Peer-to-Peer and Real-Time Energy Exchanges with Data Centers in a Transactive Energy Framework

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***Abstract*—Renewable generators can be installed behind-the-meters of the power consumers to offset a portion of the consumers' power loads. Although these generators help in lowering electricity cost of power consumers, they pose serious challenges to the operation of power distribution systems. Namely, the power consumers with behind-the-meter renewable generators compensate for their local generation shortages by adjusting their power draw from the power distribution systems. Consequently, the fluctuations in the local renewable generations are transmitted to the consumers' net loads, i.e. the actual power consumptions of the consumers minus the local renewable generations. The *rapid* fluctuations of the net loads may cause reliability issues in the operation of the power distribution systems, specially at higher levels of renewable energy penetration. To secure the reliable operation of the distribution systems under penetration of renewable generators, there is a need for a mechanism that can counterbalance the rapid fluctuations of the net loads. The transactive energy paradigm is emerging to fulfill this urgent need. This paper studies energy exchanges with data centers in a transactive energy framework. Through numerical simulations, it is shown that the fluctuations of the net loads are 53% more counterbalanced when the data centers' flexibilities are exploited in the transactive energy framework instead of a demand response framework.**

Keywords: Transactive energy, power distribution systems, power flow problem, data centers, demand response.

I. INTRODUCTION

Renewable energy comes with several key benefits, including lower cost of electricity for power consumers and lower carbon emission to the environment [1]. Because of such benefits, major efforts is taking place all around the world to integrate renewable resources of energy in power grids. For instance, wind power accounted for 15% of electricity generation in the State of Texas in 2017 [2, page 112]. Also, it is expected that 33% of the energy in the State of California will be produced from renewable generators by 2020 [3].

Renewable generators can be connected to the power transmission system [4] or power distribution system [5]. Alternatively, the renewable generators can be installed behind-the-meters of power consumers in a power distribution system, so as to offset a portion of power consumers' loads [6]. This later approach in employing renewable generators is specially favorable for design and development of zero-net energy buildings [7] and microgrids [8]. Therefore, this paper focuses on the renewable generators that are operating behind-the-meters of power consumers. Although these generators are helpful in lowering the power consumers' cost of electricity, there are serious challenges in their operations that should be responded to.

The main challenge in utilization of renewable generators is the intermittency in the amount of available energy from them. Namely, the power consumers with behind-the-meter renewable generators compensate for their local generation shortages by adjusting their power draw from the power distribution systems. Consequently, the fluctuations in the local renewable generations are transmitted to the consumers' net loads, i.e. the actual power consumptions of the consumers minus the local renewable generations of the consumers. The fluctuations of the net loads may cause reliability issues in the operation of power distribution systems, specially at higher level of renewable energy utilization [9, page 16]. For instance, the fluctuations of the net loads may combine and cause wider fluctuations in the combined power consumption of the power distribution system [9, page 25], thereby leading to congestion of the distribution lines. [9, page 38].

One mechanism to tackle intermittency of renewable generation is to deploy demand response using the flexibility that comes with certain type of loads [10]. Specially, in dynamic pricing [11] form of the demand response, the flexible loads of the power distribution system react to the price of electricity in the wholesale market which changes according to the availability of renewable generation in the distribution system. To some extend, the demand response framework is effective in addressing the fluctuations of the net loads, however it suffers from a serious shortcoming. Namely, the rapid fluctuations of the net loads are not reflected in the wholesale price of electricity which is updated once in every 15-minutes [12]. Therefore, the the flexible loads cannot react to *rapid* fluctuations of the net loads in a demand response framework.

To secure the reliable operation of the distribution system under penetration of renewable generators, there is a need for a mechanism that can fully counterbalance the rapid fluctuations of the net loads. The transactive energy paradigm [13], [14] is emerging to fulfill this urgent need. In the transactive energy framework, the power consumers with renewable generators enter into peer-to-peer and real-time energy transactions with the flexible loads to compensate for their local generation shortages. As a result of this coordination, while the power consumers with renewable generators increase their power draw from the power grid the flexible loads reduces their power consumptions. In other words, the energy transactions

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helps the power consumers to fulfill their energy demands while keeping the distribution lines uncongested.

This paper studies peer-to-peer and real-time energy transactions between data centers and power consumers with renewable generators. Data centers are big buildings that contain thousands of computer servers to process the computational tasks of their users [15]. From a power-grid point of view, data centers are major power consumers with a high level of flexibility in their power consumptions. This paper proposes a mechanism for data centers to offer energy to the consumers of the power distribution systems in the transactive energy framework. As a part of this mechanism, a bidding strategy is proposed for data centers that guarantees non-decremental profits for the data centers offering transactive energy.

