Blockchain Based Grid Operation Services for Transactive Energy Systems

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Abstract—Transactive Energy Systems (TES) are modern electric power systems that enable decentralized owners of power generation assets to engage in energy transactions and provide computing services that improve the performance of power system operation. Blockchain technology is a key enabler of TES, allowing peers to engage in trustless, persistent transactions that are both enforceable and auditable. However, previous work within this context has not adequately explored fraudulent service transactions amongst peers, and its potential negative impact on power system operation. To that end, this paper proposes a blockchain based TES that enables distributed peers (known as agents), to receive incentives for providing grid operation services in the form of voltage regulation, which is a critical operational service. The proposed system i) maintains a trustless reputation rating for each agent that is increased proportionately with each transaction that improves grid operation, ii) utilizes smart contracts to enforce the validity of each transaction and penalizes reputation ratings in case of a fraudulent transaction, iii) automates the negotiation and bidding of agent services by implementing the contract net protocol (CNP) as a smart contract. Experimental results on both simulated and real-world power systems are executed to demonstrate the efficacy of the proposed system.

Index Terms—Blockchain, grid services, distributed generation, voltage regulation, multi-agent, smart contracts, contract net protocol, smart inverters, transactive energy, distributed ledger.

1 INTRODUCTION

Aggressive climate change and sustainability initiatives have brought much needed attention to the overall operation and architecture of power systems. As such, legacy power systems are rapidly evolving from a centralized, monolithic architecture into a decentralized and modular system that is required to be highly flexible, reliable, and resilient. Where legacy power systems were characterized by large, fossil fuel based power plants that served end consumers via long-distance transmission lines, the smart grid paradigm seeks to deploy smaller, renewable distributed generators (DGs) that are placed closer to the consumer [1]. Often, the DG utilizes green sources of energy for power generation, which are largely solar and wind based. This change in architecture results in the smart grid evolving into a network of loosely coupled, yet cohesive miniature grids (referred to as microgrids), each of which is capable to handle its local power demand via DGs. The implementation of microgrids can therefore significantly decrease greenhouse gas emissions, decrease power losses that occur due to long-distance power transmission, as well as increase resiliency from outages that occur in the main grid by utilizing backup power from the DGs.

In addition to the aforementioned benefits of smart grids, additional key objectives are noted as the enhancement of the role of active consumer participation in aiding system optimization, as well as the need to improve the automation of critical power system services in providing grid reliability [2], [3]. The merging of these two objectives has evolved into a concept known as grid services, where consumer owned DGs can be used to provide ancillary services to the grid in times of need [4]. Coupled with the increased digitization of information and communication technology (ICT) infrastructure within power systems, grid services are viewed as cyber-physical computing services that enable power systems to move towards a service-oriented architecture [5]. Critical grid services include: black start (restoration of a section of the system without using power from the main grid), load balancing and frequency control (correcting power imbalances between supply and demand in real-time and maintaining an appropriate system frequency), voltage regulation (adjusting power outputs to maintain system voltage throughout the system to prevent voltage violations that could cause severe damage to grid assets), as well as congestion management (adjusting power generation to prevent excess power within transmission/distribution lines that lead to excess power losses) [6].

The evolution of consumer provided grid services has transformed the role of the previously passive consumer into an energy prosumer, capable of providing both energy and services to the grid in return for economic compensation. This shift to service-oriented smart grids is best exemplified by the concept of transactive energy systems (TES), which seeks to combine economic objectives of all stakeholders with distributed control techniques to improve overall grid reliability and efficiency. The guiding principles of TES’ place special emphasis on enabling non-discriminatory participation by qualified participants, providing observable and auditable interfaces, and ensuring that all parties are accountable for standards of performance [7].

Considering these principles, blockchain has emerged as a suitable platform for facilitating the implementation of TES’. A blockchain is a type of distributed ledger, where each party (peer) maintains a local copy of the ledger and a consensus algorithm is used to ensure consistency amongst all peers. Transactions submitted to the blockchain
network during a given time period are collected in a discrete block of data, verified by peers against a set of rules that the network is governed by, and then appended to the end of the blockchain in a tamper-proof fashion. Transactions can be automatically enforced by the use of smart contracts, which are software applications that are deployed to the blockchain and auto-execute based on the state of the ledger. As such, the ethos of TES’ align well with the ethos of blockchains, where blockchains are non-discriminatory due to consensus based decision making, observable and auditable due to the immutability property of the distributed ledger, and peers within the network can be held accountable due to the enforcement of smart contracts. Moreover, blockchains obviate the need for a trusted, centralized point of authority to operate/administer the TES, thereby allowing the trustless interaction of multiple peers within the TES.

Blockchain based TES’ have proven popular in both academic and real-world initiatives. However, its main use case has been applied to the implementation of decentralized energy trading systems, which is the focus of approximately 33% of all active projects within this space [8]. The objective of such systems is to exemplify how the implementation of local energy markets can result in the mitigation of large power imbalances while also unlocking new revenue streams for prosumers. The most publicized example is the Brooklyn microgrid (developed by LO3), where a neighborhood of 10 homes can directly sell their excess solar energy to each other at a price and time of their choosing. The system is implemented via Ethereum based smart contracts and based on the practical byzantine consensus protocol (PBFT) [9]. Further variations in academia can be found in [10], [11], [12], [13], all of which utilize smart contracts to facilitate transactions amongst peers as well as to implement a mathematical function to ensure that the market price of electricity is fair and equitable (social welfare maximization, double auction). However, the aforementioned work does not mention the possibility of fraudulent transactions between peers and its impact on energy trades between peers in the future, nor does it discuss how blockchains or smart contracts could be utilized to prevent such an occurrence.

