It is difficult to deal with MINLP, because it includes all the problems of integer linear programming (ILP) and nonlinear programming [16]. Advantages of the method is the high accuracy rate – the computational time efficiency.

The numerical methods have the following advantages: the optimal solution is usually accurate and the time to compute the optimal solution is low. On the other hand, the numerical methods have the following disadvantages: it is difficult to manage power system equations into an optimization model; in order to insert a new constraint, the optimization model has to be rearranged and new equations have to be added (Georgilakis & Hatziargyriou, 2015).

2.5.2 Heuristic (Artificial Intelligence) Techniques

Table 2.2: Heuristic Methods (Daiva et al., 2017)

Method	Specific features pf the methods
Genetic algorithm (GA)	This method is used for solving the problem of power distribution scheduling. Power distribution scheduling is carried out by means of a genetic algorithm together with a pseudo-Newton method, optimal power flow, and branch exchange. Using a balanced genetic algorithm with data envelopment analysis, the multi-stage power distribution scheduling problems, which are characterized by uncertainty, may be solved. Genetic algorithm, used in conjunction with graph theory, helps solve the power distribution scheduling problems with regard to the relationship with a distributed production. GA may be used to solve two problems: (1) problem of optimal MV substations and (2) problem of selection of optimal location for HV substation and power line route. The interior point method, inserted in the discrete genetic algorithm, helps to optimize the localization of distributed generation and smart metering, at the same time strengthening the network [7]. The weaknesses of the method are limited areas of use, a large amount of genetic algorithm parameters.
Tabu Search (TS)	TS algorithm is used to find the optimal solution for the operation of the distribution network; initial population, which must comply with the set limitations, is randomly selected. The strength of TS is that it reduces the need for data pre-treatment [19]. The weaknesses of the method are the following: it is relatively difficult to encode due to the adjustment of a number of parameters, low accuracy factor.
Particle Swarm Optimization (PSO)	PSO is a population-based stochastic optimization method. PSO as an optimization measure provides for a population-based search procedure, in which individual particles, after a certain period of time, change their position (state) [20]. PSO is an iterative algorithm, where particles are flying in multidimensional search space within the system. When flying each particle adjusts its position according to its own experience (this value is known as the local best) and according to the experience of adjacent particles (this value is known as the global best) and chooses the best position [21]. The strengths of the method are the following: it is easy to encode with several equations, as well as find examples in the literature. The weaknesses are the following: relatively poor quality in finding the global optimum, few examples in the literature.
Evolutionary Algorithm (EA)	EA is a population-based metaheuristic optimization process that converges to the global optimum solution with the unit probability up to a finite number of evolution stages according to the solutions of a finite set. EA is not applicable to find solutions for energy management problems [22]. EA, as well as GA and PSO, is used to solve many world optimization problems. The strengths of the method are the following: it is effectively used for finding the global optimum, it is easy to find examples in the literature, whereas the weaknesses are the following: it is hard coded, early convergence, the possibility of favourable conditions for trap location, low accuracy rate.
Ant Colony System Algorithm (ACSA)	Using ACSA, the most optimal network restructuring may almost be achieved [23]. The strengths of the method are that it is easy to understand and encode. The solutions are enhanced by taking one step when calculating probabilities, whereas the weaknesses are the changes in the probability distribution from iterations, uncertain time for convergence, few examples in the literature.
Bacterial Foraging (BF)	This method solves the problem of optimal power line routing [20]. This algorithm has been developed by monitoring the behavior of bacteria to find food sources, because they understand and feel certain chemical compounds which make them decide whether to move toward or away. The strengths of the method are that it is possible to find new solutions according to the removal and dissipation, short calculation time, and the search space dimension.

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Heuristic methods are based on how computer systems can simulate intelligent processes, such as learning, reasoning and understanding specific information (Daiva et al., 2017). Heuristic methods are easy to use and they do not require the conversion of the power system model into an optimization programming model. Moreover, heuristic optimization methods are usually robust and provide near-optimal solutions for complex, large-scale power distribution system problems; however, there is no guarantee that they will find a global optimum solution. Generally, they require high computational effort; however, this is not necessarily critical in PDP applications (Georgilakis & Hatziargyriou, 2015).

2.6 Blockchain

Blockchain is a ledger that distributes transactions that have been made and shares them with all participants in the network. All participating nodes have their copy of the ledger. Transactions in the public ledger undergo verification by consensus, and it involves approval from most participants in the network. Blockchain is made up of blocks of stacks that ensure data from a single block is connected in a sequence that connects the previous block. Blockchain blocks are made up of a body and header. The establishment of linkage makes it possible to store data in the block body while the block header ensures that hash functions of the current and previous blocks are stored in it, as illustrated in Figure 2.4. The hash functions use numerical strings and letters that give a unique address for a given block (Adeyemi et al., 2020).

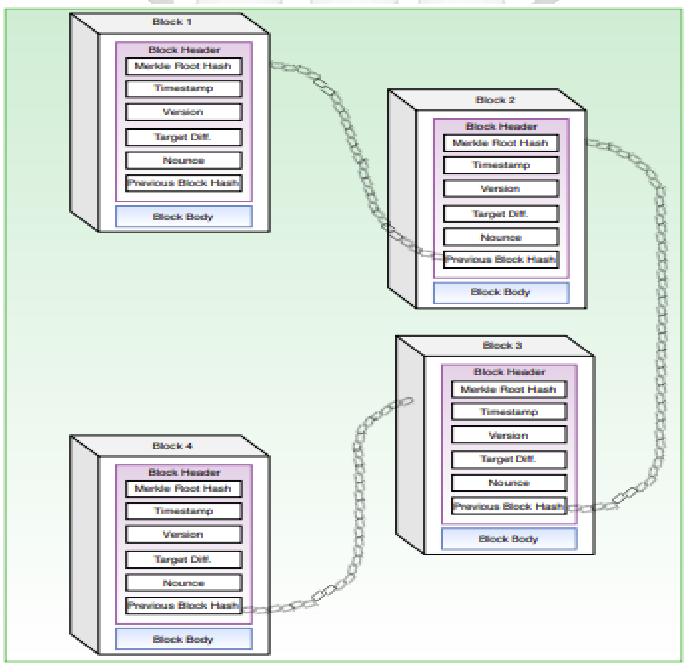

Figure 2.4: Blockchain (Alladi et al., 2019)

2.6.1 Key Blockchain Technologies

Blockchain incorporates a wide range of technologies together. As shown in Figure 2.5, it includes critical technologies such as encryption algorithms, consensus mechanisms, distributed data storage, and smart contracts (Wu & Tran, 2018).

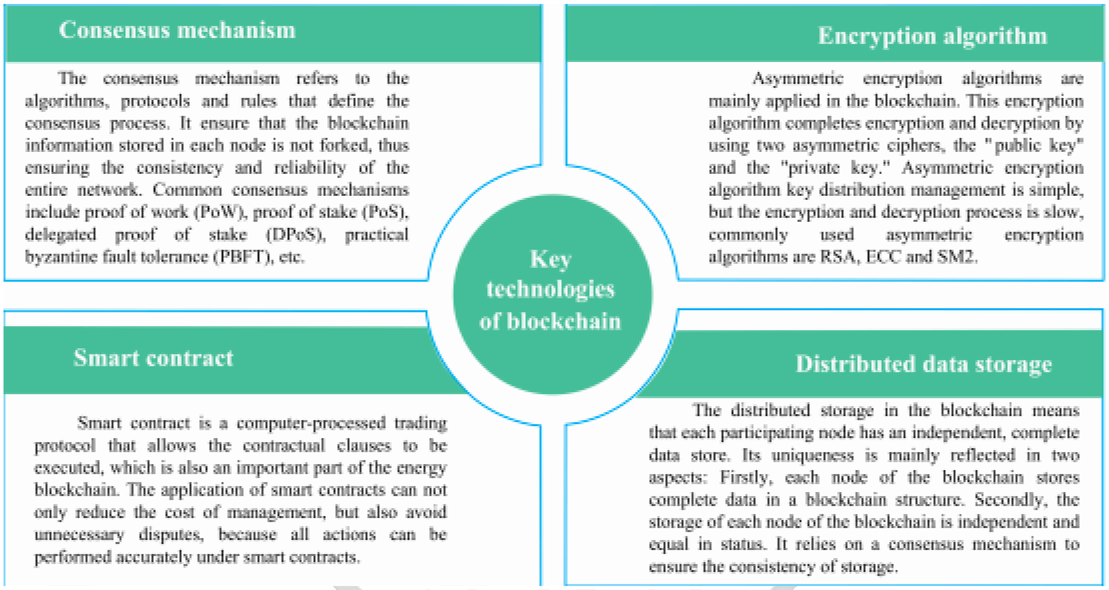

Figure 2.5: Key Blockchain Technology (Wu & Tran, 2018).

2.6.1.1 Consensus Mechanism

Consensus is the process of keeping ledger transactions synchronized across the network. A single participant cannot, on its own, update the ledger; it requires the consent of the other participants in the network. A participant requires other network participants to approve a ledger update before it can be applied to a participant's local ledger. A consensus mechanism helps participants determine the validity of the data blocks' legitimacy (Adeyemi et al., 2020). Therefore, consensus mechanisms refer to the rules, algorithms, and protocols that defines the process of consensus. This process ensures the appropriate participants approve the transaction.

The consensus algorithm is the mechanism through which a blockchain network reaches consensus. They ensure rules in the system are firmly adhered to, and there is trust in every transaction in the system.

Types of consensus algorithms

i. **Proof of Work (PoW)**

The Proof of Work (PoW) was the first consensus algorithm to be developed and is used by

Bitcoin and other cryptocurrencies first used the PoW algorithms that help bring consensus in their system. (Mollah et al., 2020). The PoW helps in the mining of cryptocurrencies. The miners who are participants in the network have a role to perform validation of new data blocks. They are also responsible for bringing new blocks to the network after solving sophisticated puzzles in mathematical form. The first miner to solve the puzzle becomes the validator, enabling them to add data blocks into the blockchain. This algorithm only validated new transactional blocks added in the network after being agreed by the participants' consensus and is found to be valid. PoW has its drawbacks; high energy consumption while mining and the possibility of a monopolize if a single participant has at least 51% of computational power in the network (Mollah et al., 2020).

ii. Proof of Stake (PoS)

This consensus algorithm was made in 2011 to ensure that it works best to solve challenges arising from PoW. Both algorithms accomplish the same goals and have differences in their particularities and fundamentals during the validation of new blocks.

The PoS consensus algorithm brings a new validation method based on the participant's stake, which is different from the PoW mechanisms. Here, every block's validator is based on the cryptocurrency investment rather than the computational might allocated. Every PoS system performs implementation in its unique way. The blockchain's security is done through a process called a pseudo-random election based on the age of the coins and the wealth of the node using randomization factoring. PoS is cheaper, faster, and uses little energy mainly because participants don't solve puzzles in this algorithm. The challenge is that this algorithm gives the stakeholders with more wealth high probabilities to be validators. This makes it unsuitable for those participants with little wealth, and it becomes unfair to them (Adeyemi et al., 2020).

iii. Proof-of-Authority (PoA)

This algorithm has a very close resemblance to PoS. This algorithm uses a pre-selected group of validators tasked with securing the network and producing new blocks. There can only be an introduction of new blocks after a vast majority of validators are in consensus.