The contributions of this paper are as follows:

- A mechanism is proposed for data centers to enter into peer-to-peer and real time energy transactions with power consumers of a power distribution system.
- A bidding strategy is proposed which guarantees non-decremental profits for the data centers that offer transactive energy in the power distribution systems.
- Using real world wind data, the performance of the proposed transactive energy framework in counterbalancing fluctuations of the net loads is studied numerically.
- It is numerically shown that, the fluctuations of the net loads are 53% more counterbalanced when the data centers' flexibilities are exploited in the transactive energy framework instead of the demand response framework.

The rest of this paper is organized as follows: The operation of power distribution systems and the behind-the-meter renewable generators are discussed in Section III and Section II, respectively. Section IV provides a summary of the transactive energy framework in [16]. Section V discusses the energy exchange with data centers in the transactive energy framework. Numerical simulations results are provided in Section VI. Finally, the paper is concluded in Section VII.

II. OPERATION OF POWER DISTRIBUTION SYSTEMS

A power distribution system receives energy in the form of electricity from the transmission system and distributes it between power consumers. A distribution system may operate in steady state or transient condition, among which the first one is under focus of this paper. Power distribution lines, buses, transformers and voltage regulators are the elements that play a role in the steady state operation of a distribution system. The transformers can be eliminated from the steady state analysis by converting parameters and variables to the per unit system [17, Section 3.3], as will be the case in this paper. The voltage regulators are incorporated in a power distribution system to compensate for voltage drops across distribution lines [18, page 100]. In this paper, the voltage regulators are eliminated from the analysis [19]. The resulted power distribution system can be modeled by a set of distribution lines and a set of buses. Fig. 1 shows the IEEE standard 33-bus system which is used in the numerical simulations of Section VI.

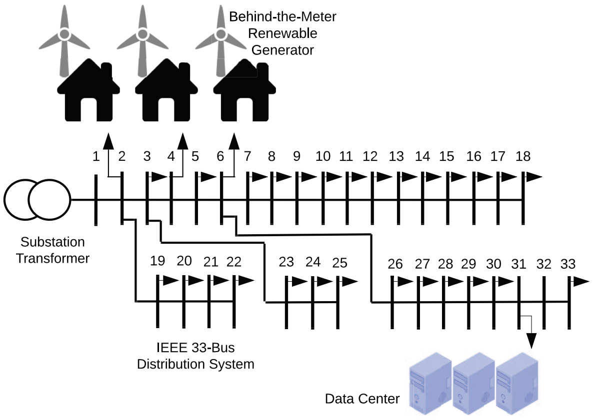

Fig. 1: A data center and three power consumers with behind-the-meter renewable generators exchange energy in a transactive energy framework. The IEEE 33-bus system is selected as the power distribution system.

A. The Bus-Branch Model of a Power Distribution System

This section discusses the bus-branch model of a power distribution system. In a distribution system, the specific bus that is connected to the transmission system is set as the slack bus. Every distribution system has a single slack bus which injects power from the transmission system into the distribution system. Other buses are set as the load buses which interface with electrical loads. The loads in a distribution system consume both real and reactive power. Following a common convention in power system analysis, power exchanges between loads and the distribution system are expressed in terms of power injections to buses [20, Section 5.2]. As a result, the real power P_k and reactive power Q_k injections to the load bus k are both negative.

Beside the buses, distribution lines make the other part of the bus-branch model. A distribution line in a distribution system includes a series resistance, a series inductance and a shunt capacitance. Since these elements impact the operation of the distribution system, they should be included in the distribution system analysis. Accordingly, a matrix known as the *admittance matrix* Y is constructed for the power distribution system which includes the series and shunt elements discussed above. The entry at row i and column k of the admittance matrix Y_{ik} is the negative of the series admittance of the distribution line i-k. Also, the entry at row i and column i of the admittance matrix Y_{ii} is the summation of all admittances connected to bus i. It worth noting that, in a steady state analysis the admittance matrix excludes the internal admittances of loads [21, page 517].