To that end, this paper proposes a novel blockchain based TES that moves away from standard energy trading applications and focuses instead on service oriented transactions that improve power system operation. The system enables distributed peers (referred to as agents) to operate their DGs in an economically strategic manner to provide grid reliability services in the form of distributed voltage regulation. Voltage regulation is a critical component of power system operation and control, and is greatly affected by the penetration of DGs within the grid as voltage has a direct relationship with power generation. In particular, overproduction of power from DGs can lead to overvoltage situations, which can cause overheating and damage to power system infrastructure, while undervoltage can lead to system collapse [14]. Voltage violations can be mitigated by the strategic operation of DGs, and therefore, the agent willing to provide such services can and should be financially compensated.

The implementation of the system is exemplified within a power system that is divided into several zones that each represent a prototypical microgrid, and where each agent must regulate the voltage in its own zone. In the event of voltage violations, an initiating agent solicits bids from neighboring agents and awards a service contract to the most suitable agent. A reputation rating is maintained for each agent that is increased for each successful mitigation of a voltage violation, and is penalized heavily if an agent engages in fraudulent transaction. A negative reputation rating has a significantly negative impact in the ability of the agent to procure bids in the future. The agent negotiation process is implemented as a smart contract and is based on a modified version of the contract net protocol (CNP) [15]. The CNP is enhanced by adding an enforcement stage after service contracts have been awarded to an agent, where the smart contract validates the service contract by checking the latest power measurement values of agent DGs on the ledger to verify the successful mitigation of a voltage violation. To validate the system as a proof of concept, two sets of experimental results are presented. The first set of results utilize a model of a power distribution system and executes the proposed TES to ensure that voltage violations can be mitigated effectively. The second set of results involve a real-world implementation of the TES at a smaller Canadian microgrid located in Vaughan, Canada.

The contributions of this paper are as follows:

1) Proposing the novel implementation of a distributed voltage regulation algorithm using blockchain technology. To the best of the authors’ knowledge, only one previous paper has explored voltage regulation in this context, but neglects to explore penalization of fraudulent transactions or incentive schemes for voltage regulation services. [16].
2) Modifying an existing agent negotiation protocol (CNP) by adding an enforcement stage and implementing it as a smart contract to handle the initiation, negotiation, and finalization of all service contracts between agents.
3) Execution of a real-world, off-chain simulation at a Canadian microgrid to demonstrate how voltage violations can be mitigated by distributed control and communication.

The organization of the remainder of the paper is as follows. Section II provides background of the real-world microgrid where the simulation results were executed, and describes the challenges the microgrid operators face in addressing voltage regulation. Section III presents the system modeling of a typical power distribution system and defines the mathematical relationship between a power injection of an DG and the system voltage. Section IV introduces the distributed voltage regulation algorithm and provides design principles for its implementation using the blockchain. Section V introduces the blockchain system architecture and design of the smart contracts to facilitate the agent negotiation process. Section VI presents a selection of case studies to demonstrate the efficacy of the TES, where the simulations are executed on a large, simulated microgrid, as well as a smaller, real-world microgrid. Finally, Section VII is reserved for conclusions and future work.
2 INTRODUCTION TO THE KORTRIGHT CENTRE MICROGRID

The Kortright Centre Microgrid (KCM) is an initiative of the Toronto and Region Conservation Authority (TRCA), which is the largest conservation authority in the Canadian province of Ontario. The KCM is managed by the Sustainable Technologies Evaluation Program (STEP), whose mission is to increase awareness and adoption of innovative low-carbon, green infrastructure solutions by way of real-world demonstrations. Constructed in 2009, the KCM consists of over 75 kW of renewable power capacity (solar panels and wind turbines), over 100 kWh of battery energy storage, and two smart buildings that have intelligent, energy saving thermostats. In total, the KCM spans over 2 acres of land and has over 700 monitoring and control points dispersed throughout the area. Fig. 1 shows the solar field and smart homes of the KCM. Starting in 2020, the KCM will construct 7 additional smart buildings that will be owned by different stakeholders, each with varying degrees of renewable DGs, energy storage, and loads.

KCM operators face significant challenges in managing the KCM due to its unique voltage profile, which is dominated by the dynamics of its solar and wind DGs. With peak renewable power generation at 75 kW and a peak demand of only 15 kW, the KCM produces significant excess power even on moderately sunny days. As mentioned earlier, there exists a positive correlation between power generation and voltage, in that power injections lead to an increase in voltage. As such, the KCM experiences significant overvoltage violations on a regular basis. The overvoltage violations create excess heat that have caused damage to critical microgrid infrastructure, and regularly trip/reset protective devices that require manual intervention to reset. A 2 hour plot showing the extent of the overvoltage violations at the KCM is shown in Fig. 2, where the normal operating voltage of the microgrid should be 240V. According to power system standards in Ontario, the maximum threshold for normal operation for 240 V systems is 250 V (approximately 4.2% of the nominal 240V), while the maximum threshold for extreme operation is 254 V (approximately 5.2% of the nominal 240V) [17]. As seen in the figure, the voltage measured at the KCM violates even the extreme operating conditions for hours at a time.

As such, an implementation of voltage regulation services under a TES paradigm would greatly benefit the KCM operators in preventing overvoltage violations and reducing damage to critical infrastructure. Furthermore, recall that the microgrid will accommodate seven new buildings within the next year, each of which belong to different stakeholders and will possess varying degrees of additional generation capability. A blockchain based TES will certainly be needed to facilitate and keep track of the level of contribution that each building will have in the successful mitigation of voltage violations, as well as to operate the TES in a non-discriminatory and trustless manner.