2.6.1.2 Smart Contract

Smart contracts are scripted programs having rules for guidance and are usually stored in blockchains (Adeyemi et al., 2020). If all sets of rules have been fully adhered to, the smart contract's self-execution starts until it completes. Upon completion, it becomes part and parcel of the blockchain and is inseparable.

They are programs that contains the logic functions of a blockchain business network. The program runs in a container that is detached and isolated from peer containers. A smart contract typically handles business logic that was agreed to by members of the network.
State that is created by a smart contract is scoped exclusively to that smart contract and cannot be accessed directly by another smart contract. However, within the same network, given the appropriate permissions, a smart contract may invoke another smart contract to access its state.

2.7 Blockchain Classification

According to Tan and Chan (2016), there are three variations of blockchain, that is private, public and consortium blockchain.

2.7.1 Public Blockchain

This network is available to every participant because of their open-source databases. In this blockchain, every member can read the stored data and become part of the validators.

2.7.2 Private Blockchain

In this case, some organizations own and control the blockchain. They only give access to the blockchain to participants that are trusted and certified. The participants can manage their data without showing it to the public. This blockchain gives participants the authority to do validation and record data, usually at supersonic speeds, and reduce resource consumption. Proof-of-Authority (PoA) is used chiefly as a consensus mechanism for this type of blockchain.

2.7.3 Consortium Blockchain

Consortium blockchains, also known as integrating private and public blockchain, give organizations with authorization credentials to become part of the consensus and perform data writing. Stored data in the consortium is then divided into two classes, namely public and private data. The private data is made accessible to it managing entities, while public data can be accessed by all authorized network participants. The participants can determine which data to go public and which one to be stored privately.

Table 2.3 compares the public chain, the consortium chain, and the private chain in terms of openness, write access, read access, anonymity, transaction speed, and decentralization (Wu & Tran, 2018).

Table 2.3: Blockchain Classification (Wu & Tran, 2018)

Parameter	Public Blockchain	Consortium Blockchain	Private Blockchain
Receptivity	Fully open	Open to some nodes	Open to a person/entity
Access to Write	Anyone	Specific nodes	Internally controlled
Access to Read	Anyone	Anyone	Open to the public
Obscurity	More	Less	Less
Speed of Transaction	Low	High	Extremely high
Decentralization	Fully decentralized	Less decentralized	Less decentralized

2.8 Blockchain Characteristics

Blockchain has numerous characteristics that distinguish it from other technologies. They include:

i. Decentralized: eliminates the need for management in a central way of the transactions in the network.
ii. Resilience: blockchain is decentralized, preventing it from attacks.
iii. Saves time: transactions are done quickly because they do not require intermediaries.

iv. Reliable: the blockchain ever recorded data history has never been changed all through its life which gives assurance to participants.
v. Prevent fraud: courtesy of the information sharing and consensus agreements, there is the security of users in the network, and no one can defraud.
vi. Security: attacks on the network are impossible because it has been architecturally distributed.
vii. Transparency: any change made or transaction is visible to the users in the network.

2.9 Application of Blockchain in Power Distribution Grid

Blockchain technologies application on power distribution systems can offer interconnection at extensive scales, fast interaction, intelligent decision making, and open data (Zhu, 2019). The use of blockchain for distributed power systems can make it possible for autonomous rerouting of power when blackouts or equipment fail. This will lower the number of blackouts and reduce the power grid's adverse effects (Adeyemi et al., 2020). Figure 2.6 summarizes numerous different applications of blockchain technologies to power distribution systems.

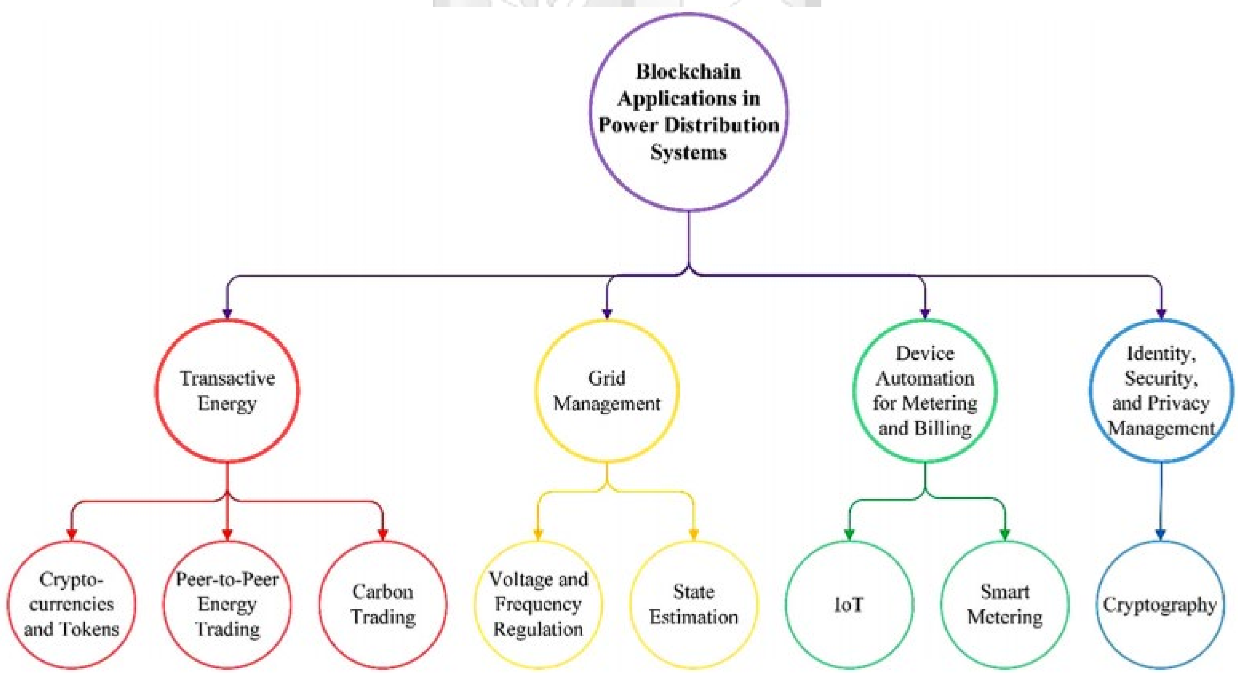

Figure 2.6: Blockchain Application in Power Distribution Grid (Adeyemi et al., 2019)

2.9.1 Transactive Energy

Transactive energy is a system that allows people on the grid to trade electricity amongst themselves. The energy network is decentralized. The transactive energy structure can make interactions between the energy production and energy consumption. There is communication between the two ends (Huang et al., 2021). In addition, transactive energy allows the systems in place to communicate and allow energy data to be shared while in operation. It is advantageous over conventional energy systems because it improves consumer satisfaction, lowers costs, and utilizes grid assets better.

2.9.1.1 Peer-to-Peer Energy Trading

Peer-to-peer (P2P) energy transactions can be made possible in numerous ways. Blockchain technology is proving to be the best solution to make it possible for P2P energy transactions to happen in this industry (Sabouchi & Wei, 2017). Incorporating this technology will wipe out intermediaries in this market. This will make it possible to make the market a trading platform that enables P2P trading. To make it a reality, many pilot projects and studies have been done on the blockchain regarding peer-to-peer trading.

There are different P2P platforms in different countries. They have varying details. Mengelkamp et al. (2018) came up with a new blockchain that focused on energy. The project resulted in the formation of the Brooklyn Microgrid. The platform allowed members to have the ability to purchase or sell energy amongst themselves. The smart contract enabled this blockchain to be able to operate.

Another P2P platform is the Centrica PLC in the United Kingdom. The project differs from the Brooklyn Microgrid in how it operates. Centrica started to create an energy market in Cornwall. The project tests flexibility of demand, generation and storage, and rewards energy consumers with higher flexibility. All transactions are performed in a virtual market digitally. Here the flexible energy capacity both wholesale and grid are sold. Centrica uses local energy solutions (LO3's) blockchain-powered energy trading platform (Centrica, 2018).

In the United Kingdom, there is another P2P trading platform called Piclo. Piclo is unique in that it can match prosumers and consumers according to what they need. The matching is done after every half an hour. The customers are given consumption data visualizations. They also have generators used to allow control and visibility. It means they can control and see whom they can transact with. The platform does the balance of the high peaks and low peaks during power generation. More so, it provides meter data, billing, and contracts (Piclo, 2019).

In Germany, there is a P2P platform called Lumenaza. The platform can enable sharing of energy on the local, regional and national levels. It has software that does most of the work from connecting producers, controlling supply and demand, visualization, aggregation, group management, and billing. In this platform, the communities help in market design during participation (Lumenaza, 2020).

2.9.2 Grid Management

The use of blockchain technologies can bring autonomous grid control and monitoring in addition to decentralizing it. These technologies enable autonomous maintenance of the grid by attaching smart contracts to the grid devices. The purpose of smart contracts is to quickly identify and rectify the problems affecting the grid's smooth operation. An example is how frequency and voltage controlling devices embedded with smart contracts can autonomously change voltage and frequency (Adeyemi et al., 2020). The system can monitor, control devices and manage the functions of the grid. In the energy blockchain, automation and decentralization are achieved by applying blockchain technologies (Banks et al., 2019).

2.9.3 Device Automation for Metering and Billing

Blockchain technologies allow for secure P2P architecture that utilizes internet of things (IoT) for billing and metering in the network. Integrating IoT platforms and blockchain technologies create autonomous billing for energy consumers (Andoni et al., 2019). This lowers administrative costs. The smart contracts put in the smart meters allow sharing of consumption information between consumers and prosumers. The data is interpreted to see if consumers meet the rules put in place. If they meet the requirements, the smart meters on the prosumer will sell automatically to the consumer (Andoni et al., 2019). Münsing, Mather, and Moura (2017) used each building's smart meters to perform calculations of nodes present in the network then afterward create chains of Ethereum that will utilize smart contracts to bring security, trust, and transparency. The coordination was decentralized whereby agents that were not trusted were eliminated, reducing risks of a monopoly of prices and safety issues.

2.9.4 Identity, Security, and Privacy Management

Due to increased communication involved in the network, there is increased vulnerability to malicious attacks. Usually, ill-natured organizations try to analyze the energy consumption profiles of users, according to Alladi et al. (2019). The blockchain, therefore, has to be cyber secured, enabling a secure and credible flow of information between participants. To make these possible cryptographic techniques are used for protection, such as encryption. Smart contracts have a role in monitoring data and determining the security level intelligently for the system (Alladi et al., 2019).

2.10 Conceptual Framework

Figure 2.7 illustrates the conceptual framework that was used to implement and design the system prototype. As shown, the transformer data is updated in the meter reading automatically; when the data change to indicate a change in transformer status, it invokes the energy lose detection contract, which will request energy from the energy supply contract. The energy supply contract will supply the energy to the affected end-user through the next immediate transformer, and the data passes through a process of validation and encryption before it is stored in the distributed ledger. The system administrator can access the data stored in the ledger through visualization and analytic tools in real-time. The transformer is the independent variable, while the feeders/substation being the dependent variable.

