Towards Resilient Networked Microgrids: Blockchain-Enabled Peer-to-Peer Electricity Trading Mechanism

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***Abstract*—Integrative various distributed generation in energy infrastructure have brought great opportunities in recent years. However, this integration has also led to critical challenges in energy management, such as congestion pricing and non-optimality of dispatch. To address these challenges, deregulation and decentralization of electricity market is one of the effective solutions. Although various deregulation schemes have been proposed in recent years, there still remain some serious challenges in achieving resilient management of real-time energy deregulation especially in the presence of disasters. To counter this issue, in this paper, we propose a model for a Peer-to-Peer (P2P) transactive microgrid where prosumers (Producer/ Consumer) can trade local generation with each other via a smart management system. Furthermore, in our proposed model, the energy trading is executed in a decentralized manner by leveraging Blockchain technologies. Among different Blockchain technologies, we adopt the Ethereum Blockchain in our work. The auction models for energy trading are proposed by incorporating a smart contract that is the essential component of the Blockchain. In our simulations, the proposed P2P energy trading model is evaluated.**

***Index Terms*—Blockchain, P2P Electricity Market, Contract Theory, Coalition Game, Smart Contract, Distributed Generation.**

I. INTRODUCTION

One of the critical challenges in market planning and demand response management in recent years, is the rapid growth of the electricity demands both in size and scope and this challenge demands novel solutions as well. The conventional architecture of electricity markets is hierarchical, dependent on the centralized generation, inflexible and with a limited pool of bidders with a few sellers and buyers, and restricted scalability. This structure is not efficient in several ways such as restricted Demand Response Manage-ment (DRM) options, inevitable centralized hierarchical con-trol algorithms and the fact that, it is much less adaptable to Distributed Generation (DG) integration. To counter these problems, several solutions have been proposed, such as price-based algorithms (Dynamic pricing) [1], buying demand cuts from consumers [2], and decentralization of generation to local level. Various financial models have also been proposed in order to utilize decentralized generation. Haring *et al.* in [3] presented a comprehensive survey and comparison of various models of load control in which three standard methods of *benchmark approach*, *centralized approach* and *coaition-based* are compared. They claimed that the coalition-based strategy is the most effective method for utility maximization. The work in [4] designed, developed, and implemented architecture building blocks of an energy management system (EMS) for the distribution grids. The work in [5] utilizes Q-learning to implement an optimized decentralized generation dispatch in which results in a dispatch with higher privacy and lower communication demands.

In this paper, we propose a P2P marketing model for electricity trading in residential microgrids between local prosumers. This idea of P2P mechanism has already been widely used in communication and data transfer. This type of electricity market structure, also called *Transactive Grid*, can be described as an electricty marketing model in which a significant portion of the demand is supplied by local generation using small scale DG units. This decentralized model, if fully utilized, can potentially minimize the power transmission dissipation, reduce the probability of cascade failure due to its inherent islanding capability, and obviously minimze the load on the grid by a significant ratio. One of the necessities in implementing a fully decentralized power system is an adaptable and secure financial model. To achieve this goal, we leverage Ethereum Blockchain. Blockchain is a new technology that allows the fast, secure, and reliable transfer of information and logging of transactions. It has the capability, of decentralizing of data, financial and status update. It also has the capacity of informing the status of all nodes in the the network to each other and this makes it suitable for disaster relief efforts, and rescue and support programs using decentralized autonomous sensors. Furthermore, this financial model must be reliable, scalable, secure and certifiable by all parties, and thus in our work we adopt the contract theory proposed in [6] to design the smart contract in which, we define a single local seller (Principle) and multiple buyers (Agents) in an iterative market. The single principle (Seller),

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is defined by incorporating a coalition model between all sellers. In other words, all sellers form a coalition and a single representative of them, takes part in the market and since [7] has proved that, the core of such a game for all sellers is non-empty, we can safely assume that, there won't be any other sellers outside the coalition. We will loosely use the term *aggregator* for this representative.

On the other hand, the buyers, each participate in the market separately and propose their prices. The buyer with the highest price, wins that round and gets to buy electricity. We know that in local markets the average prosumers (Producer/Consumer) do not possess the necessary time, expertise and incentive to form such a market. This is our another motivation to apply Blockchains and smart contracts in our work. Blockchains are decentralized networks of agents, each of which occupying a certain node on the network with a specific address, resources and capital [8]. All events on the Blockchain are certified by all parties, which eliminates the possibility of fraud and ensure the security of the electricity trading. Furthermore, all the financial transactions, taking place on the Blockchain use pre-defined and accepted *smart contracts*. Smart contracts are the protocols that facilitate, verify and implement the contexts of a contract. Smart contracts use the reasoning and structure of normal contracts and furthermore enable the rulings of the contract to be implemented, according to its terms with minimal human intervention [9].