3 MODELING OF POWER DISTRIBUTION SYSTEMS

A modern power distribution system is shown in Fig.3, where its infrastructure consists of a substation, buses, distribution lines, DGs, and loads. The electric utility (or distribution system operator) operates the substation, which is responsible for receiving power from the upstream transmission system, stepping down its voltage to an appropriate level for the distribution system, and delivering it through the downstream distribution lines. The lines connect different buses together, which represent interconnection points in the system and are analogous to nodes in networks. In the figure, DGs and loads are connected to buses \( \{i, j, k\} \).

The power flow within the system is dictated by the supply and demand of the DGs and the loads, respectively. If the total demand is greater than the supply of the DGs, power flows from the substation to the downstream loads. If the total demand is less than the supply of the DGs, power flows from the DGs back towards the substation, which is undesirable due to high power losses. Typically, the utility owns and is responsible for the operation of the substation and distribution lines, while the DGs and loads are owned by the prosumer (agent).

Power flow within distribution system is typically alternating current (AC), where sinusoidal waveforms of current and voltage operate at a fixed frequency. When both waveforms are in phase, their multiplicative product generates active power, and all power is transferred to the loads to do useful work. However, when the waveforms are not in phase, reactive power is generated, where power is stored by the load for one cycle, and returned to the source in the next cycle. Motors and lighting ballasts are examples of loads that require reactive power. In power distribution systems,
both active and reactive power injections have an affect on system voltage, which will be seen in the remainder of the subsection.

Generally, both the active/reactive power flows within line $i$ that connect buses $i$ and $j$, as well as the voltage at bus $i$ can be expressed at time instant $t$ as [18]:

$$ P_i(t) = P_j(t) + \sum_{n=1}^{n=j-1} (P_{L,n}(t) - P_{DG,n}(t)) $$

$$ Q_i(t) = Q_j(t) + \sum_{n=1}^{n=j-1} (Q_{L,n}(t) - Q_{DG,n}(t)) $$

$$ V_i^2(t) = V_j^2(t) - 2 \sum_{n=1}^{n=j-1} (r_n P_n(t) + x_n Q_n(t)) $$

where $n$ is the line iterator, $\{P_n, Q_n\}$ are the output active/reactive powers, $\{P_{L,n}, Q_{L,n}\}$ are the active/reactive loads, $\{P_{DG,n}, Q_{DG,n}\}$ are the injected active/reactive powers from the DGs, $V_i$ is the voltage at each bus, and $\{r_n, x_n\}$ is the resistance/reactance of each line (its overall internal impedance). It should be noted that while (1) and (2) have been formulated with respect to active/reactive (P/Q) injections from DGs, it can be generalized to any distributed energy resource (DER) that is capable of controlling its output P/Q, such as battery energy storage systems (BESS). DGs are capable of injecting active power within a system, as well as injecting and absorbing reactive power.

From (1)-(3), it can be seen that changes in the injected/absorbed active and reactive power play a dominant role in shaping the voltage profile of the overall network. Assuming the system is in steady state allows the neglect of the change in load demand, and further linearization of (3) leads to:

$$ \Delta V_i(t) = \frac{1}{V_i(t-1)} \left[ V_i(t-1) \Delta V_i(t) + \Delta P_{DG,i}(t) \sum_{n=i}^{i-1} r_n x_n + \Delta Q_{DG,i}(t) \sum_{n=i}^{i-1} x_n \right] $$

The voltage at the substation is typically very stiff given the overall impedance of the main grid. Given this, the substation voltage ($V_1$) is typically held steady and $\Delta V_1$ can be set to zero. This results in:

$$ \Delta V_i(t) = \Delta P_{DG,i}(t) \sum_{n=i}^{i-1} r_n x_n + \Delta Q_{DG,i}(t) \sum_{n=i}^{i-1} x_n \frac{1}{V_i(t-1)} $$

It is now possible to determine the sensitivity of each bus to any P/Q power injection/absorption as follows:

$$ SP_i = \frac{\partial V_i}{\partial P_i} = \sum_{n=i}^{i-1} r_n x_n, \quad SQ_i = \frac{\partial V_i}{\partial Q_i} = \sum_{n=i}^{i-1} x_n $$

Further, the impact of any control action (changes in P/Q) at bus $j$ on the voltage at bus $i$ can be expressed by:

$$ \Delta V_i(t) = \frac{1}{V_i(t-1)} \left[ V_j(t-1) \Delta V_j(t) + \Delta P_{DG,j}(t) \sum_{n=j}^{j-1} r_n x_n + \Delta Q_{DG,j}(t) \sum_{n=j}^{j-1} x_n \right] $$

From (7) it can be seen that the penetration of large amounts of DGs within power systems can both cause and mitigate voltage violations. Large injections of active power may result in an overvoltage violation, whereas the curtailment of active power and/or absorption of reactive power may resolve the violation. As such, strategic coordination amongst agent owned DGs is required to ensure that the voltage throughout the system is within normal operating conditions. However, this exposes the overall system to a trust issue, wherein the system voltage is largely dependent on the control actions decided by disparate agents. Mitigating this trust issue is one of the key features of the blockchain, and this will be discussed in the following subsection.

### 3.1 Design Principles for Blockchain Implementation

Recall that under the proposed TES paradigm, agents are awarded service contracts to mitigate voltage violations via the P/Q operation of their DGs. The critical question, therefore, is how to utilize the blockchain to trustlessly enforce and validate such service contracts. Smart contracts are an ideal candidate for this task, however, the information the smart contract would need from the ledger, as well as the business logic required to properly validate the service contract must be defined. The required business logic is defined in (7), where the level of impact of any agent owned DG due to its power injection can be assessed in terms of its level of contribution towards a voltage violation. This logic would therefore require a static, $n \times n$ matrix of the sensitivity of each bus towards P/Q modulation, the latest P/Q measurements of each DG averaged over a discrete time interval, as well as measurements of voltage at every bus in the system.