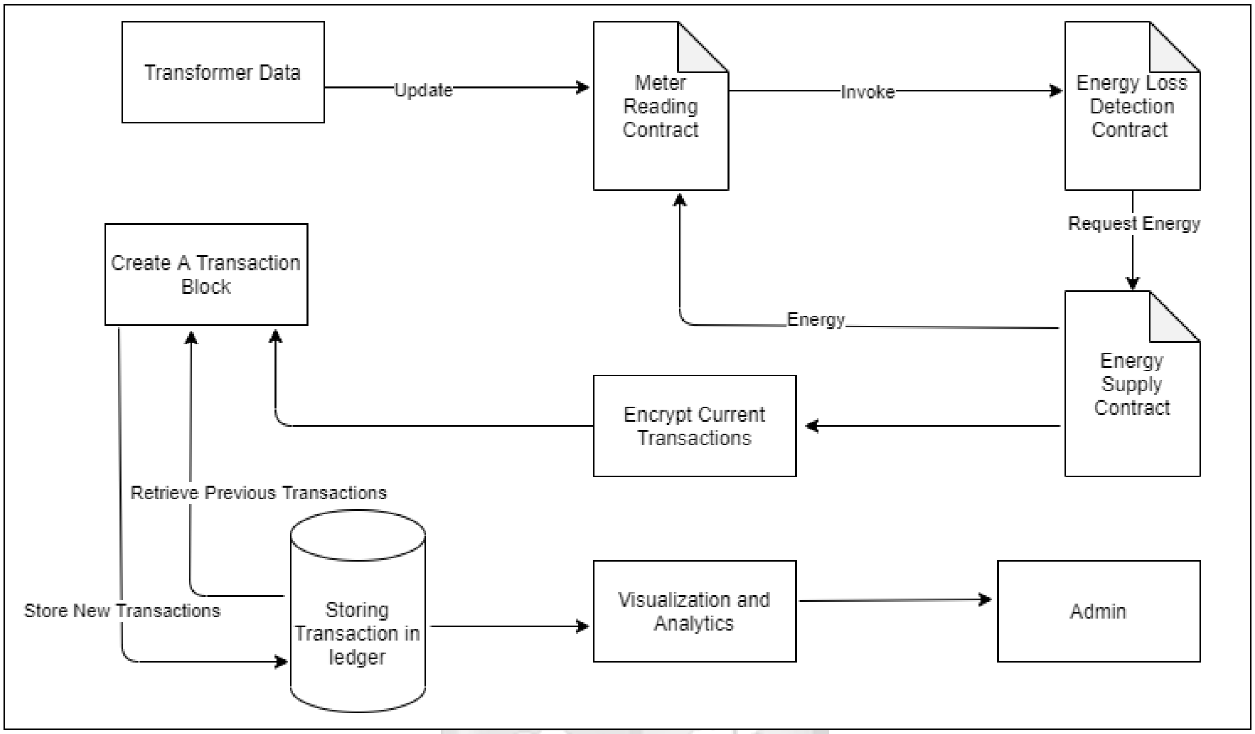

Figure 2.7: Conceptual Framework

Chapter 3: Research Methodology

3.1 Introduction

The research aims at designing and implementing a distributed hybrid power distribution grid using blockchain. In this chapter, is discussed the methodology which is used for the research project to achieve the research objectives. The research design, system development, system design and analysis, system implementation and evaluation, and ethical considerations are carried out.

3.2 Research Design

According to Thomas (2010), research design can be described as the realization of a specific logic in a set of procedures. This action usually optimizes the validity of data for a noted study problem. It gives directions from the underlying philosophical assumptions to research design, and data collection. Research design then remains an action plan that shows how to get to Point A from Point B with resultant answers to specific queries. Since this research involves the design and implementation of a distributed hybrid distribution grid it adopted the experimental research design.

The study adopted the experimental research design since the research covers an emerging area with relatively new technologies and it might be resource-intensive in terms of finance if implemented in a real power distribution grid. The research approach was a virtual practical simulation that involves setting up an experimental distributed hybrid power distribution system prototype on the Ganache local personal Ethereum blockchain as a single organization. The study used each distribution transformers in power distribution grid to act as computer nodes in the blockchain network and whenever a transformer failure occurs, the next immediate neighboring transformer get notified and reroutes power to end users in the region the affected transformer was serving. This was achieved by embedding distribution transformers with smart contracts, that identified and resolved anomalies in the distribution grid.

The blockchain platform was used to store transactions made by the actors in the network. A blockchain-based react web page was exposed for interaction with the blockchain. The simulations focused on the power reliability aspect of the architecture with the deployment of smart contracts to ganache local blockchain. Consequently, target population, sample techniques, location of the study as well as data collection and data analysis were not required in this study.

A quantitative approach was used in the sense the number of simulations that were performed during the test is quantified. All the simulations were done in an experimental power distribution grid environment setup hence the study was not tied to any location and did not involve any human participant. Consequently, the target population, sample techniques, and location of the study were not required.

3.3 System Development Methodology

The system development methodology that was used is Rapid Application Development (RAD). RAD is a model within agile software development with rapid prototyping at the forefront (Demchenko, 2020). According to Bieman (2006), prototyping is the process of designing and developing a trial version of the system or its components to clarify the requirements of the system or reveal critical design considerations.

The RAD development model has phases such as analysis, design, building and testing distributed into a series of short and iterative development cycles as shown in Figure 3.1. The lifecycle of the methodology comprises of four stages that are requirements planning, user design, development and transition. This method was adopted since it offers numerous advantages such as safer, quicker, encourages creativity, and boosts collaboration. It enabled easy incorporation of changes to the prototype.

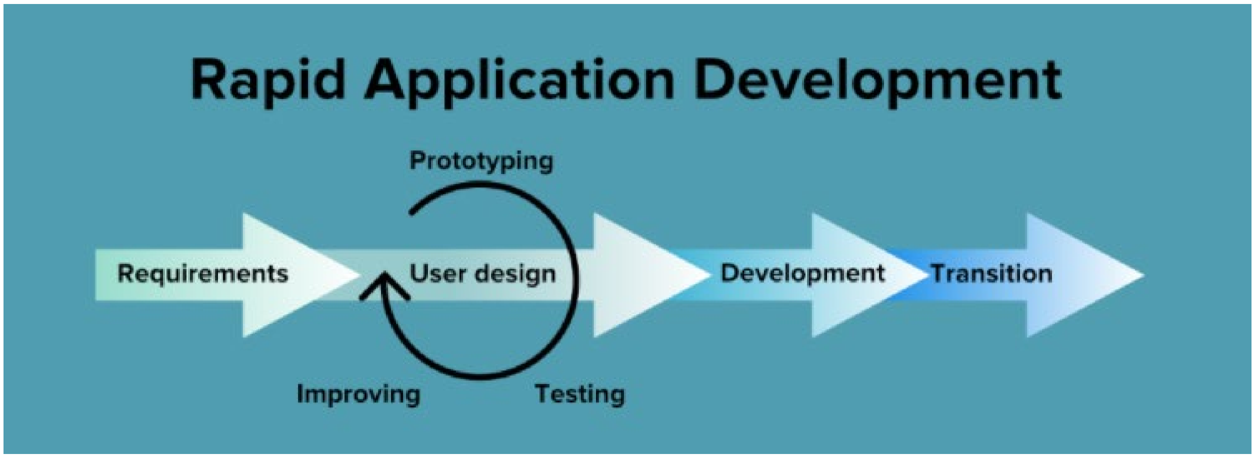

Figure 3.1: Rapid Application Development (Demchenko, 2020)

3.3.1 Requirements Phase

In this phase, the scope of the project and the application's functional and non-functional requirements were identified by the researcher to facilitate the commencement of the next phases. The functional requirements are sometimes referred to as business processes.

3.3.2 User Design

This stage entailed the design of the prototype and architecture of the solution. The business process from the requirements gathering phase was divided into two groups namely system inputs and system outputs. The system processes were modelled using Unified Modeling Language (UML) diagrams to describe flow of information and interaction of the different system components. These was achieved using data flow diagrams, use case diagrams, and sequence diagrams showing how actors interacted with the system. Draw.io application was used for drawing.

3.3.3 Development

This stage involved the implementation of the model following the information in the user design stage. The development language used is Solidity and JavaScript. This was followed by testing and validation of the solution through conducting of experiments.

3.3.4 Transition

The final stage followed the implementation and testing tasks with the prototype solution was deployed for a tool for tracking power distribution status in power distribution grid. The prototype was modified until it realized aim of the study.

3.4 Testing

The system underwent the following tests to ensure that the user requirements were met:

3.4.1 Functional Test

The system's functional and non-functional requirements were tested against the new system. This ensured that every line of code executed and ensured that every function produced the expected outcome.

3.4.2 Compatibility Test

The blockchain web application was tested against the following browser versions:

i. Safari – OS X 10.9 Mavericks to macOS 10.12 Sierra Versions.
ii. Google Chrome – all versions.
iii. Mozilla Firefox – all versions.

3.5 Research Quality

According to Kombo (2006), the validity of an instrument is a measure of how well the instrument measures what it is intended to measure. It is the extent to which the data accurately measures what they were intended to measure. The reliability, on the other hand, is a measure of how consistent and stable the results from a test are (Kombo, 2006). To ensure the validity of the research design, the research instrument was presented to the supervisor for guidance, recommendations, and advice. Also, necessary amendments were made based on the input of the supervisor.

3.6 Ethical Considerations

In this study, the researcher adopted a high level of professional ethics in conducting the research. To ensure that this project complies with the ethical requirement, the researcher made sure to get approval from The Strathmore University Institutional Ethics Review Committee (SU-IERC). Forgery of documents, fake data, plagiarism, and other unethical practices was avoided, and intellectual property and copyright upheld.

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Chapter 4: System Analysis and Design

4.1 Introduction

In retrospect, system design entails a definitive process that incorporates the wholesome description of the structure, components and interface of the system that would satisfy the requirements of the users and bridge the gap from the previous systems. This section then presents the process for development of the prototype as well as describing the various functional and non-functional system requirements. High-level system architecture and system design are presented using layered system architecture, use case diagram and system sequence diagram.

4.2 Requirement Analysis

Requirements analysis can be defined as a complete and detailed description of the behavior of the intended system prototype. The proposed system should be secure, immutable, efficient, reliable and should allow for power rerouting. This can be achieved by following the designed pattern layered out and apply the standards applied currently in the industry. This phase involves identifying the functional and non-functional system requirements and clearly stating them.

4.2.1 Functional Requirements

Functional requirements describe the processes that the application is going to execute. This entails power rerouting in the power distribution grid and other processes that the system must deliver at any given time. These requirements included:

i. The system should be able to reroute power automatically to the affected users.
ii. The system should reduce the power restoration time from long waiting days.
iii. The system should keep records of every transaction in the transformer processes and ensure data remain immutable.
iv. A system administrator should be able to add, modify and update blockchain nodes which can interact in the network.
v. Visualize the content of the ledger in a web application.