In this paper, we implement our P2P electricity marketing mechanism, by defining a smart contract on the Ethereum Blockchain and thus utilizing a well-defined auction. The smart contract is defined based on the aforementioned contract in certain pre-determined time windows, and it is written in *Solidity* programming language. In the simulations, the generation model for the sellers is simulated based on the model of *SunPower SPR-305E* Photovoltaic (PV) panel from the Simulink Simscape package. The whole platform is tested on the *TestRPC* test Blockchain and the interactive platform is finalized using *Truffle* API. In section II, we will introduce the general structure of the grid and implemented network. In section III, the mathematical model of the coalition game will be introduced and section IV will present a case study of the market and the general conclusions will be presented in section V.

II. Blockchain-based Peer-to-Peer Energy Trading

A. Peer-To-Peer Marketing Modeling

In our proposed mechanism, each residential consumer is equipped with distributed generation units (PV Panels) and smart meters which simultaneously monitor, record and transmit its generation and consumption levels to the smart contract. The microgrid of the said prosumers is connected to the main grid with a singular *Point of Common Coupling* (PCC). In our model, the main grid is able to provide the necessary power supply to the local grid whenever the local generation is not sufficient to meet the demand or purchase the extra generation from the local grids. The energy trading between the main grid and the local grids is realized between the operator of the main grid and the aggregators of the local grids. Obviously, the main grid price for sellers should be designed lower than the local price and the for the buyers should be higher than the local prices to incentivize both buyers and sellers to trade inside the local market. The architecture of the model can be seen in Fig.1. The rules defined in Fig. 1 are applied using JSON

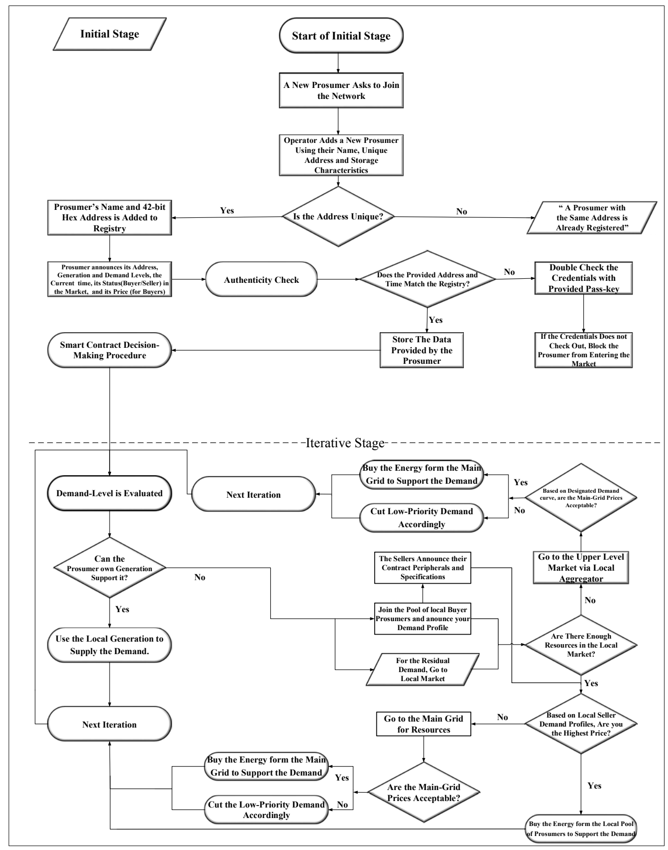

Fig. 1: The Structure of our P2P Market

platform of the prosumers' priorities into our decentralized system.