The latter two measurements are readily observed by the deployment of smart meters throughout the system, however, the on-chain complexity of storing this metered data may severely degrade the performance of the blockchain over time, which is a critical feature that limits its scalability [19]. This type of big data challenge is faced in power
4 PROPOSED DISTRIBUTED VOLTAGE REGULATION ALGORITHM

So far, the discussion of voltage regulation has been considered in the context of a centralized implementation. A distributed implementation involves spatially partitioning the power distribution system into several zones, each governed by a software-based agent as seen in Fig. 4. It is assumed that the agent owns and operates the DGs within its zone and is responsible for regulating the zonal voltage. If it is unable to mitigate a voltage violation in its own zone, it may solicit bids from neighboring agents to help resolve the violation, as seen in Eq. (7). The neighboring agents compute a price for their services, send a bid to the initiating agent, and if successful, are awarded a service contract that involves altering the P/Q output of its DGs to resolve the violation. As such, this section will discuss the algorithm that is divided into three stages. The first stage utilizes real-time measurements from smart meters within the zone to obtain state estimates for the voltage profile of the zone to determine the presence of any violation. The second stage presents the mathematical formulation of how agents aim to bid for the procurement of a service contract.

The third stage describes the negotiation protocol that the agents use to come to consensus on how bids are fairly won. A flowchart is provided in Fig. 5 to support the description of the algorithm. Most importantly, design principles for a blockchain-based implementation will be included with each stage of the distributed voltage regulation algorithm. It should be noted that for the purposes of this paper, the assumption is that each zone has only one DG, each agent does not especially trust each other, and that the configuration of the zonal boundaries is pre-decided to satisfy the power adequacy constraint as in [24].

4.1 Stage I: Detection of Zonal Voltage Violation

Referring back to Fig. 4, each zone is defined as zone \( z \), and governed by an agent with unique ID \( A_{ID} \). All zones are coupled with each other such that they have one bus in common, referred to as the point of zone coupling \( PZC_z \). A small deployment of smart meters are placed at specific buses within the zone, which the agent can query in real-time to obtain measurements of power generation, demand, and voltage at specific buses. As discussed earlier, state estimation can be performed by the agent to take these partial measurements and subsequently estimate the voltage at each bus within the zone. Upon computing the estimate of all voltages within its zone, the agent can determine the presence of any voltage violation and attempt to resolve it locally and/or initiate negotiations with neighboring agents to resolve the violation. In the latter case, the agent must
determine the voltage required at the PZC of its neighboring zones that would effectively mitigate the violation in its own zone. This can be determined from the following sensitivity equation:

\[
\frac{\partial V_{\text{PZC},z}}{\partial V_i} = \frac{V_{\text{PZC},z}(t) - V_{\text{PZC},z}(t-1)}{V_i(t) - V_i(t-1)}
\]  

(8)

where \(V_{\text{PZC},z}(t)\) is the voltage at the PZC of the violated bus \(i\), and \(V_i\) is the voltage at the violated bus. The value of \(V_{\text{PZC},z}(t)\) will be sent to each neighboring zone as the target setpoint of the voltage at the shared bus between the zones, as given by the power system standards governing the region.

From the perspective of the blockchain implementation, the querying of real-time data from the smart meters, as well as the state estimation process can be done off-chain to reduce the amount of data stored to the ledger. The estimate of the zonal state of the agent does not hold value for the rest of the agents, nor is there a trust issue that requires consensus from other zones. For these reasons, the communication between agents and smart meters is best done via a low-bandwidth communication middleware such as Data Distribution Service (DDS), as discussed in [25], [26].

4.2 Stage II: Determination of Agent Bid Prices

A realistic implementation of a TES involves a competitive market that allows disparate agents to offer bids for services in return for economic compensation. Therefore, agents are self-interested and rational, focused on earning as much revenue as possible while also maintaining their zonal voltage. The agent can earn revenue via the strategic operation of the DGs in two ways: selling excess active power back to the grid at the wholesale price of electricity, or modulating the P/Q output of the DG to mitigate a voltage violation as a grid service. An agent must ensure that the control actions it selects for its DGs are economically and operationally viable. The selection of control actions is reminiscent of a classic optimization problem, wherein the agent finds optimal values for its control actions \(\{\Delta P, \Delta Q\}\), depending on device and system constraints, while seeking to be as profitable as possible. It is important to note that the optimization is run only when there is an instance of a voltage violation, and as such, is an online process. This results in the control actions and constraints being time-varying. The control actions available to each zonal DG are its active and reactive power output:

\[
X_z = \{\Delta P_{DG,z}(t), \Delta Q_{DG,z}(t)\}
\]  

(9)

The constraints revolve mainly around the physical operational limits of the zonal DGs as well as the physical constraints of the distribution system infrastructure of the zone itself. The constraints for the DGs are as follows:

\[
C_{DG,z} = \begin{cases}
P_{DG,z}(t) \leq P_{\text{MAX,DG},z}(t) \\
Q_{DG,z}(t) \leq Q_{\text{MAX,DG},z}(t) \\
\sqrt{P_{DG,z}(t)^2 + Q_{DG,z}(t)^2} \leq S_{\text{MAX,DG},z}(t)
\end{cases}
\]  

(10)

where \(P_{\text{MAX,DG},z}, Q_{\text{MAX,DG},z}, S_{\text{MAX,DG},z}\) are the maximum ratings of the active, reactive, and apparent power settings of the DG. Apparent power is the vector sum of active and reactive power. It is worth noting that \(P_{\text{MAX,DG},z}\) is further constrained by the availability of the input fuel of the DG (whether gas, diesel, solar irradiance, or wind speed).