4.2.2 Non-Functional Requirements

Non-functional requirements are not necessary for the core operation and functionality of the system but make the system more interactive and cannot be ignored. They do not affect how the system works but can be used to judge the operability of the system. These requirements include:

i. Reliability and Availability- The solution should have consistent performance and available to perform its functions.
ii. Scalability and Flexibility- The solution should be modelled such that it is easy to incorporate additional modules in the event of enhancement.
iii. System performance responsiveness- The solution should be having a satisfactory response time while accomplish its functions.
iv. The solution should be easy to manage, maintain and debug.

4.3 System Architecture

The system architecture shows the major system components while describing the services provided by each component. The proposed solution relies on blockchain technologies to achieve the research objectives. Figure 4.1 shows the detailed layered system architecture of the proposed distributed hybrid power distribution grid system. The first layer represents the interface of the system admin, the second layer demonstrates the operations that are performed on the ledger and the last layer is for P2P networking. The proposed system is comprised of four entities: transactions, authority, blocks and contracts:

i. Authorities $\{A_1, A_2, \ldots\ldots., A_n\}$,
ii. Transactions: $\{Tx_1, Tx_2, \ldots\ldots., Tx_n\}$,
iii. Blocks: $\{B_1, B_2, \ldots\ldots, B_n\}$,
iv. Contracts: {Transformer, Grid}.

4.3.1 Interface Layer

The System Administrator setup the Blockchain Network at this layer. Thereafter, the System Administrator create and modify the system contracts. Other activities performed by the System Administrator are monitoring the Blockchain Transactions Logs.

4.3.2 Decentralized On-chain Layer

This layer allows creation of the different smart contracts to be used in the system. It is through this layer that the transformer reading is recorded in the meter reading. The transformer reading is the transformer serial number, location and the accumulated energy units of all the end user in a particular area.

When a failure occurs in a transformer the meter reading should be updated automatically using the transformer and meter contracts. The meter contracts execute and triggers the energy loss detention contract, which execute and request for energy from the energy supply contract. The energy supply contract has transformer readings of all the transformers in the network, this is necessary for ensuring accurate initial supplied units. The supplied units are the energy supplied by the grid. The energy supply contract execute itself and supply the requested energy units to the affected end users through the next immediate transformer. Whenever a contract is executed, a transaction is created and validated by all the nodes. The data entered into the contracts are from the transformer datasets.

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This layer combines the different transactions and creates a hashed block of transaction. A block contains the data in encrypted form, time stamp and digital signature, which will be broadcast to all the nodes in the network. The structure of the block contains a block header, hash of the previous block, number of transactions, transaction hash of current block, digital signature, time stamp, send address, receiver's address and data transactions. These details are combined with the previous transaction from the blockchain

4.3.3 Network Layer

The last layer is the Ethereum which is a public blockchain database that allows for transparency and no downtime as the smart contracts will not face any issues and would always be available.

The power consumption hourly or daily is stored into the ledger. Carefully analysing the stored reading, the area which a transformer failure has occurred can be easily tracked down.

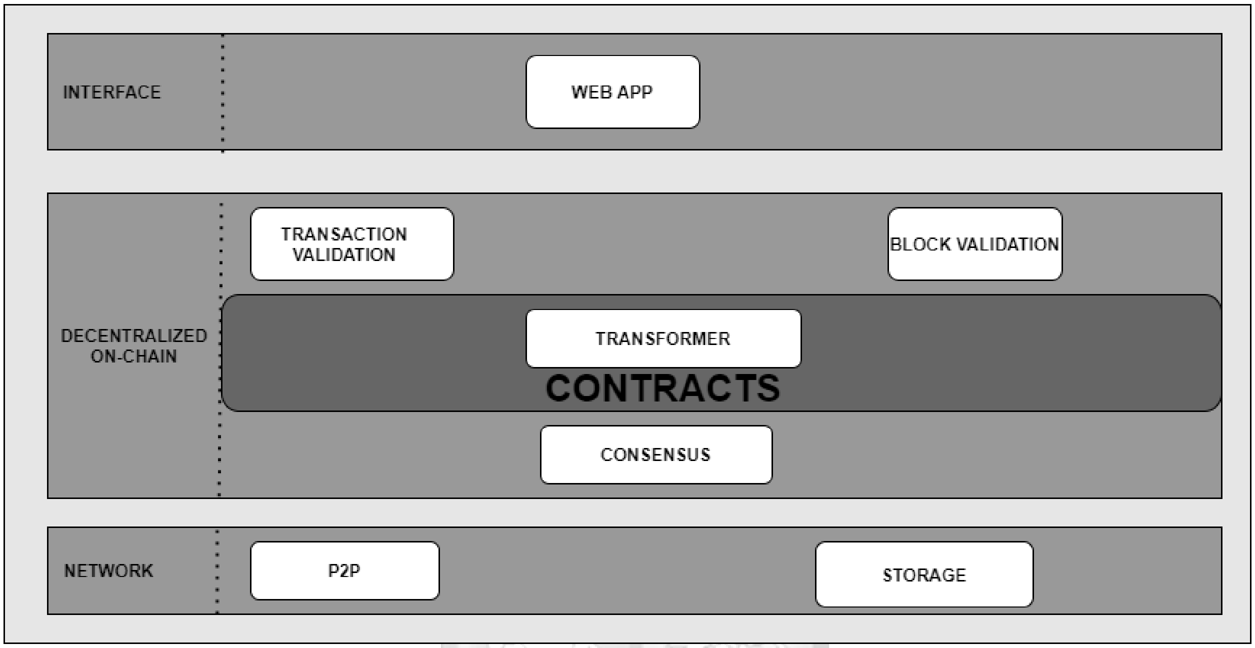

Figure 4.1: The Blockchain-Layered Architecture

4.4 System Design

The system design is a detailed expectation on how the system is expected to behave. A blend of user specific requirements and ideas from the researcher were used to come up with the most relevant system designs that would help achieve the objectives laid out. The system design is done, using UML diagrammatic representation such as use cases, system sequence and interaction diagrams to give a good representation of how the system works. The following design diagrams and their descriptions are what were used to guide the system implementation process.

4.4.1 Use-Case Diagram

The use case diagram is presented to visually illustrate the different functionalities of the system relative to the actors involved and the goals that they are meant to achieve. Figure 4.2 shows the interaction between actors and system contracts processes. Table 4.1 and Table 4.2 show the use case descriptions of meter reading contract and supply energy contract respectively.

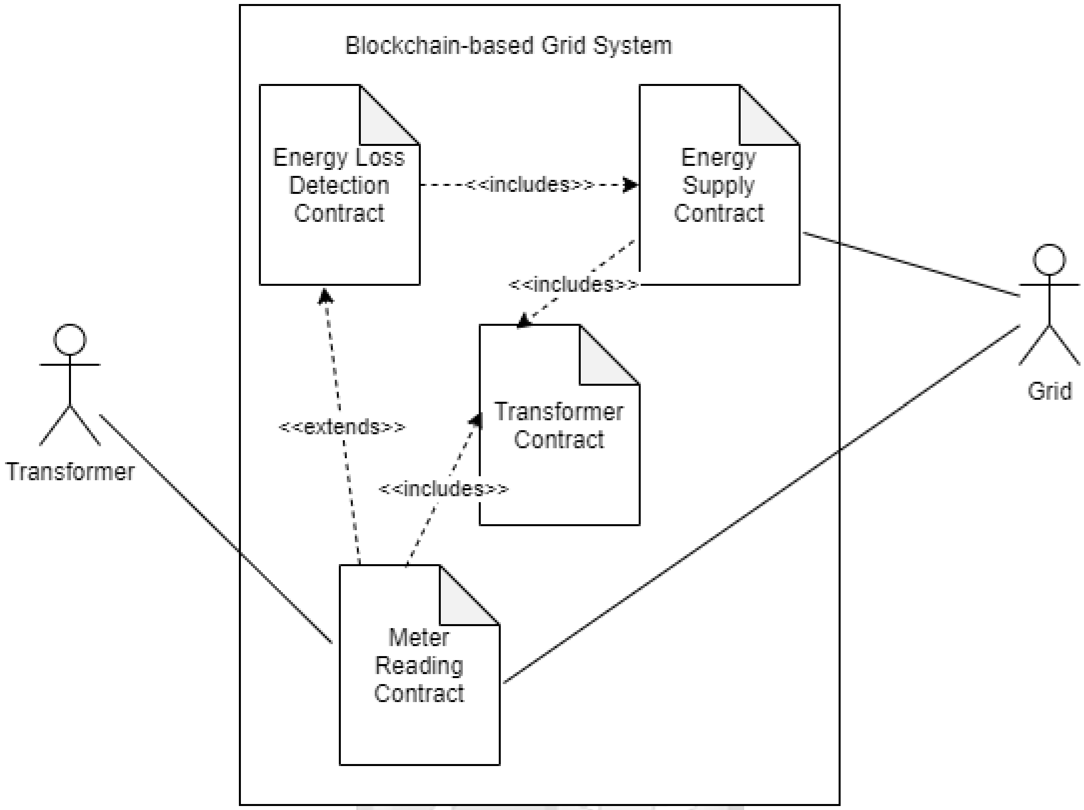

Figure 4.2: Use Case Diagram

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4.4.2 Use-Case Description

Table 4.1: Meter Reading Contract

Use Case Name	Meter Reading Contract
Description	The contract receive the transformer current energy supply status, records, starts energy detection contract to request energy supply in case of failure occurs.

Primary Actor	Transformer
Trigger	Transformer Contract
Pre-Condition	The meter reading contract has transformer status and readings.
Post-Condition	Accurate readings are recorded and executed.

Table 4.2: Energy Supply Contract

Use Case Name	Energy Supply Contract
Description	The contract receives energy unit supply request, Records then supply.
Primary Actor	Grid
Trigger	Energy Detention Contract
Pre-Condition	Has access to the affected transformer reading and enough energy to be supplied.
Post-Condition	Requested energy unit supplied.

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4.4.3 System Sequence Diagram

The general functionality of the proposed system is to reroute power to end users in case a transformer failure occurs. The system should at all times be updating the transformer status and when a failure occurs the contracts should be triggered and power restored from neighbouring transformer to the affected area automatically. The system sequence diagram in Figure 4.3 illustrates the interactions amongst the different contracts of the system.