B. Blockchain-Based Mechanism

As stated earlier, each of the prosumers, also occupies an account on the Ethereum Blockchain with a specific address, and an array of specific characteristics. At each time iteration, all prosumers who want to sell their excessive generation form a coalition to sell their generation in a unified set to maximize their profit. For simplicity, the profit allocation for each individual seller is proportional to the amount of generation that they contribute to the coalition. The buyers on the other hand are completely unaware of each others' decisions and take part in a multiple-stage non-cooperative auction for the available resources at each iteration. The users are given option of adjusting their own demand to support the market in various levels and the result and every single action in the auction happens without the human interaction. The link between the buyers and the sellers aggregator, is the smart contract. There are five essential functions for a smart contract are: (1) Dictating and announcing the start of each iteration of the auction. (2) Receiving the current available resources from the seller coalition and announcing it to the buyers. (3) Waiting until a certain time or until all of the bids of all buyers are received (whichever happens earlier). (4) Comparing all of the buyers' bids, finding and announcing the winner. (5) Finally, transferring the appropriate funds form the account of the winner to the seller coalition. These tasks are done completely autonomous without any third-party oversight and since all of data can be seen publicly (After all bids are announced by the bidders or after the time of that iterations auction passes), there can be no data incest or fraud. The algorithm of the smart contract is illustrated in Fig. 2.

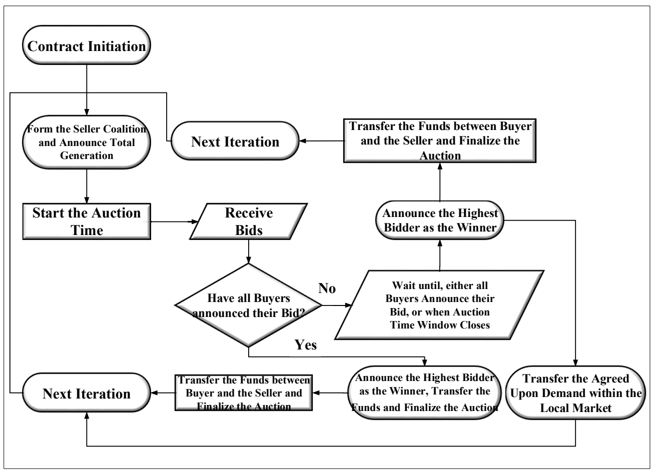

Fig. 2: The Algorithm for the Smart Contract

C. System Implementation Model

In order to implement the proposed algorithm on the Ethereum Blockchain, first we carry out the process on a smaller network using a local Blockchain; for which we use TestRPC test Blockchain [10] to develop our prototype. As mentioned earlier, the contract is written in *solidity* language, we also develop the JavaScript platform to correspond to the agents and objects defined in the contract. We use *Truffle* [11] to create the decentralized system application and to deploy it on to our test Blockchain and set up the market in real time. The structure of this system is presented in Fig.3

III. Contract Theory Based Modeling Scheme

As claimed in [12], any practical contract designed for marketing should satisfy the following three rules: (1) Individual Rationality (IR): Each player in the market acts based on rationality and works towards maximizing its personal gain. (2) Incentive Compatibility (IC): The players will participate in the market only when there are incentives that encourages them to do so. In other words, there always must be a parameter that propels player to actively engage in the market. This principle is usually justified by using financial compensation, which will be detailed later. (3) Preserving utility and satisfaction level: To encourage the consumer to engage and actively participate in the market, there needs to be an acceptable level of satisfaction that keeps them from leaving the market.