B. Power Flow in a Distribution System

In operating a power distribution system, it is of the utmost importance to make sure that the amount of power flowing in the distribution lines are within the safe ranges. For calculating the power-flows in the distribution lines, one should first calculate the voltages magnitudes V_k and phase angles θ_k at all buses of the distribution system. Once the voltages are calculated, the power flow in the distribution lines can be calculated readily. For instance, the power injection to the distribution line i-k from bus i can be calculated as follows:

$$P_{ik} = \text{real}\{V_i\,\overline{I_{ik}}\} = \text{real}\{-V_i\overline{(V_i - V_k)Y_{ik}}\}, \qquad (1)$$

where $\overline{I_{ik}}$ is the conjugate of the current I_{ik} that is injected from bus i to the distribution line i-k.

The variables V_k and θ_k can be calculated by solving the following power flow problem:

$$P_k = \textstyle\sum_{j=1}^{N} V_k V_j \big(G_{kj} cos(\theta_k - \theta_j) + B_{kj} sin(\theta_k - \theta_j)\big) \forall k, \quad (2)$$

$$Q_k = \textstyle\sum_{j=1}^{N} V_k V_j \big(G_{kj} sin(\theta_k - \theta_j) - B_{kj} cos(\theta_k - \theta_j)\big) \forall k, \quad (3)$$

where N is the number of buses in the power distribution system, and $G = \text{real}\{Y\}$ and $B = \text{imag}\{Y\}$ are the real and imaginary parts of the admittance matrix Y, respectively. Equations (2) and (3) establish a relationship between power injections and voltages at buses of the distribution system. For load buses, the real P_k and reactive Q_k power injections to the buses of the power distribution system are given parameters and the voltage magnitude and phase angles are variables to be calculated. By contrast, for the slack bus the voltage magnitude $V_1 = 1$ and the phase angle $\theta_1 = 0$ are given parameters and the real power P_1 and reactive power Q_1 injections are variables to be calculated. The equations in (2) and (3) are a set of nonlinear equations which can be solved by the Newton-Raphson algorithm [22, Section 7.1].

C. Advanced Metering Infrastructure in Power Grids

In the United States and several other countries, the traditional metering system is being replaced with a modern metering system known as Advanced Metering Infrastructure (AMI). In such a modern metering infrastructure, smart meters provide a two-way communication between the operator of the power distribution system and the power consumers [23]. This real time communication provides several benefits to the distribution system operator. For instance, smart meters save the distribution system operator the cost of period trips to power consumers locations for reading the meters [24]. Also, the higher resolution data from smart meters help the distribution system operator to react faster to the distribution line congestions [24].

It is anticipated that by 2020, almost 800 million smart meters would have been installed in the world, among which 135 million meters would have been installed in the United States [25]. Accordingly, in this paper we assume that smart meters are installed at all buses of the power distribution system under study. These smart meters measure the real power P_k and reactive power Q_k injections to the buses with a rate of one sample per minute, and report the measurements to the distribution system operator. The distribution system operator collects the data and use them as the needed parameter to formulate the power from problem in (2) and (3). The distribution system operator solves the power flow problem once in every minute and calculates voltage magnitudes V_k and phase angles θ_k at all buses of the distribution system.

III. LOCAL RENEWABLE GENERATION

Utilization of renewable energy for producing electrical power comes with several key benefits including lower cost of electricity for power consumers and lower rate of carbon emission to the environment [1]. Renewable generators may be connected to the power transmission system [4] or to the power distribution system [5]. However, the focus of this paper is on the renewable generators that are installed behind-the-meters of power consumers in a power distribution system. These renewable generators are not connected to the power grid and are rather used to offset a portion of power consumers' power loads [6]. This later approach in employing renewable generators is specially favorable in design and development of zero-net energy buildings [7] and microgrids [8], since for these buildings the total amount of energy consumption should be roughly equal to the total amount of energy generation. This section discusses the operation of power distribution systems under penetration of behind-the-meter renewable generators.

A. Reliability Issues Caused by the Renewable Generators

The main challenge in utilizing renewable generators is the intermittency in their energy productions. More precisely, the energy production of a renewable generator does not remain the same over the time but rather fluctuates. These fluctuations may cause reliability issues for the operation of the power distribution system. Namely, the power consumers with behind-the-meter renewable generators may need a certain amount of power over the time. Therefore, these power consumers need to compensate for the shortages of renewable energy by adjusting their power draws from the power grid. As a result, the fluctuations in the renewable generations are transmitted to the net loads of these power consumers.

The fluctuations of the net loads may cause voltage volatilities or power imbalances in the power distribution systems, specially at higher levels of renewable energy penetration. Therefore, there is a need for a mechanism that can counterbalance the fluctuations of the net loads in power distribution systems, thereby ensuring a reliable operation of the distribution systems. The next section discusses three such mechanisms along with their shortcomings.