The physical constraints of the zone are to obey the maximum current carrying capacity of each distribution line and to maintain the voltage between specified limits for each bus within the zone.

\[
C_z = \begin{cases}
I_{i,z}(t) \leq I_{\text{MAX}}^i, & \forall i \in F^z \\
V_{\text{MIN}}^i \leq V_{i,z}(t) \leq V_{\text{MAX}}^i, & \forall i \in M^z
\end{cases}
\]  

(11)

where \(I_{\text{MAX}}^i\) is the maximum carrying capacity of a distribution line, \(V_{\text{MIN}}^i, V_{\text{MAX}}^i\) are the minimum and maximum voltage limits at each bus \(i\), \(F^z\) is the set of all lines within zone \(z\), and \(M^z\) is the set of all buses within zone \(z\).

Finally, the objective function of each agent can be formulated as:

\[
F = \begin{cases}
\text{Max} \rightarrow R_z(t) \\
R_z(t) = R_{DG,z}(t) + R_{SRV,z}(t)
\end{cases}
\]  

(12)

where, \(R_{DG,z}(t) = PR_P(t) \times (P_{DG,z}(t) \times \Delta t)\)

(13)

\(R_{SRV,z}(t) = PR_Q(t) \times Q_{DG,z}(t) \times \Delta t + R_{DG,z}(t) \times \alpha\)

(14)

where \(R_z(t)\) is the overall revenue of an agent commanding zone \(z\), \(R_{DG,z}\) is the revenue associated with the selling of excess active power back to the grid, \(\Delta T\) is a fixed amount of discrete time, \(R_{SRV,z}\) is the revenue associated with providing voltage regulation as a grid service to other agents, \(PR_P\) is the wholesale price of active power that is assumed to be set by the transmission system operator in the day-ahead market [27], \(PR_Q\) is the price of reactive power that can be set arbitrarily by the agent, and \(\alpha\) is a markup factor that is used when a DG must reduce its active power injection to help mitigate a voltage violation. An example of the usage of markup factor would be when a zone has an overvoltage violation, and requests another zone to reduce the voltage at its PZC. If the neighboring zone must reduce its active power generation to lower the voltage and resolve the violation, it will result in a loss of revenue as per (13). As such, a markup factor can be added to the grid service to ensure that the agent receives some profit instead of simply meeting its marginal costs. The value of the markup factor can be arbitrarily decided by the agent.

Solving the above optimization problem results in the precise values for the \(\Delta P\) and \(\Delta Q\) setpoints of each DG in the zone that can potentially mitigate a local or neighboring voltage violation, as well as the final price of the agent bid. Agents may still solicit bids from neighboring agents while being fully capable of resolving the voltage violation locally if the bids are less expensive than the local operation would cost.

In order to further incentivize agents to participate in the mitigation of voltage violations, as well as to guard against fraudulent transactions, a reputation rating system is established amongst all agents. The reputation rating is a reflection of both the ability and trustworthiness of the
agent to provide voltage regulation services to the rest of the agents in the system. It is a crucial metric that heavily influences the procurement of voltage regulation services that earn additional revenue for the agent. The reputation rating of the agent is increased with each successful mitigation of a voltage violation request, with the increase being proportional to the severity of the voltage violation as follows:

$$G_{AID}^{\text{NOW}} = G_{AID}^{\text{PREV}} + \gamma \Delta V$$ (15)

where $G_{AID}^{\text{NOW}}$ is the reputation rating for an agent, the superscripts $\text{NOW}$ and $\text{PREV}$ are representations of the current and previous reputation ratings, respectively, $\Delta V$ is the magnitude of voltage deviation, and $\gamma$ is a scaling factor that can be arbitrarily set in consensus with all agents within the system. If an agent engages in a fraudulent transaction, harsh penalties are imposed on its reputation rating by setting $\gamma$ to a negative value. Reputation ratings are taken into account when agents compete in the bidding process to procure grid services, and a negative reputation rating greatly affects the ability of an agent to generate revenue for itself. This is explored in further detail in the next subsection.

Returning to the design of the blockchain implementation of the algorithm, the execution of the optimization problem can be done off-chain, as it does not require any of the existing data from the ledger. It is assumed that the sensitivity factors that are stored on the ledger are also available in the local memory of the agent in order to solve the optimization problem. However, the maintenance of the reputation rating metric is something that must be stored and updated on-chain via consensus, particularly since it is a sensitive metric that affects the revenue generating ability of the agents. As such, allowing a smart contract to automatically adjust the reputation rating of an agent after validating the successful mitigation of a voltage violation is a feasible solution to this problem. This obviates the need for one of the agents, or a central authority, to manage the reputation rating of all agents.

4.3 Stage III: Agent Negotiation Process

To lend structure to the negotiation process between the agents, the well-known contract net protocol (CNP) is proposed. The CNP was originally introduced in 1981 as a negotiation protocol to be used in multi-agent systems to allow for efficient task allocation between agents [15]. Agents using the CNP can be “initiators” or “responders”, in which initiators request assistance from responding agents to complete a particular task. The CNP has three stages, which are: announcement, bidding, and assignment. In the announcement stage, initiators that require assistance for a task send a “call for proposal” (CFP) to other agents that request them to submit bids to obtain a prospective service contract. In the bidding stage, responding agents compute and submit bids to the initiator. Finally, in the assignment stage, the initiating agent evaluates the contracts and awards them to the agent(s) that have the best proposal, where the term “best” is dependent on the context of the problem at hand. It is worthwhile to note a responding agent can choose to “subcontract” a task to another agent, thereby becoming the initiating agent for the subcontract.