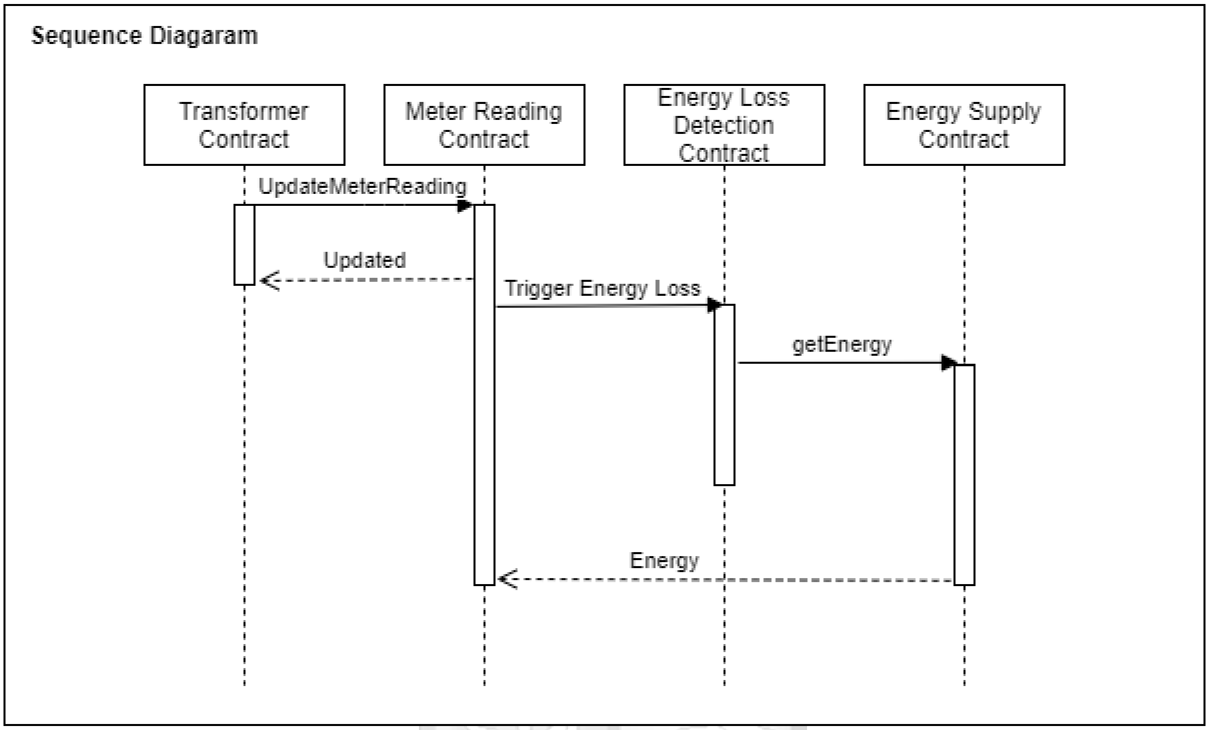

Figure 4.3: System Sequence Diagram

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Chapter 5: System Implementation

5.1 Introduction

This section describes the various implementation and testing phases of underwent during the development of the system. The implementation illustrates the different hardware and software platforms used to develop the system. The user interfaces of the system are also described here. It also focuses on the implementation of various system requirements and functionalities needed by application to function.

5.2 System Development Tools

The proposed tool is developed using solidity programming language; an object-oriented programming language for writing smart contract. Since the tool is a web based, we used the React framework which offers high scalability and fast prototyping environment. We used truffle utility to test and deploy the contracts to ganache; which is a personal local development blockchain that can be used to mimic the behavior of a public blockchain, for verifying the functionality of the blockchain as it directly interacts with the contract for the testing purpose. Most major web browsers do not currently connect to the blockchain networks, so we installed a browser extension that allow them to connect. We used MetaMask extension to turn our web browser into a blockchain browser, this ensures that the web-based application can communicate with the local blockchain.

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5.3 System Requirements

The system is expected to run on a web-based environment. Hence, the computers must have the following to operate:

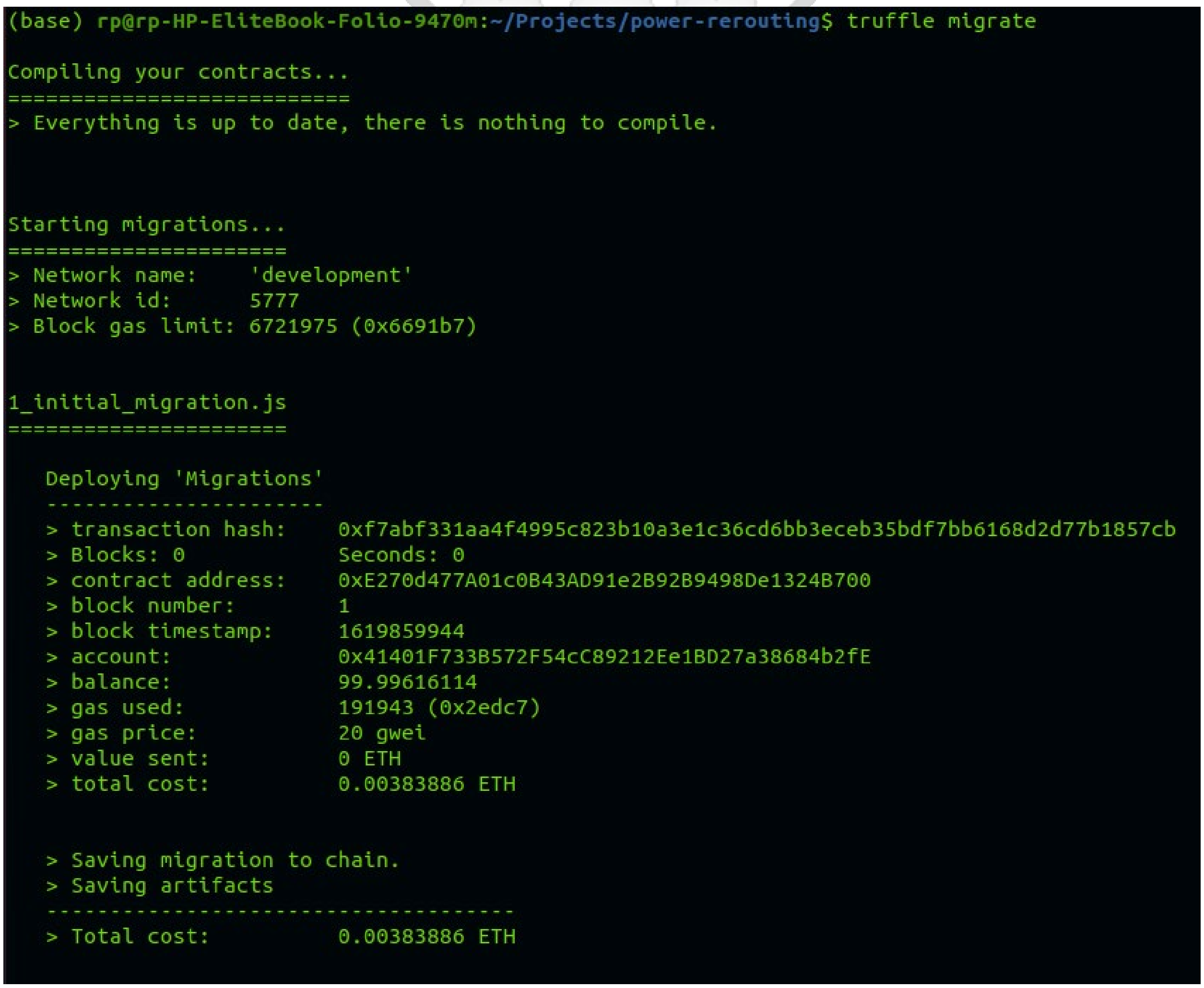
i. A laptop with operating system; windows 7 or higher, Ubuntu 16.04 or higher and Mac OSX.
ii. The computer processor should be above i3 2.4GHz, with a minimum RAM of 4GB and minimum hard disk of 20GB.
iii. The computer must be pre-installed with a web browser preferably chrome, MetaMask extension and Ganache.

5.4 System Functionality Summary

The blockchain network in use is designed to enable power rerouting to end users in case of a transformer failure or blackout which are later published and stored on the blockchain network. The admin can monitor the affected transformer location from the application front-end interface thus less repair time by engineers.

5.4.1 Deploying Contracts to Ganache

Migration and Grid contracts were deployed successfully to the blockchain as shown in Figure 5.1 and Figure 5.2 respectively, using truffle utility command line.


```
(base) rp@rp-HP-EliteBook-Folio-9470m:~/Projects/power-rerouting$ truffle migrate

Compiling your contracts...
===========================
> Everything is up to date, there is nothing to compile.


Starting migrations...
======================
> Network name:    'development'
> Network id:      5777
> Block gas limit: 6721975 (0x6691b7)


1_initial_migration.js
======================

   Deploying 'Migrations'
   ----------------------
   > transaction hash:    0xf7abf331aa4f4995c823b10a3e1c36cd6bb3eceb35bdf7bb6168d2d77b1857cb
   > Blocks: 0            Seconds: 0
   > contract address:    0xE270d477A01c0B43AD91e2B92B9498De1324B700
   > block number:        1
   > block timestamp:     1619859944
   > account:             0x41401F733B572F54cC89212Ee1BD27a38684b2fE
   > balance:             99.99616114
   > gas used:            191943 (0x2edc7)
   > gas price:           20 gwei
   > value sent:          0 ETH
   > total cost:          0.00383886 ETH


   > Saving migration to chain.
   > Saving artifacts
   -------------------------------------
   > Total cost:          0.00383886 ETH
```

Figure 5.1: Deploying Migration Contract.

```
2_deploy_contract.js
====================

   Deploying 'GridContract'
   ------------------------
   > transaction hash:    0xc4af0f92be4779d7b5561f09b56751908a7e17aa7d9111fa4f3f7f4e87bbd010
   > Blocks: 0            Seconds: 0
   > contract address:    0xF64Ac8ccE2c87A82AFb35Fb68C1125ad73B38221
   > block number:        3
   > block timestamp:     1619859944
   > account:             0x41401F733B572F54cC89212Ee1BD27a38684b2fE
   > balance:             99.9797582
   > gas used:            777809 (0xbde51)
   > gas price:           20 gwei
   > value sent:          0 ETH
   > total cost:          0.01555618 ETH


   > Saving migration to chain.
   > Saving artifacts
   -------------------------------------
   > Total cost:          0.01555618 ETH


Summary
=======
> Total deployments:   2
> Final cost:          0.01939504 ETH
```

Figure 5.2: Deploying Grid Contract.

5.4.2 Ganache Accounts after Deployment

The successful deployment and storage of the contract on the blockchain is monitored in Ganache by keeping track of gas used to mine a block as shown in Figure 5.3.