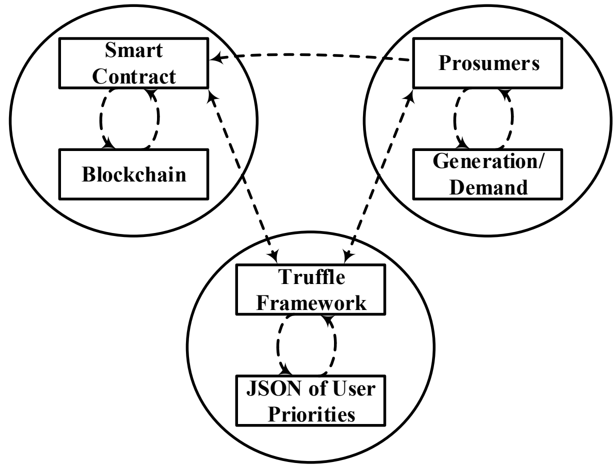

Fig. 3: The Ethereum-based Market Structure Framework

Based on the above principles, we design the coalition and in the second step, its marketing appeal. Each group of geographically related prosumers with residential demand forms a microgrid. As mentioned earlier, each coalition is linked to the wholesale market via an aggregator. The sellers engage in limited P2P energy trading via the associated aggregator. Considering that practically, it is difficult for the local generations to be capable of meeting the demands throughout the whole day. Especially in peak hours, the microgrid demands will always be dependent on the main grid and wholesale market. In this context, the aggregators are market entities that put their financial utility and profit as their main motivation and in the context of the contract, they are considered as the principles of the contract. Based on the current maximum market price X^{t_n}, the coalition's total wholesale generation G^{t_n} and the total payment to the seller prosumers for their contribution to the coalition P^{t_n}, and A^{t_n} as the profit of the aggregator which is not a non-beneficiary entity, the contract is formed. To clarify the structure of both sides of the market, the structure follows this set of rules: the amount that each prosumer *j* contributes to the main market is called $G_j^{t_n}$ which consists of its generation from its DG unit, and based on this local generation, the aggregator will pay the prosumers a collective compensation which is proportional to their level of generation. Each seller will have the option of cutting its own demand to contribute more to the coalition. If, Seller *j* cuts more from its demand to contribute to the sales, its financial turn over will be more and its *satisfaction* level, V_j will be less. The satisfaction level of the seller *j* can be defined as:

$$V_j^{t_n} = \frac{D_j^{t_n}}{D_{j_0}^{t_n}} \tag{1}$$

where $D_j^{t_n}$ and $D_{j_0}^{t_n}$ are, respectively the demand of Seller j, after and before demand cut. We can calculate, the total *available for sale* generation of the coalition as:

$$G^{t_n} = \sum_j \left(G_j^{t_n} - D_j^{t_n} \right) \quad (2)$$

Based on this, the payment of each Prosumer j at Time-step t_n can be calculated as:

$$P^{t_n} = \left(G^{t_n} - A^{t_n} \right) X^{t_n} \quad (3)$$

and A^{t_n} itself is proportional to total sales and in other words it represents a constant ratio of total sales which we call α, so eq. (3) can be rewritten as:

$$P^{t_n} = \left(G^{t_n}(1-\alpha) \right) X^{t_n} \quad (4)$$

Obviously, the transaction should be profitable to the sellers to take part in the market, so the generation profit for each seller prosumer should be higher than its cost of generation. We note the cost of generation for Prosumer j at Time-step t_n as $C_j^{t_n}$. So each seller determines what amount of electricity generation it should contribute to the coalition while preserving its satisfaction by optimizing the following cost function:

$$\underset{j}{\text{Maximize}} \left(P^{t_n} + \sum_{j=1}^{m} V_j^{t_n} \right) \quad (5)$$

$$Subject\,to: \begin{cases} V_j^{t_n} \geq T_j \\ P_j^{t_n} \geq C_j^{t_n} \end{cases}$$

where P^{t_n} is the individual payment of Seller j at the Time t_n for all m prosumers, which as mentioned earlier is proportional to its generation contribution to the coalition and T_j is defined as the minimum acceptable range of satisfaction index for Seller j which is a pre-determined threshold. Therefore P^{t_n} can be calculated as:

$$P_j^{t_n} = \frac{\left(G_j^{t_n} - D_j^{t_n} \right)}{G^{t_n}} P^{t_n} \quad (6)$$

The model stated in Eq. (5) is a convex optimization problem and can be solved with a normal linear programming. Therefore, we can safely assume that based on various thresholds of different sellers, their participation ratio will also vary from prosumer to prosumer.

IV. The Case Study

In our case study, we exploit a system with one hundred prosumers with various satisfaction index thresholds and different demands which form the coalition and unlimited number of potential buyers. The total generation is based on the accumulated generation of the PV panels of the same prosumers. The prices are modeled in a manner to be only dependent on the decision-making priorities of the buyers and the cost of generation as described in previous section. The demand profiles are based on average residential demand in Akron, OH in 24-hour cycles [13]. Considering that showing the behavior of all 100 prosumers can be very chaotic, we demonstrate this behavior using bars which is presented in Fig. 4.