An example of the three stage CNP is described below as an negotiation process between initiating Agent $A_{IN}$ and responding Agents $A_{R}$ that are neighbors of Agent $A_{IN}$. It should be noted that the magnitude of voltage violation will be addressed symbolically, however, it is assumed that they are represented in the per unit style (p.u.), which represents all system quantities as fractions of a base unit value:

1) Announcement: Agent $A_{IN}$ encounters a voltage violation and determines the magnitude of voltage deviation needed at its PZC with Agent $A_{R}$, $\Delta V_{PZC,z}$. This is computed using (8). Agent $A_{IN}$ initiates a CFP to Agents $A_{R}$ in the form of a four-tuple $\{AID, CFP, \Delta V_{PZC,z}, \Delta T\}$, where $AID$ is the initiating Agent ID, $CFP$ is the ID of the CFP, and $\Delta T$ is the timeout period (in seconds) that specifies how long the bid will remain valid.

2) Bidding: Agents $A_{R}$ evaluate the CFP by determining its feasibility using (9)-(11). If successful, each $A_{R}$ sends back a reply in the form of $\{AID, CFP_{ID}, PR_{BID}\}$, where $PR_{BID}$ is the price of the bid and is computed by (12).

3) Assignment: Agent 1 collects all bids and multiplies the bid price with the reputation rating at each agent to determine the final bid price. The lowest bid of the Agents $A_{R}$ is awarded the service contract in the form $\{AID, CFP_{ID}, DEC\}$, where $DEC$ is a binary decision variable (1 for assignment, 0 for rejection).

It can be seen that the determination of the best proposal is a function of the bid price, as well as the reputation rating of the agent. Therefore, it is vital that the agent maintain a positive reputation rating to enhance its chances of generating revenue for itself.

Within a blockchain implementation, it can be seen that all agent transactions should be executed off-chain since each transaction contains all the pertinent information that can be used to enforce the awarded service contract. This information includes: the bid price agreed upon by the agents, the timeout period until the bid is valid, and the magnitude of voltage violation the agent agrees to mitigate. Using this information, a smart contract implementation of the CNP would be used to: i) validate that the initiating agent has enough money to pay the responding agent, ii) verify that all bids received past the timeout period are invalid, and iii) enforce the service contract post-assignment by checking the P/Q measurements of the responding agent on the ledger along with the voltage measurements at the PZC to determine that the violation was mitigated by the rightful service provider.

The enforcement of the service contract between agents warrants a modification to the existing CNP by adding an enforcement stage after the assignment stage. If the smart contract determines that the service contract was invalidated due to a fraudulent or failed transaction, penalties should be levied upon the reputation rating of the responding agent and the announcement stage should recommence with a new voltage deviation magnitude.
5 Blockchain Implementation of the TES

In reviewing the earlier outlined design principles for the blockchain implementation of the TES, the following observations have been made:

1) The ledger should store the following data: P/Q measurements of each DG, voltage measurements from smart meters deployed at the PZC, voltage sensitivity factors of each bus within the system, reputation ratings of each agent, all CFPs, bids, and awarded service contracts.

2) Of the above ledger data, the only items that require dynamic updates are the reputation ratings and the current dollar amount of each agent. The rest are appended as new blocks at the end of the ledger.

3) A smart contract implementation of the CNP should facilitate all aspects of an agent transaction, from sending a CFP, evaluating the bids, awarding the service contract, and enforcing the contract. After the enforcement stage, the smart contract should update the reputation rating of the agent providing the service and arrange for the payment of the bid price of the service contract.

4) Procedures involve state estimation of the voltage profile of the zone, as well as the computation of bid prices should be conducted off-chain.

From the above design principles, it can be seen that the role of the blockchain is to obviate the need for an external central authority to manage the complexity of regulating the system voltage in the presence of disparate agents. This role is traditionally played by power distribution system operators (DSO), given that they own and operate the distribution system. In the proposed implementation of the TES, the role of the DSO is implemented in the form of a smart contract. For this reason, another design principle should be to enforce that the network should be private and permissioned, instead of public and permissionless. Unlike permissionless blockchains that are completely open to the public (e.g. Bitcoin), permissioned blockchains require an invitation to join the network. As a result, the identities of the agents within the network can be known [28]. Permissioned blockchains have found success in use cases where there are shared business networks in which agents i) might have conflicting incentives or ii) do not necessarily trust each other, yet must still conduct transactions for a shared business objective [29], [30], [31], [32]. Since an invitation is required to participate in a permissioned blockchain, the consensus algorithm is not susceptible to Sybil attacks, alleviating the concerns about scalability and excessive energy usage associated with permissionless blockchains [33], [34]. The remainder of the section will discuss the system architecture of the TES and implementation of the smart contract.

5.1 Blockchain System Architecture

The proposed blockchain system architecture is depicted in Fig. 6, where the vital components are the ledger, smart contract, front-end interface, and the agent wallets. The front-end interface is the interface by which a human operator can access data inside the ledger. Within the ledger, P/Q measurements are timestamped and indexed by the owning agent, the reputation rating is maintained as a flat array, the sensitivity factors are stored as an nxn matrix, where n is the number of buses within the system, and service contracts are stored as a standard data structure. The smart contract is utilized by the agents to execute all stages of the CNP process, as indicated by the method names in the figure. The agents access the blockchain either to record measurements to the ledger or trigger instances of the smart contract when a voltage violation is encountered. It is assumed that the smart contract receives real-time P/Q measurements from
smart meters that are placed at the output of the DGs within
the agent’s zone and automatically stores the measurements
to the ledger in discrete time intervals. Each agent has a wa-
let that stores its public and private keys \(SK_{ID}, PK_{ID}\),
respectively. The public/private keys are used by the agent
to digitally sign and verify transactions within the network.

### 5.2 Smart Contract Implementation

The implementation of the smart contract is devised as
a set of functions that mirror the CNP process, with an
added stage for the enforcement of service contracts. The
pseudo code for the smart contract is depicted in Algorithm
1, while a more detailed description is given below. For
the remainder of the text, \(A_{ID}\) will describe the unique ID
assigned to an agent, but to differentiate between initiating
agents and responding agents, the terms \(A_{IN}\) and \(A_{R}\) will
be used, respectively.