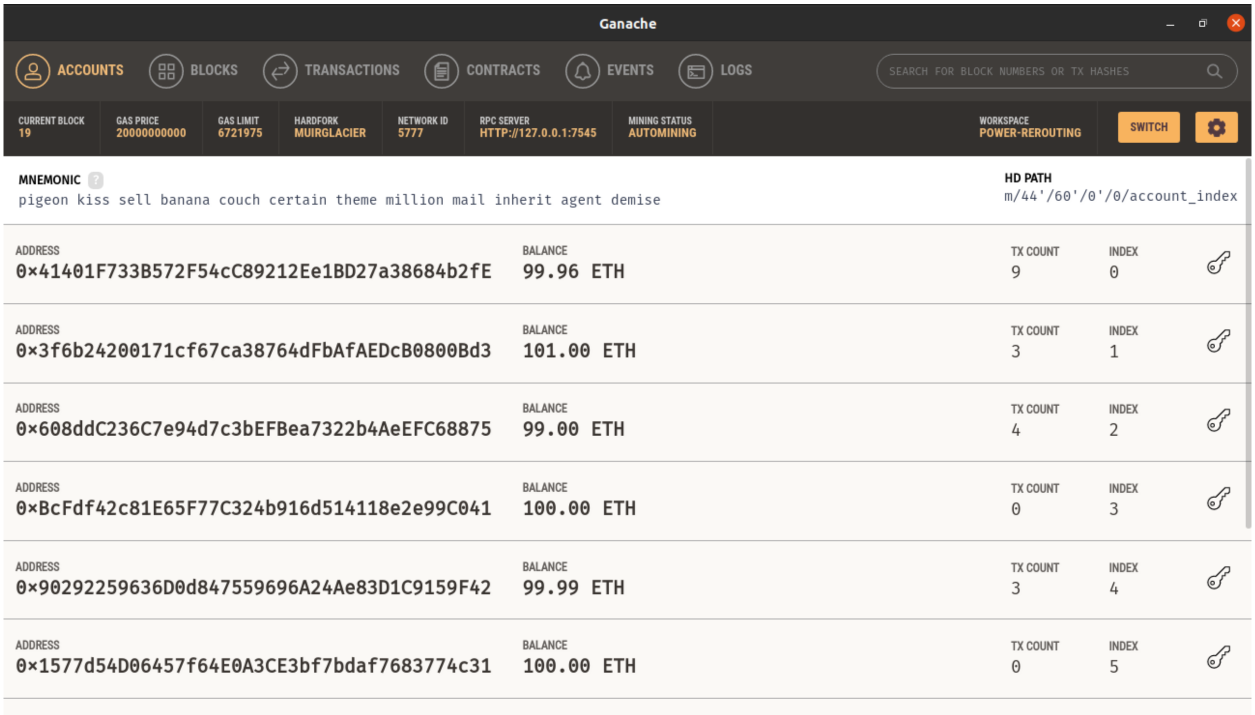


Figure 5.3: Ganache

5.4.3 Deployed Contracts on Ganache

The proposed contracts are deployed to the local personal blockchain as shown in Figure 5.4

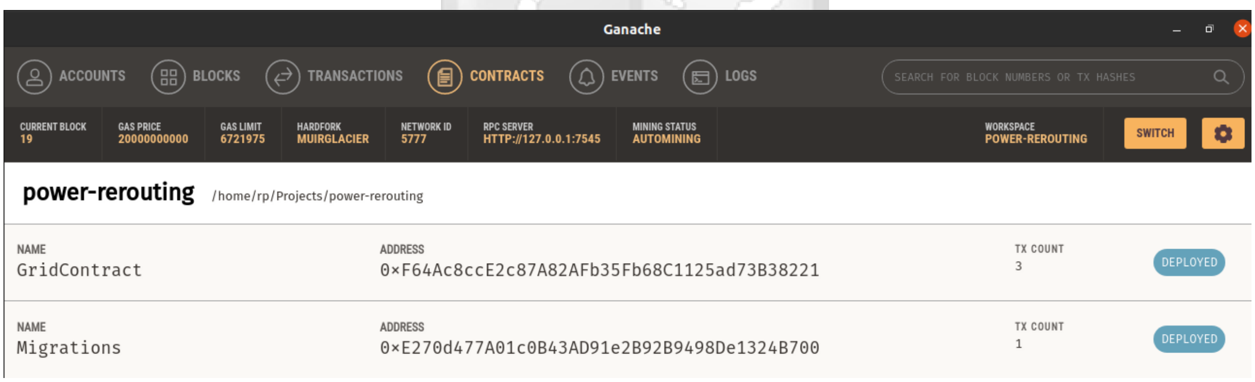


Figure 5.4: Smart Contracts

5.4.4 Starting Web Server, Webpage and MetaMask Login

A set of interfaces is developed to interact with system administrator. First the web server run from the terminal using the following command: 'npm run start' This is a web server that came with the react app. Once the server is running the browser should open automatically and load the web page as shown in Figure 5.5.

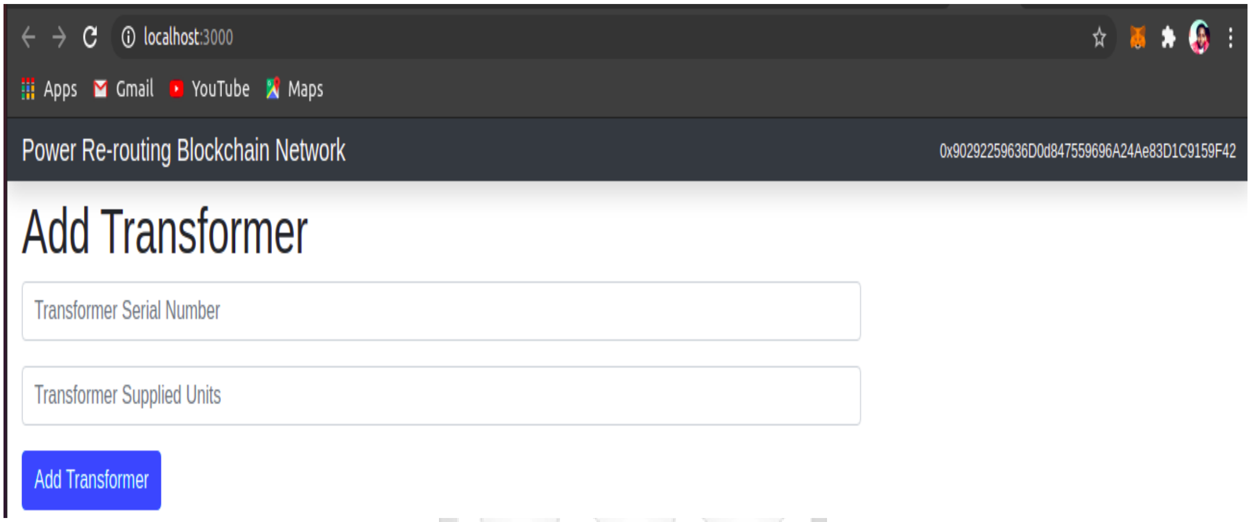


Figure 5.5: Power Re-routing Blockchain Web Page

Once the administrator is on the web page, they should sign-up and sign-in to MetaMask. MetaMask allowed us to manage our personal account when we connect to the blockchain, as well as manage our Ether funds that we needed to pay for transactions. Figure 5.6 illustrates the captures the sign in process and account importation form Ganache.

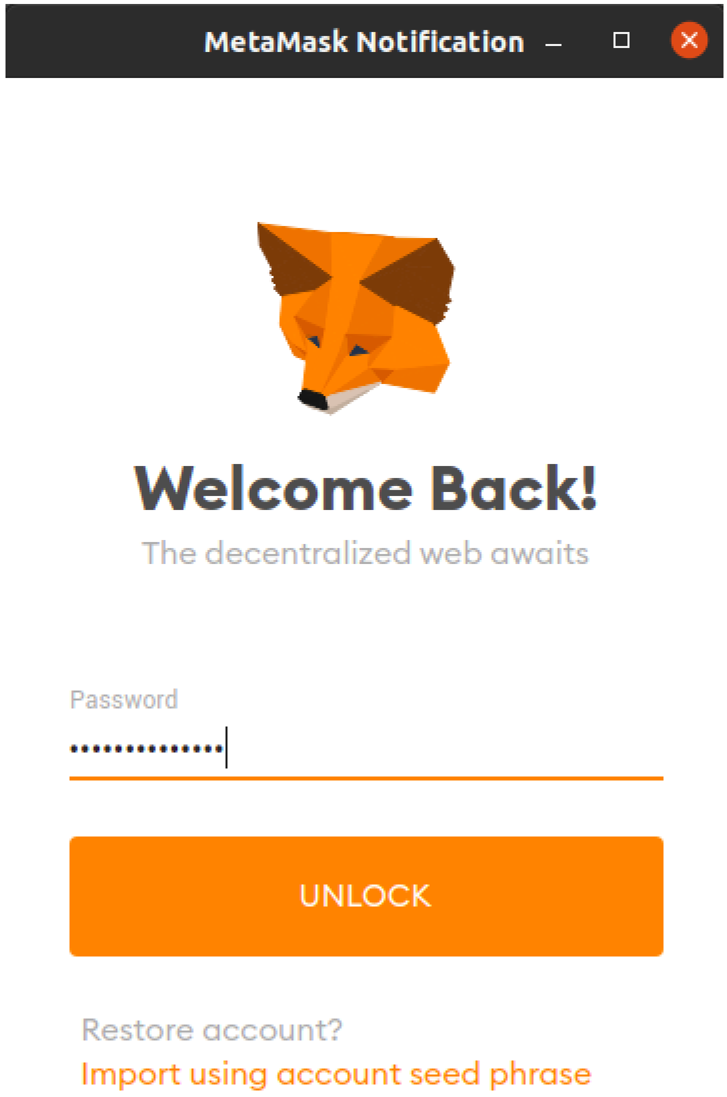


Figure 5.6: MetaMask Login

5.4.5 Adding Transformers and MetaMasks Gas Transactions

The system administrator can add transformers to the blockchain network using react front-end application by providing their names, supplied units and location. Once the administrator fills in the required data the system invokes the blockchain and retrieve the previous block and append the new block to it. The new data has been added to the local blockchain since the integration of Ganache and react front-end application was successful as shown in Figure 5.8. Ganache uses gas to monitor the executed contracts for validating and storage of the block as shown in Figure 5.7.