B. Compensating for the Fluctuations of the net Loads

One mechanism for counterbalancing the fluctuations of the net loads is to conduct frequency regulation using the available reserve generation in the transmission system [26]. Since the power consumers are billed for the services of the reserve generators, relying on this mechanism ruins the main benefit of renewable generators, i.e. cutting the electricity cost of power consumers. Another mechanism is to employ energy storage units which are charged and discharged according to the availability of renewable generation, thereby flattening the net loads of power consumers. The drawback to the above mechanism is the additional expenses that power consumers will incur to install energy storage units.

The third mechanism for counterbalancing fluctuations of the net loads is to deploy demand response [10]. Namely, certain types of loads in a power distribution system come with a degree of flexibility in their power consumptions. When being incentivized, these flexible loads can adjust their power consumptions according to the availability of renewable energy in the power distribution system. The adjustment in power consumption of the flexible loads in response to the availability of energy supply is referred to as demand response. Demand response comes in two different forms, i.e. direct load control [27] and dynamic pricing [11]. In direct load control, the control of flexible loads is given to a central agent, e.g. the distribution system operator, which adjusts the power consumptions of the flexible loads according to the availability of energy supply in the power grid. The direct load control form of demand response comes with privacy and security issues [27].

Another form of demand response is dynamic pricing, where the flexible loads react to the circumstances of the power grid by responding to the price of electricity. In this form of demand response, a shortage of renewable energy results in an increase in power consumption of the consumers with behind-the-meter renewable generators, which makes these power consumers to draw additional power from the distribution system. The wholesale market that runs in the transmission system reacts to the resulted increase in the power consumption of the distribution system by increasing the price of electricity. Finally, the flexible loads react to the increase in the price of electricity by lowering their power consumption. Although the dynamic pricing form of demand response may be partially effective to counterbalance fluctuations of the consumers' net loads, it suffers from a major shortcoming.

Namely, the rapid fluctuations of the consumers' net loads cannot be reflected in the 15-minutes [12] updates of the wholesale price of electricity. Consequently, the fluctuations of the net loads cannot be counterbalanced by the reaction of the flexible loads that respond to the wholesale price of electricity. As a result, the fluctuations of the net loads may cause interruptions in the operation of the power distribution system before any reaction from flexible loads can take place. Furthermore, the likelihood of the above detrimental conditions increases as the level of renewable energy penetration in the distribution system increases. Therefore, demand response is not capable of addressing the reliability concerns regarding the fluctuations of the net loads.

IV. TRANSACTIVE ENERGY FRAMEWORK

In counterbalancing the fluctuations of the net loads, there is a need for a mechanism that enables instantaneous reaction of the flexible loads to the fluctuations of the net loads. The transactive energy paradigm [13], [14] is emerging to fulfill this need. In the transactive energy framework, an energy market referred to as the distribution market operates at the power distribution system and enables real time and peer-to-peer energy exchanges between consumers of the power distribution system [13]. In the distribution market, consumers with behind-the meter renewable generators enter into energy transactions with flexible loads to compensate for their renewable energy shortages. In dispatching the transacted energy, while the consumers with renewable generators increase their power draw from the distribution system the flexible loads lower their power draw. Such coordination between power consumers help in fulfilling energy demands of the consumers while keeping the distribution lines uncongested.

The structure of the transactive energy framework and the operation of the distribution market are detailed in [16]. This section only discusses the specific features of the transactive energy framework in [16] which are relevant to the discussion of this paper.

A. The Operation of Distribution Markets

To enable the real time power exchanges between the power consumers in a distribution system, the operation of the distribution system is divided into successive time intervals of *short* length T, e.g. $T = 10$ mili-seconds. Each time interval is referred to as a *transaction cycle*. At the beginning of a transaction cycle, power consumers indicate their energy demands or their energy offers by submitting price bids to the distribution market. A power consumer with behind-the-meter renewable generator that is experiencing shortage of renewable energy submits a negative price bid to indicates its demand for energy. The absolute value of this price bid reflects the highest rate at which the power consumer is still willing to pay for energy. On the other hand, a flexible load submits a positive price bid to the market which indicates an energy offer. This price bid reflects the least rate at which the consumer expects to receive payment for its energy offer to the market.