1) \textit{initAccount()}: This function initializes an account
for the agent and assigns it an ID based on its
zone number. To verify the identity of the agent
calling this function, an input message that defines
the Zone ID and is digitally signed by \(SK_{ID}\) must
be provided to the function. Upon verification, the
functional initializes the number of dollars in the agent
wallet to zero (\(B_{ID}\)).

2) \textit{createCFP()}: This function is called by an initi-
ating agent, \(A_{IN}\), and creates a CFP that stores the
Agent ID, a unique ID for the CFP, the required
change in voltage needed at the PZC \(\Delta V_{PZC,z}\),
as well as a timestamp for when the bid will expire
\(expiryCFP\). The \(A_{IN}\) signs the CFP with \(SK_{IN}\)
and this generates a new CFP on the blockchain.

3) \textit{replyCFP()}: This function is called by agents, \(A_{R}\),
responding to an active CFP with a bid price. The
function validates the incoming bid by checking i)
if the price of the bid is less than the balance of the
initiating agent and ii) if the recorded timestamp of
the bid is less than the expiry time of the CFP. If both
conditions are true, the bid is added to a list stored
in memory.

4) \textit{assignCFP()}: This function is auto-executed when a
bid expires. The latest reputation ratings for each
agent are retrieved from the ledger, multiplied by
bid price, and sorted in ascending order. The lowest
cumulative bid is assigned the service contract.

5) \textit{enforceCFP()}: This function is auto-executed after
the execution of the assignCFP() function. Using the
latest P/Q measurements on the ledger for \(A_{R}\) over
a configurable time \(\Delta T\), as well as the sensitivity
factor of the bus where the DG of \(A_{R}\) is located,
the change in voltage magnitude at \(\Delta V_{PZC,z}\) can be
calculated and checked against the value specified
in the service agreement. If successful, the function
updates the reputation rating of the responding
agent and transfers the balance from the initiating
agent to the responding agent using (15). If not,
the responding agent’s reputation rating is heavily
penalized.

### 6 Experimentation Results

Two sets of experimentation results have been prepared to
demonstrate the efficacy of the proposed system. The first
set of results is conducted on the IEEE 37 bus system test
case that is depicted in Fig. 4, and is representative of a real-
world power distribution system. The second set of results is
from a real-world experiment conducted at the KCM. Experi-
ments were conducted off-chain, where the first experiment
was simulated using MATLAB and the second experiment
involved controlling the smart inverters with the MODBUS
protocol and DDS to facilitate inter-agent communication.
The discussion of the results will still reference the role of the
blockchain and smart contract within the implementation of
the results.

### 6.1 Case Study: IEEE 37 Bus Power System

The settings for the DGs within the system are shown in
Table 1, where the pricing for reactive power follows the
ranges of real-world power system operators as reported
in [35] and [36]. The markup factors have been arbitrarily
initialized, however, can change depending on the bidding
process. The reputation ratings for all agents are initialized
to 1, while its scaling factor is set to 10. The DG type is
assumed to be solar.

| DG Index | \(P_{MAX}\) | \(Q_{MAX}\) | \(PR_{P}\) | \(\alpha\) |
|----------|------------|------------|------------|-------|
| 1        | 1.0        | 0.6        | 1050       | 1.1   |
| 2        | 1.5        | 0          | 0          | 1.3   |
| 3        | 1.0        | 0.5        | 1200       | 1.2   |
| 4        | 1.0        | 0.5        | 1100       | 1.1   |

The experimentative results are depicted in Figs. 7-10,
based upon a 12 hour snapshot between the hours of 6:00
AM and 6:00 PM. Fig. 7 shows the active power generated
from the DGs, as well as its price as set in the wholesale elec-
tricity market, which was gathered from real-data from the
Ontario transmission system operator data archives (IESO).
This work assumes that the DGs use the wholesale price
of electricity as the price of active power, \(PR_{P}(t)\), which
varies hourly. As can be seen in Fig. 7, DGs 1-3 experience
steady active power production throughout the time period,
however, DG2 experiences an outage from the hours of 7:30
AM to 9:30 AM. The direct correlation between active power
generation and voltage can be seen in Fig. 8, where the
voltage profiles for buses 33 and 37 can be seen. As DG
2 faces a power outage at 7:30 AM and drops its generation
to zero, an undervoltage violation occurs in its zone at bus
33. When the DG comes back online and reaches its capacity
at 10:30 AM, an overvoltage violation occurs at bus 37. Both
violations are mitigated by the proposed distributed voltage
regulation algorithm, where Fig. 8 shows the voltage profile
in both uncontrolled and controlled cases. The message
exchange between the agents can be seen in Figs. 9 and 10,
and is also explored in more detail below.

For the first undervoltage violation, Agent 2 issues a
smart contract (ID 1) that generates a CFP to Agents 1 and 3
specifying the voltage magnitude needed at their respective
PZCs to mitigate the voltage. Agent 2 computes a total
reactive power injection of $\Delta Q = 0.5691 \, \text{p.u.}$, and responds to the CFP with a marked up bid of $704, where Agent 3 follows a similar process and comes up with a setpoint of $\Delta Q = 0.1296 \, \text{p.u.}$ and correspondingly submits a lower bid of $257 using obj1. The smart contract evaluates the proposals based on price, since the reputation ratings are equal at this stage, and awards the service contract to Agent 2. The smart contract enters the enforcement state, querying the ledger to find the latest voltage measurement at the PZC of Agent 2 and 3, as well as the latest Q measurement from the DG of Agent 2. After the bid expires, the smart contract penalizes the fraudulent transaction of Agent 3 by 0.034 (multiplying the scaling factor of 10 by the deviation required for mitigation 0.0034 p.u., resulting in the reputation rating being 0.966), and updates the ledger. The smart contract issues a fresh CFP (ID 2), which is readily accepted by Agent 1, which when enforced by the smart contract, leads to a voltage mitigation and an increase in reputation rating for Agent 1 (1.0033). The service contract is honored for 2 hours (until 9:30), when DG 2 comes back online, resulting in a net earnings of $1408 for Agent 1.