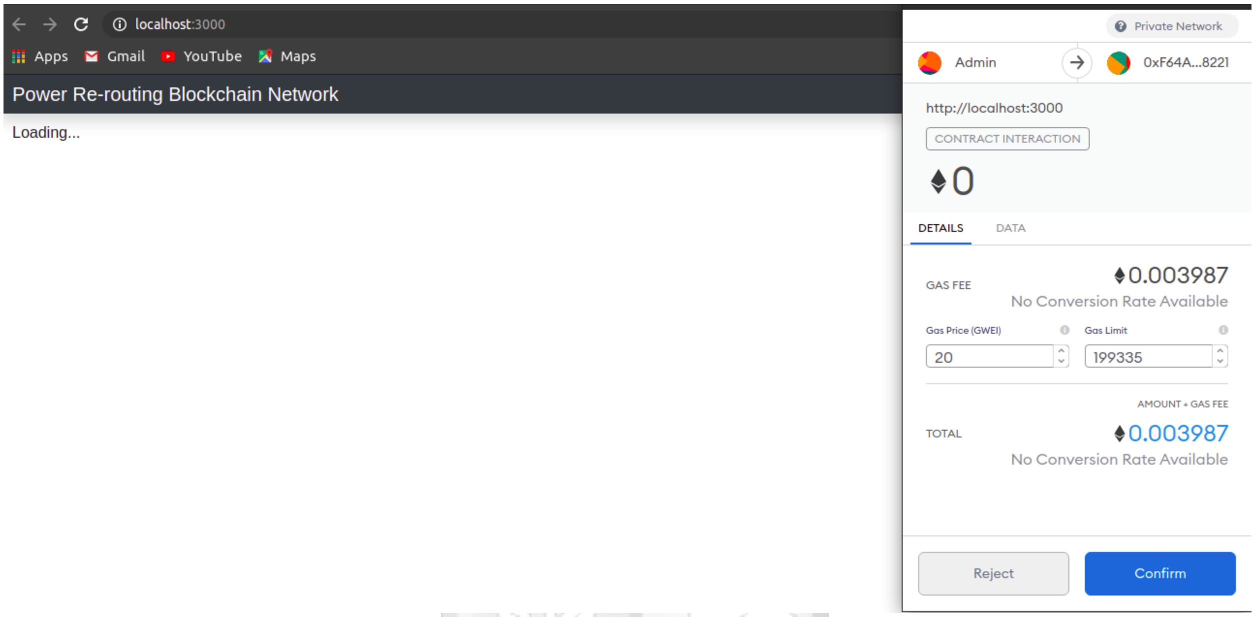


Figure 5.7: Adding Transformers Gas Transactions

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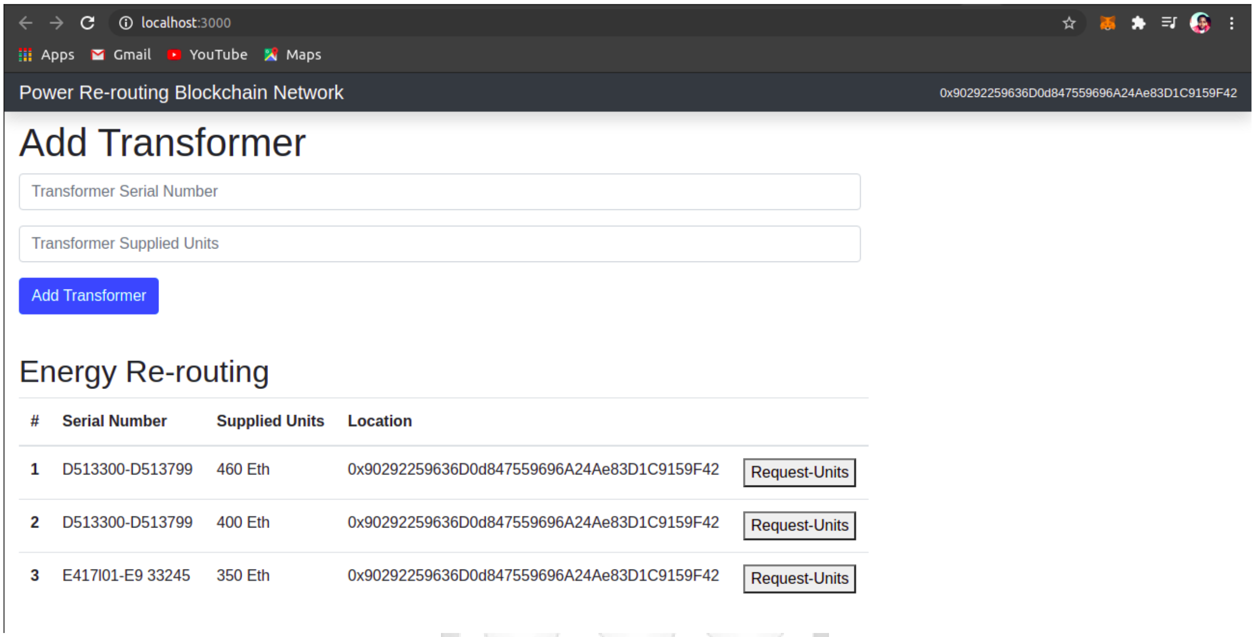

Figure 5.8: Successfully Added Transformers

5.4.6 Ganache Blockchain Recorded Transactions

Every block contains a transaction. The block created has a unique block value, gas used, mined date and time and transaction linked to it, shown in Figure 5.9. The transaction has gas used, sender address, receiver address and a unique hash value, which can be used to identify and track specific transaction as shown in Figure 5.10.

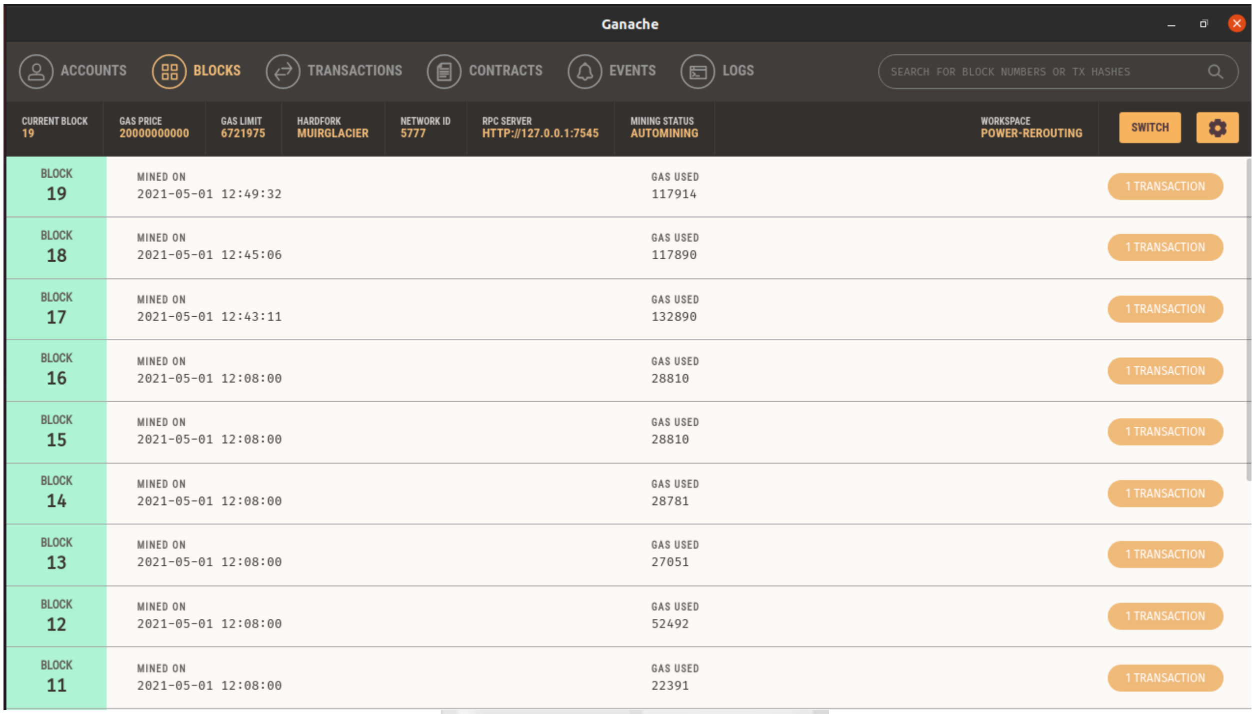

Figure 5.9: Created Blocks

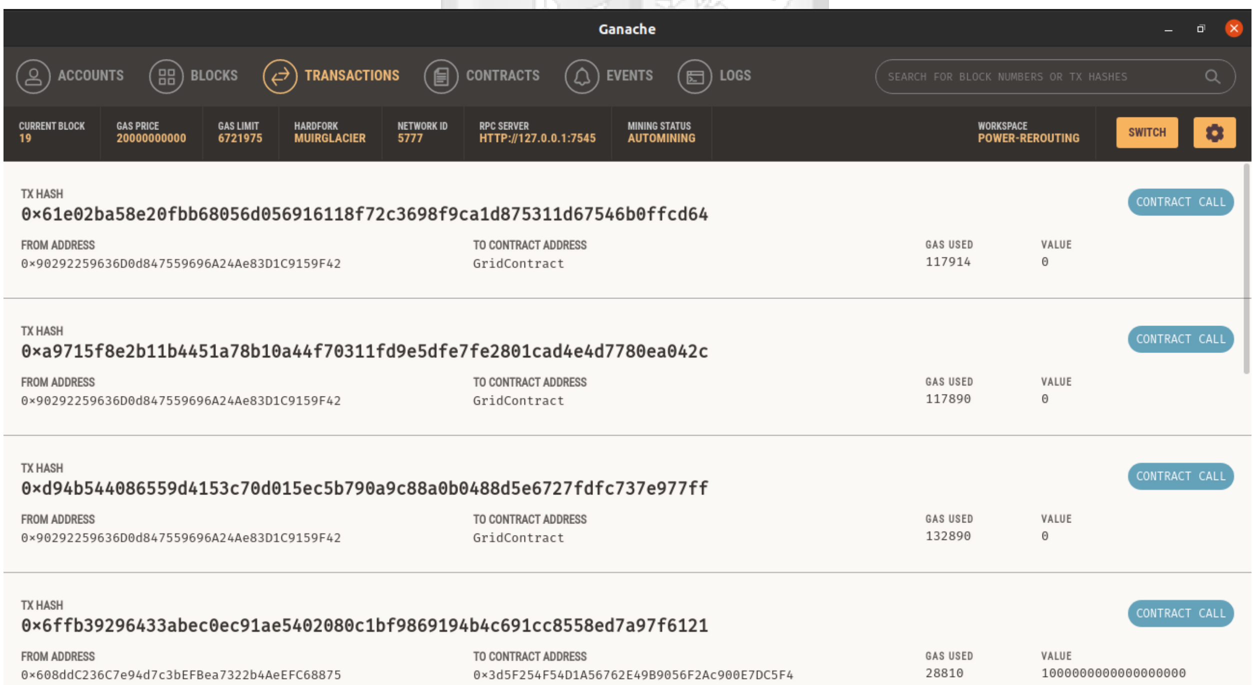

Figure 5.10: Ganache Transactions

5.4.7 Contracts Unit Tests

Using truffle utility and ganache, we have tested our contracts to check whether they help in power rerouting in case of a transformer failure and they passed as show in Figure 5.11.