In each transaction cycle, the power market operator collects all the price bids and clears the market by solving a linear optimization problem that maximizes the social welfare:

$$\text{Social Welfare} = \textstyle\sum_{k=1}^{N} -|\text{Bid}_k|\, \Delta P_k, \tag{4}$$

where Bid_k is the price bid submitted to the distribution market by the power consumer at bus k. Also, ΔP_k is the amount of energy exchange at bus k, expressed in terms of additional power injection to bus k. Once the market is cleared, the dispatch instructions are sent to the flexible loads and the power consumers with renewable generators. Since each transaction cycle has a short duration T, the maximum energy that a power consumer can sell or purchase in a transaction cycle is upper bounded by $P_{max}T$, where $P_{max} = 0.01$ Mega-Watts. Such an upper bound on the energy purchases ensures that the power consumers can follow the dispatch instructions before the start time of the next transaction cycle.

We note that, in clearing the distribution market the power system operator considers the physical constraints in the operation of the distribution system, including the limited capacity of the distribution lines and the safe range of voltage magnitudes. As a result, power flow equations are included in the social maximization problem that is solved in the distribution market; see [16]. However, since the energy transactions in each transaction cycle are small amounts upper bounded by $P_{\max}T$ the nonlinear power flow equations in (2) and (3) are *accurately* approximated by the following linear differential power flow equation:

$$\Delta P_k = \textstyle\sum_{i=1}^{N} \frac{\partial P_k}{\partial V_i}\Delta V_i + \frac{\partial P_k}{\partial \theta_i}\Delta \theta_i, \qquad (5)$$

where ΔV_i and $\Delta\theta_i$ are the small adjustments applied to the voltage magnitude and phase angle of the bus i in the transaction cycle of interest.

B. Real Time Price Bidding in Distribution Markets

The price bids submitted by buyers in the distribution market may be interpreted as an indication of their urgency in their energy demands. More precisely, a power consumer with an urgent demand of energy may submit negative price bids with large absolute values to indicate its urgent need for energy. In clearing the market, the distribution system operator considers urgency of power demands by dispatching the available energy offer according to the submitted price bids. Furthermore, the price bids submitted by the power consumers may change from transaction cycle to transaction cycles in accordance with the real time energy demands of the consumers. For instance, a power consumer with renewable generator may submit non-zero price bids to the distribution market up to the specific transaction cycle where its energy demand is fully met. After that, the power consumer keeps submitting zero price bids to the distribution market. Also, the flexible loads can alter their price bids from transaction cycle to transaction cycle to better reflect their real time monetary expectations from the energy transactions.

V. DATA CENTERS IN DISTRIBUTION MARKETS

Data centers are big buildings that contain thousands of computer servers to process the computational tasks of their users [15]. From the power-grid point of view, data centers are power loads with three special characteristics. First, a data center is a major power consumer of the power grid as it operates a large number of computer servers. Seconds, a data center is a controllable load as its power consumption can be adjusted by switching the operational mode of its computers between busy and idle modes. Third, a data center is a geographically shiftable load as it can forward its computational workload to another data center [28]. Considering the above three characteristics, this section discusses a mechanism for participation of data centers in distribution markets. As a part of this mechanism, a bidding strategy is provided for data centers which guarantees non-decremental profits for the data centers that offer energy to the distribution markets.

A. A Data Center's Revenue from Computational Services

A data center's revenue from its computational services depends on the quality of service that the data center offers to its users, where the quality of service is specified in a *service level agreement* between the data center and its users. A typical service level agreement includes a parameter D and a parameter δ that specify the deadline and the monetary revenue in processing each service request, respectively [29]. The data center processes the service requests in a first-come-first-served order, and therefore can estimate the queuing time of every new arrived service request [29]. If for a service request the estimated queuing time is more than the deadline D, the data center withdraws from the process of the service request and its associated revenue, and rather forwards the service request to another data center.

We consider a data center with a total number of M_{max} computer servers. Also, we assume that the service requests received by the data center are all from a same type, and can be processed with a rate of κ service requests per computer per second. Therefore, the maximum service rate of the data center in processing the computational workload is $\mu_{\text{max}} = \kappa M_{\text{max}}$. We also assume that at any instant of time the average rate of service request arrival to the data center λ is higher than the aforementioned maximum service rate, i.e. $\lambda > \mu_{\text{max}}$. Therefore, there are always service requests queued in the data center awaiting for service. As a result, the revenue per second of the data center in processing the service requests is as follows:

$$\text{Revenue} = \mu\delta, \qquad (6)$$

where μ denotes the service rate of data center in processing the computational workload.

When not participating in the distribution market, the data center sets $\mu = \mu_{\text{max}}$ to achieve the highest revenue from processing service requests. However, a data center that participates in the distribution market may set a lower service rate $\mu < \mu_{\text{max}}$ in processing the service requests. This later case is discussed in Section V-C.