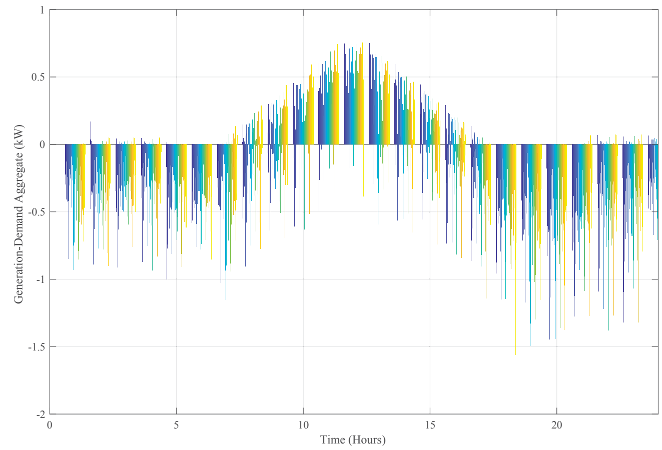

Fig. 4: Generation and Demand of all of the Prosumers in 24 Hours

As shown in Fig. 4, the generation during the sunlight hours is much higher and this causes most prosumers to enter generation mode, which means that their generation is higher than their demand, and thus the whole grid is in excess mode, in which most of the prosummers are self-sufficient and generation outweighs the demand. After the sunlight diminishes and simultaneously the demand increases, the reliability in local market also decreases and the more prosumers are forced to incorporate the main grid to support their demand. In the early morning hours, this trend also follows with this difference that, the demand is lower in those hours and the only possible limited local generation can be from remnants of the local small scale energy storage systems or by discharging electric vehicles. To fully understand the effect of the local transactive grid on the market and the satisfaction level of the prosumers, we present the cumulative demand, generation and satisfaction index of all the prosumers in Fig. 5. As shown in Fig. 5, the demand

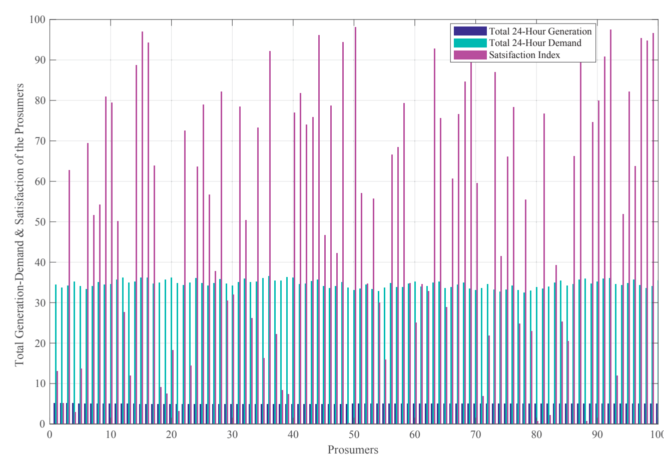

Fig. 5: Total Generation and Demand of all of the Prosumers vs. Satisfaction Index

of all prosumers in 24-hour periods is obviously higher than the local generation. However, we can see that the prosumers who sacrifice their satisfaction level for lower demand counter demand deficit, which is an obvious result of the compromise that they have made. Moreover, Fig.6 compares the ratio of generation to demand versus satisfaction indices. From Fig.6, we can observe that, the prosumers with a higher index of satisfaction have lower generation to demand ratios, which is expected. (Note: In Fig.6, the exact value of satisfaction index is used, which is not the percentage, in order to show the contrast better.)

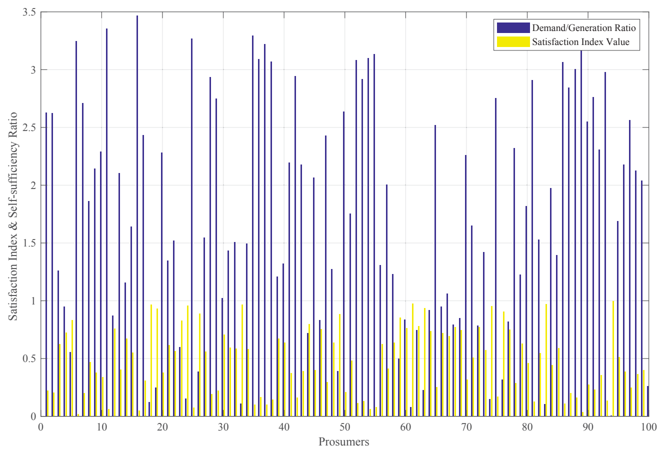

Fig. 6: Demand/Generation Ratio vs. Satisfaction Indices

V. Conclusion

By leveraging the opportunities that the Blockchain provides for us, we develop a transactive electricity marketing model in which local prosumers have the opportunity to engage in P2P energy trading. In our model, we exploit the contract theory to design a smart contract that ensures the real-time trade of electricity with minimal need for oversight. The smart contract provides a significant platform to establish and implement real-time contracts for the electricity market. Our ongoing work moves towards the design of electricity markets with more adaptable smart contracts in which not only inputs and outputs vary but also the structure of the contract will also change to better replicate real life situations.

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