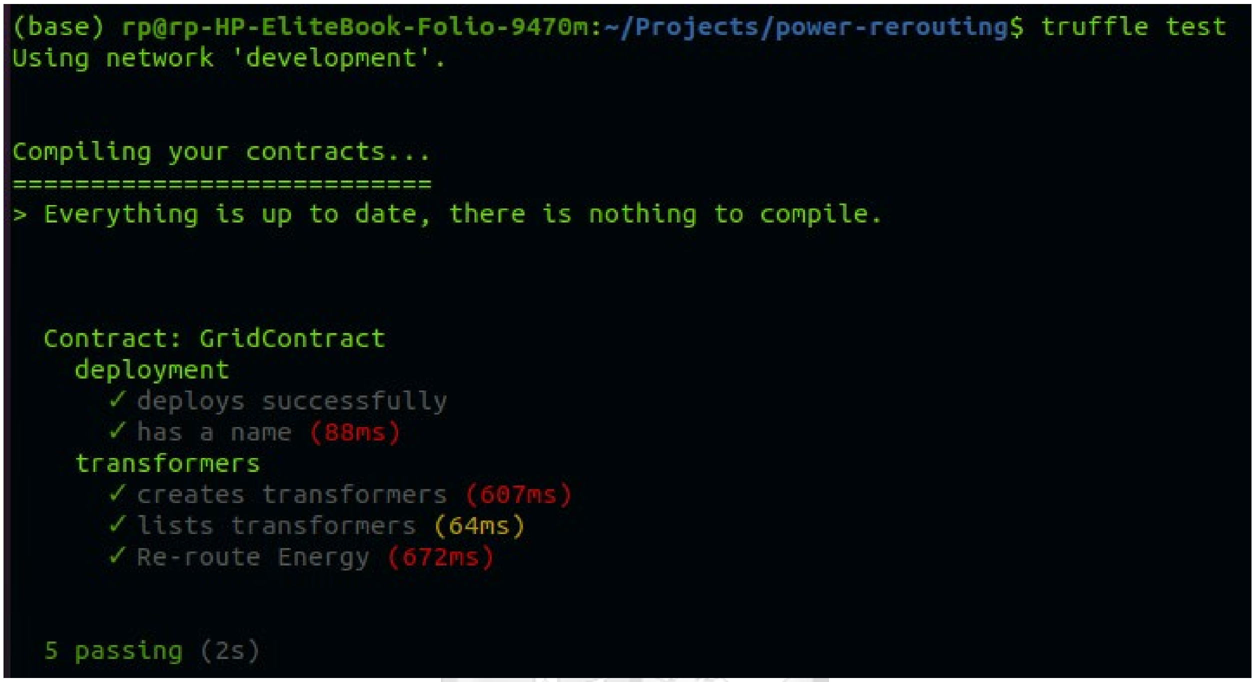

Figure 5.11: Unit Tests

5.5 System Testing

System testing was carried out to evaluate the systems compliance with the functional requirements specified earlier. The blockchain application was subjected to functional and compatibility tests as described in section 5.5.1 and 5.5.2.

5.5.1 Functional Testing

Table 5.1: Summary of the Functional Tests

No	Test	Expected Results	Achieved Results
1	Loading of Blockchain Application	The system to be successfully launched via a web browser	The system was successfully launched on a web browser

2	Connecting to the Blockchain Network	A system administrator with valid credentials should be allowed to connect to the blockchain network	An authorized administrator was able to successfully connect to the blockchain network
3	Add and listing Transformers to the Blockchain Network	Authenticated administrator should be able to successfully add and list transformers to the blockchain network.	An authenticated administrator was able to successfully add and list transformers to the blockchain network
4	Power Re-routing by the Blockchain Network	The blockchain network should be able to re-route power to the affected end user in case of a transformer failure.	The blockchain network successfully re-routed power to the affected end-users via the next immediate transformer.

5.5.2 Compatibility Testing

The application was developed and hosted on Ubuntu a Linux based Operating system. Test were later carried out to determine how the application launched on the latest versions of different web browsers.

Table 5.2: Compatibility Test Outcomes

Browser Type	**Compatibility**
Google Chrome	Yes
Internet Explorer	Yes
Mozilla Firefox	Yes

5.5.3 Integration Testing

This was done with an aim of confirming whether the React Front-end app and Ganache integrated seamlessly. This was achieving since system administrator can add and retrieve data to local ganache blockchain from React front-end application as shown in Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8 above.

Chapter 6: Discussion

6.1 Introduction

This research was aimed at achieving a blockchain-based distributed hybrid system for real-time identification and resolution of anomalies in power distribution grids. Our work attempts to configure how the technology can be modified and adopted with least alteration in existing system and what are the requirements of the system to gain maximum benefits. We have found out that even though the system the blockchain-based adaptation does not require full scale distribution grid transformation of the existing distribution setup; however, few infrastructural changes are required.

In order to identify transformer failure and its location in a grid, the present infrastructure lacks metering at each transformer. We suggest that metering at distribution transformer should be employed, and not necessarily smart meters even dumb meters can be used with blockchain-based solution.

6.2 Review of the Research Objectives for the Blockchain Application

Through reviewing different literature sources, the first and second objectives were achieved successfully.

The first and second objective were to investigate the current challenges facing power reliability on distribution grid and to analyze the existing techniques, models and approaches of guaranteeing reliability in power distribution respectively. It was noted that the main challenge was on identification and restoration of power loss at the end user distribution level. The manual identification methods by waiting for end users to report the loss were expensive and time consuming. Literature revealed several techniques that are currently used for guaranteeing reliability in distribution grid. These include numerical and heuristic techniques. Both techniques have their own merits and demerits and they mainly focus on high power voltage. It was noted that the existing power distribution system had challenge such as time consumption and tediousness in the locating and repairing of affected transformer. The blockchain solution was therefore seen as the most appropriate technology to use as it offers smart contracts, immutability with strong cryptographic mechanisms in place.

The third and fourth objective was to develop and test a blockchain-based distributed architecture for real-time identification and resolution of anomalies in power distribution grids. This was achieved through actual design, implementation and testing of the blockchain solution. Use cases, sequence diagrams and layered architecture diagrams aided in the design phase of the application. Truffle utility, react framework and Ganache Ethereum personal blockchain were the main tools used to develop the application. The responsiveness and functionality of the system was tested on different operating systems and browsers.

6.3 System Assessment

The blockchain application prototype was developed and requires a user to have internet connectivity for better user experience in accessing the systems services. The following section briefly describes the benefits and limitations presented by the application.

6.3.1 Benefits of the Developed Blockchain Solution

i. The application can be used across all platforms, that is operating systems and browsers
ii. Constant power reliability was achieved through automatic power re-routing in case of transformer failure.
iii. The disadvantages of time wasting when restoring power and locating the affected transformers are eliminated.
iv. Enhanced security of records as compared to other systems due to strong cryptographic mechanisms in place.

6.3.2 Limitations of the Developed Blockchain Solution

i. The application is only limited to the distribution transformers in distribution grid.
ii. The blockchain application requires a user to have internet connectivity for best user experience when using the system.
iii. The application does not provide the diagnosis report of the affected transformer.

Chapter 7: Conclusion, Recommendation and Future Work

7.1 Conclusions

The study aimed at developing a blockchain-based distributed hybrid system for real-time identification and resolution of anomalies in power distribution grids. This was made possible by reviewing existing literature to examine the different methods used for ensuring power reliability is achieved at the distribution level, analyzing the blockchain technology architecture and finally identification of a suitable technologies to use for the development of the application.

A prototype was developed that allowed power re-routing to the affected end users via the next immediate neighbour transformer. The system was then tested to ensure that it was able to meet the functional requirements.

7.2 Recommendations

This study has presented a relatively new solution to address the issue of power reliability in distribution grids. However, for last mile power connectivity companies to reap maximum benefit from such technology, the following is recommended:
The companies are encouraged to employed metering at the distribution transformers levels.

7.3 Future Work

The following are the recommendations for future work relating to the blockchain application:

i. In future, we would like to extend our solution in collaboration with companies from the energy generation and transmission sector.

ii. With more research, the improved web application version of the solution can be adopted in a real industry environment and assist in tracking of power distribution in electric power system.

iii. The application can be further developed to integrate with an external web-based system that has a more user-friendly graphical interface.

VT OMNES VNVM SINT

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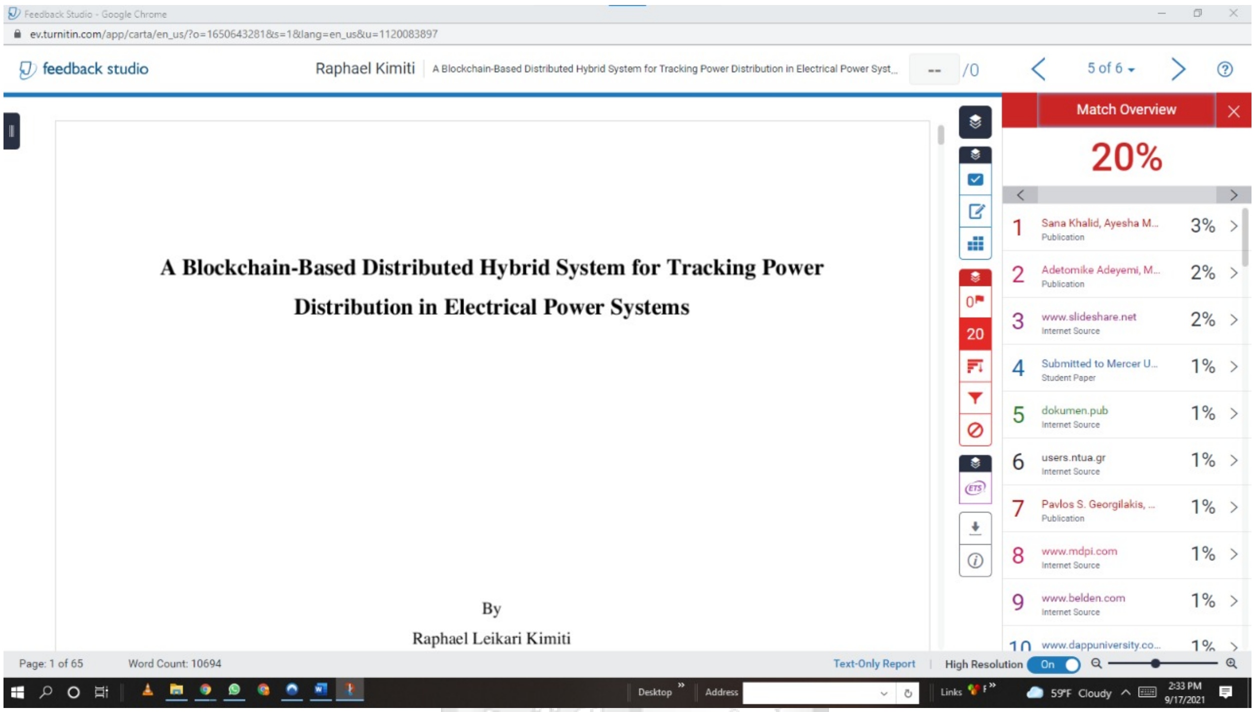
Appendices

A.1 Originality Report



A.2 Ethical Approval

Strathmore
UNIVERSITY

28th April 2021

Mr. Kimiti, Raphael Leikari
raphael.kimiti@strathmore.edu

Dear Mr. Kimiti,

RE: A Blockchain-Based Distributed Hybrid System for Tracking Power Distribution in Electrical Power Systems

This is to inform you that SU-IERC has reviewed and **approved** your above **master's** research proposal. Your application reference number is **SU-IERC1012/21.** The approval period is **28th April 2021 to 27th April 2022.**

This approval is subject to compliance with the following requirements:

i. Only approved documents including (informed consents, study instruments, MTA) will be used
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-IERC.
iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-IERC within 48 hours of notification
iv. Any changes, anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-IERC within 48 hours
v. Clearance for export of biological specimens must be obtained from relevant institutions.
vi. Submission of a request for renewal of approval at least 60 days prior to expiry of the approval period. Attach a comprehensive progress report to support the renewal.
vii. Submission of an executive summary report within 90 days upon completion of the study to SU-IERC.

Prior to commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology and Innovation (NACOSTI) https://research-portal.nacosti.go.ke/ and also obtain other clearances needed

Yours sincerely,

for: Dr Virginia Gichuru,
Secretary; SU-IERC

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28 Apr 2021
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