B. Data Centers' Cost of Energy

The two main electrical loads in a data center are the computers that serve the computational workload, and the cooling system that ventilate the building. Considering the substantial amount of heat produced by the servers, the power consumption of the cooling system can make up a large portion of the data center total power consumption. The power usage effectiveness E_{usage} is defined as the ratio of the power consumption of the whole data center to the power consumption of the computer severs. For a typical data center, E_{usage} can be as low as 1.12 [30]. Assuming that all the computer servers in the data center are switched-on at all the time, the total power consumption of the data center is as follows [29]:

$$P = M_{\text{max}}\big(P_{\text{idle}} + (E_{\text{usage}} - 1)P_{\text{peak}} + (P_{\text{peak}} - P_{\text{idle}})U\big), \qquad (7)$$

where P_{peak} is the power consumption of a single computer server when the server is busy processing a service request, and P_{idle} is the power consumption of the same computer server when the server idles. Also, U denote the average utilization of the computer servers, i.e. the percentage of time that the computer servers are busy processing service requests.

To have a service rate of μ in the data center, μ/κ computers should operate in the busy mode processing the computational workload. For these set of computers the utilization is $U = 1$. The remaining $M_{\text{max}} - \mu/\kappa$ computers idle and have a zero utilization $U = 0$. Therefore, the average utilization of the computers in the data center is:

$$U = \frac{\frac{\mu}{\kappa} \times 1 + (M_{\max} - \frac{\mu}{\kappa}) \times 0}{M_{\max}} = \frac{\mu}{\kappa M_{\max}}. \tag{8}$$

Substituting the server utilizations U from (8) into the power consumption model in (7), the power consumption of the data center can be obtained as a function of the service rate μ. Accordingly, the per second energy cost of the data center in drawing power from the power distribution system is as follows:

$$\begin{aligned} \text{Cost of Energy} =& \omega M_{\max}\big(P_{\text{idle}} + (E_{\text{usage}} - 1)P_{\text{peak}} + \\ & (P_{\text{peak}} - P_{\text{idle}})\frac{\mu}{\kappa M_{\max}}\big), \end{aligned} \tag{9}$$

where ω denotes the price of electricity that the data center draws from the distribution system.

C. Data Centers Participation in the Distribution Market

A data center may offer energy to the distribution market by lowering its power consumption, which is doable by lowering the service rate μ of the data center. When reducing the service rate by $\Delta\mu$, a total number of $\Delta\mu/\kappa$ computers are switched from the busy mode to the idle mode. From (7) and (9), the resulted cut in the power consumption and energy cost of the data center are as follows:

$$\Delta P = \frac{\Delta\mu}{\kappa M_{\max}}. \tag{10}$$

and

$$\Delta\text{Cost} = \frac{\omega\Delta\mu}{\kappa M_{\max}}. \tag{11}$$

Furthermore, from (6) the $\Delta\mu$ change in the service rate of the data center results in the following cut in the data center's revenue:

$$\Delta\text{Revenue} = \Delta\mu\delta \tag{12}$$

From (11) and (12), the data center profit loss caused by $\Delta\mu$ change in its service rate is as follows:

$$\Delta\text{Profit} = \Delta\mu\delta - \frac{\omega\Delta\mu}{\kappa M_{\max}} \tag{13}$$

From (10) and (13), the data center losses ΔProfit in selling ΔP energy to the distribution market. To compensate for this profit loss, the data center can set the following price bid for its energy offer to the distribution market:

$$\text{Bid} = \frac{\Delta\text{Profit}}{\Delta P} = \kappa M_{\max}\delta - \omega. \tag{14}$$

By submitting the above price bid, the data center requests at least $\kappa M_{\max}\delta - \omega$ payment for every unit of energy that is offers to the distribution market. Such pricing strategy guarantees a non-decremental profit for the data center that participates in the distribution market. That is because, the nodal price of transactive energy at any bus of the distribution system is always greater than the price bid of energy offer at the same bus [16]. It worth noting that, depending on the price bids submitted by power consumers the nodal price of energy in the distribution market can be higher than the price bid submitted by the data center. In such a case, participation of the data center in the distribution market increases the data center's profit.

VI. NUMERICAL SIMULATIONS

Through numerical simulations, this section studies the performance of the proposed transactive energy framework in counterbalancing fluctuations of the net loads.