In the case of the overvoltage violation, Agent 2 simultaneously generates a smart contract (ID 3) for both neighboring agents, while also computing the total loss to its revenue if it were to curtail the power locally, which is a total curtailment of $\Delta P = 0.3 \, \text{p.u.}$, or $77.7 at the current wholesale price of $222.2 \, \text{p.u.}$ Agent 1 executes (12), and returns with setpoints of $\Delta Q = -0.50 \, \text{p.u}$ and $\Delta P = -0.38 \, \text{p.u.}$, with a corresponding bid price of $750. Agent 3 computes setpoints of $\Delta Q = -0.50 \, \text{p.u}$ and $\Delta P = -0.28 \, \text{p.u.}$, however, seeking to reduce the reactive power needed in an effort to reduce the cost of the bid, Agent 2 issues a CFP to Agent 4 downstream. A new smart contract (ID 4) is generated, which specifies a voltage adjustment at the PZC between Agent 3 and 4 to be -0.0106 p.u.. Agent 4 computes the setpoints of its DGs to be $\Delta Q = -0.50 \, \text{p.u}$ and $\Delta P = -0.2 \, \text{p.u.}$, and returns a bid price of $458 to Agent 3. Agent 3 rejects this bid since the price of its own control actions would itself result in an aggregated bid of over $1000. Seeking to improve its reputation rating, Agent 3 reduces its bid by 90% by applying a negative markup factor, essentially providing the service at marginal cost. After finalizing the bids, the smart contract applies the reputation rating of Agent 3 to compute an aggregate bid price of $70, and assigns the service contract to Agent 3 since it is less than the bid of Agent 1 and also less than the $77 cost it will cost Agent 2 to solve the problem locally. The smart contract
Fig. 11. A single line diagram of the KCM and its controllable assets.

enters the enforcement stage upon verification of the voltage magnitude at the PZC, Z of Zone 2 and 3 (bus 7), as well as the correct P/Q measurements from the DG of Zone 2, the service agreement is validated. The smart contract upgrades the reputation rating of Agent 2 to 0.99. The service is provided for 5 hours, resulting in a net savings of Agent 2 of $35.

6.2 Case Study: Kortright Centre Microgrid

A simplified single-line diagram of the KCM is shown in Fig. 11, where two agents are deployed at buses 3 and 4. At bus 3, there is a 20 kW solar DG (SolarEdge 5000) that is under the command of Agent 1, and at bus 4 downstream, there is a 75 kWh battery bank (Xantrax 6848) and 5 kW electronic load (e-load) that is under the command of Agent 2. In terms of measurements, there is a smart power quality meter deployed at the point of common coupling (PCC), while measurements of voltage are also read directly from the SolarEdge and Xantrax devices at a sampling rate of 1 second. All agents control the devices via the MODBUS protocol, but communicate with each other using DDS, which is a communication middleware used in applications related to the Internet of Things (IoT).

In Fig. 12, two major instances of overvoltage violations are observed at timesteps 53 and 125 (1.052 p.u. and 1.053 p.u., respectively). This is due to the active power generation by the solar DG and the lack of load within the system. This can be seen in Fig. 13, where the net demand of the KCM measured at the PCC is negative, indicating that 0.1 p.u. of active power is flowing back towards the main grid. Once the voltage violation occurs, Agent 1 issues a CFP to Agent 2, specifying the voltage deviation to be -0.02 p.u. Agent 2 evaluates the feasibility of the request by assessing the device constraints of the battery and e-load. Since these devices do not have reactive power modulation ability, the only option is to modulate active power. Agent 2 queries the battery status, and finding that it is not online, immediately switches on the e-load. As shown in Fig. 12, the voltage immediately begins to decrease until it reaches the setpoint of 1.03 p.u. The control action of Agent 2 can be confirmed by observing the plot of the demand of the KCM after timestep 52. Previous to accepting the CFP from Agent 1, the demand was -0.1 p.u., while afterwards, the demand increased to -0.05 p.u., thereby decreasing the voltage at bus 3. The experiment is repeated again at timestep 125 with similar results.

It should be noted that the experiment was conducted off-chain and without incentives, because all agents are operated by the KCM. However, the purpose of the experiment was to prove that strategic, distributed control/communication methods can be effective in mitigating real-world problems. In the case of the KCM, the deployment of the agents has completely mitigated any occurrences of voltage violations.

7 Conclusion and Future Work

This paper proposed a blockchain based, transactive energy system to allow disparate agents that own DGs to provide voltage regulation services to the grid in return for economic compensation. The implementation of these cyber physical computing services were facilitated by the implementation of a smart contract that impartially audits each service contract between agents and enforces its validity by directly observing power measurements on the ledger provided by smart meters throughout the power distribution system. The major contributions of this work were to investigate the impact of fraudulent/failed transactions on power distribution system operation and its financial implications on
agent interactions as a result. As such, the solution proposed a reputation-based rating system that was increased and decreased based on the successful/unsuccessful execution of service contracts between agents, and significantly affected the agents’ ability to generate revenue in future transactions. The efficacy of the system was tested on both a large, simulated model of a power distribution system, as well as a real-world Canadian microgrid, where experimental results showed the ability for distributed agents to resolve voltage violations. Future work within this space involves validating the implementation of the smart contract within a permissioned blockchain platform such as Hyperledger Fabric to ensure that consensus can be achieved in a duration suitable for real-world deployment.

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