A. Simulation Setup

The IEEE 33-bus distribution system is selected as the power distribution system in the simulations. In this distribution system, the first bus is the slack bus and the other buses are load buses. The admittance matrix and the load data for the IEEE 33-bus system are obtained from MATPOWER [31]. Specially, the admittance matrix of the distribution system is obtained by running the command `makeYbus()` in MATPOWER. The base of apparent power in the IEEE 33-bus distribution system is 100 MW. Therefore, all the per unit (p.u.) power consumptions and power generations reported in this section are normalized by 100 MW.

A portion of the power loads at buses 2, 4 and 6 of the distribution system are offset by three behind-the-meter wind turbines. The power output of the wind turbines is obtained from the following model [32]:

$$\text{Power Generation of a Wind Turbine} = \rho A C_{p,eq}\nu^3/2 \tag{15}$$

where the parameters $\rho = 1.225$ kg/m^3 and $C_{p.eq} = 0.40$ are given in [32]. The parameter A is the wind turbine swept area, i.e. $A = \pi r^2$, where r is the length of the wind turbines' blades. The blades' lengths of the wind turbines at buses 2, 4 and 6 are 31.5, 17.5 and 42 meters, respectively. The parameter ν in (15) is the wind speed. The wind speed at the location of buses 2, 4, and 6, are set to the real-world wind speed measurements at a distance 50 meters from the ground during the time interval from 3:00 p.m. to 3:10 p.m on March/16/2019 to March/18/2019 [33]. The resolution of wind speed measurements in [33] is one data per minute.

A data center is set to draw power from bus 31 of the IEEE 33-bus distribution system. The data center has 10000 computer servers all of which are switched-on. The power consumption of a computer server is $P_{\text{peak}} = 200$ and $P_{\text{idle}} = 100$ in the busy and idle modes, respectively [29]. Each computer server in the data center can process $\kappa = 0.1$ service requests per second [29]. The parameter δ of the data center's service level agreement is $\delta = 0.007$ cent per service request [29]. Also, the data center's power usage effectiveness is set to $E_{\text{usage}} = 1.2$ [15]. The price of electricity drawn from the power distribution system is 19.0 \$/MWh.

B. Demand Response in Tackling net Loads' Fluctuations

Consider a time interval of 10 minutes. In this time interval, the power consumers at buses 2, 4 and 6 consume 0.001, 0.0012 and 0.0006 p.u. power, respectively. These power consumers have behind-the-meter renewable generators to offset a portion of their power consumptions. Fig. 2-(a) to Fig. 2-(c) show the local renewable generations at buses 2, 4 and 6 over the 10-minutes time interval of interest. From Fig. 2-(a) to Fig. 2-(c), the amounts of renewable generation from renewable generators don't remain the same and rather fluctuate. These fluctuations cause the power consumers with renewable generators to compensate for the renewable generation shortages by adjusting their power draw from the distribution system. As a result, the fluctuations of the renewable generations are transmitted to the net loads that power consumers draw from the distribution system.

In a demand response framework, the data center in bus 31 of the distribution system cannot respond to these fluctuations, because the fluctuations are not reflected in 15-minutes updates [12] of the wholesale price of electricity [34]. Therefore, the fluctuations of the net loads combine and make a wider fluctuation in the power injection of the slack bus to the distribution system, see Fig. 3. Consequently, the distribution line that is connected to the slack bus may be congested even before the data center can respond to the net loads' fluctuations. Also, the wide fluctuations of the power injection into the slack bus cause wide fluctuations in the wholesale price of electricity [34], which in turn results in wholesale price instability.

C. Transactive Energy in Tackling net Loads' Fluctuations

In a transactive energy framework, the power consumers with renewable generators come into energy transactions with the data center to compensate for their renewable generation shortages. Namely, once in every minute a power consumer with renewable generator measures the amount of power from its renewable generator and calculates the resulted renewable generation shortage. The power consumer participates in the distribution market to procure its energy demand. Initially, the power consumer submits a negative price bid with large absolute value to indicates its urgent need for energy. Once the power consumer accrues its demanded energy from the distribution market, the consumer keeps submitting zero-price bids to the distribution market.

On the other hand, the data center as a flexible loads submits positive price bids based on equation (14) to the distribution market, thereby offering energy to the power consumers. The energy that the data center transacts in the distribution market is supplied by the cut in the power consumption of the data center. Such a cut in data center's power consumption is resulted from switching operational mode of the data center's computer servers from busy mode to idle mode. Fig. 4 shows the number of computers operating in the busy mode over the 10-minute time interval of interest.

Two points are notable about the energy transactions. First, the energy transactions between consumers with renewable generators and data centers are valid for a total duration of 1-minute. Therefore, once in every minute the power consumers with renewable generators and the data center come into new energy transactions to fulfill their new energy demands. Second, because of the upper bound on energy transactions $P_{\max}T$ in distribution market, several transaction cycles should pass before the consumers with renewable generators can procure their energy demands in full. However, since the length of the transaction cycles T is short, consumers with renewable generators procure their energy demands in less than a second.

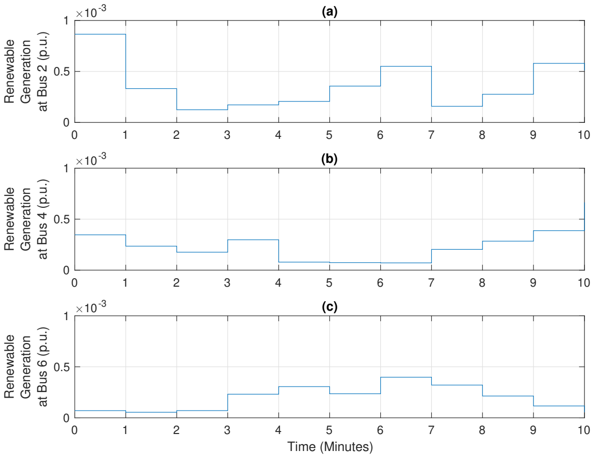

Fig. 2: Behind-the-meter renewable generation at buses 2, 4 and 6 of the power distribution system in Fig. 1

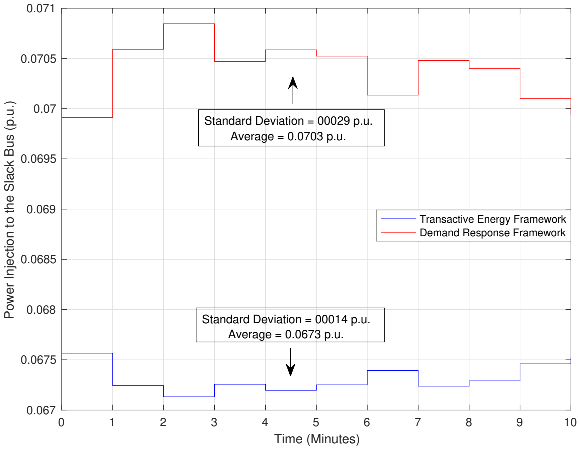

Fig. 3: The power injection from the transmission system to the power distribution system in Fig. 1

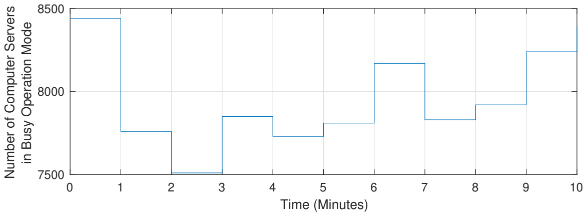

Fig. 4: The number of computer servers in the data center that are operating in the busy mode.

In the transactive energy framework, the fluctuations of the net loads are counterbalanced with the real-time reaction of the data center. As a result, the fluctuations of the net loads are not combined to create wider fluctuations in the power injection of the slack bus to the distribution system. Fig. 3 compares the power injection of the slack bus for the two cases of demand response and transactive energy framework. From Fig. 3, the variations in the power injection of the slack bus is 47% less in the transactive energy framework compared to the demand response framework, where the variation is expressed in terms of the standard deviation [35, page 14]. This means that, the fluctuations of the net loads are $100\% - 47\% = 53\%$ counterbalanced more when the data centers' flexibilities are utilized in the transactive energy framework instead of the demand response framework. Also, the average power injection of the slack bus to the distribution system in the transactive energy framework is 4.3% less than that of the demand response framework.

VII. CONCLUSION

In this paper, a mechanism is proposed for data centers to enter into peer-to-peer and real time energy transactions with power consumers of a power distribution system. Such energy transactions help the power consumers to fulfill their energy demands while keeping the distribution lines uncongested. As part of the proposed mechanism, a bidding strategy is proposed which guarantees non-decremental profits for the data centers that offer transactive energy in the power distribution systems. Using real world wind data, the performance of the proposed transactive energy framework in counterbalancing fluctuations of the net loads is assessed numerically. It is shown that, the fluctuations of the net loads are 53% more counterbalanced when the data centers' flexibilities are exploited in the transactive energy framework instead of the demand response

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