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Blockchain Smart Contracts for Grid Connection Management in Achieving Net Zero Energy Systems

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ABSTRACT

Energy systems are transitioning towards a decentralized and decarbonized paradigm with the integration of distributed renewable energy sources. Blockchain smart contracts have the increasing potential to facilitate the transition of energy systems due to the natures of automation, standardization, and self-enforcement. This paper proposes a Blockchain smart contracts based platform to manage the grid connection for both large scale generation companies and individual prosumers (both producers and consumers). Through evaluating the capacity margin and carbon intensity for each substation or feeder in power networks, the incurred connection fee and low carbon incentive are formulated for incentivizing the local energy balance and connection of renewable energy sources. Case studies testify the effectiveness for encouraging the low carbon grid connection.

Keywords: Blockchain smart contracts, grid connection, net zero emissions, prosumers, renewable energy.

1. INTRODUCTION

In efforts to achieve the targets of net zero carbon emissions and clean energy supply, increasing penetration of renewable energy sources enables the transition of energy systems towards a decentralized and decarbonized paradigm. These renewable energy sources can be possessed either by the large scale generation companies, or by small to medium sized prosumers (both energy producers and consumers) [3].

Accommodating large amounts of the grid connection by both generation companies and prosumers would amplify the burden of information infrastructure of energy systems. The recent scientific innovation on Blockchain technology, as a distributed ledger technology has the potential to assist the information infrastructure of energy systems. The smart contracts [2] based on the Blockchain technology enable programable procedures to be executed in an automatic, secure, and self-enforcing manner. While current research and industrial practice exploit the Blockchain smart contracts for the operation [5], planning [1], and trading [4] in energy systems, the grid connection has been barely focused.

This paper proposes a Blockchain smart contracts based platform to manage the grid connection for both large scale generation companies and prosumers, by offering the following contributions:

- The capacity margin and carbon intensity of substations and feeders in power networks are investigated, upon which incentive schemes are designed in achieving local energy balance and carbon reduction.
- A novel Blockchain smart contract is designed for managing the grid connection with ensured information efficiency and security.
- Case studies verify the benefits of our proposed model in terms of local energy balance and carbon reduction.

2. PROBLEM FORMULATION

For the purpose of facilitating the local energy balance and achieving net zero energy systems, on one hand, the substations/feeders with low capacity margin will be prioritized. On the other hand, the generation companies or prosumers with renewable energy sources

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will be prioritized. These priorities are capitalized as the connection fee and low carbon incentive, respectively. In this section, the methods for evaluating the capacity margin and carbon intensity are introduced, upon which the incurred connection fee and low carbon incentive are formulated.

2.1 Capacity margin and connection fee

The capacity margin is defined as the total installed generation capacity at a substation or feeder minus the peak demand in a year at the same substation or feeder, which can be described as

$$m_n = c_n - d_n^{peak}, \tag{1}$$

Where m_n is the capacity margin at the substation/feeder n, c_n is the total installed capacity of the substation/feeder n, and d_n^{peak} is the peak demand in a year at the substation/feeder n.

According to Eq. (1), a negative value of the capacity margin m_n indicates that the total installed capacity is insufficient to supply the peak demand at a substation/feeder, and therefore this substation/feeder has to import electricity from other substations/feeders over the transmission and distribution networks. Under this circumstance, building up new generation capacity at this substation/feeder would reduce the electricity import and incurred losses. To facilitate the connection to the substations/feeders with negative capacity margin, the power system operator will provide the monetary compensation, i.e., negative connection fee, for generation companies or prosumers which plan to connect to these substations/feeders. The lower negative capacity margin would result in a higher monetary compensation, i.e., lower negative connection fee.

By contrast, a positive value of the capacity margin m_n indicates that the total installed capacity is sufficient to supply the peak demand at a substation/feeder. Building up new generation capacity at this substation/feeder would be less priority, since transmitting the surplus electricity would require the reinforcement of power networks. To avoid the connection to the substations/feeders with positive capacity margin, the power system operator will charge connection fee from generation companies or prosumers which plan to connect to these substations/feeders. The higher positive capacity margin would result in a higher connection fee.

In this research, a linear relationship between the connection fee and capacity margin is assumed to drive generation companies and prosumers to build new capacity on the substations/feeders with low or negative capacity margin as

$$\gamma_n = \alpha \cdot m_n + \beta, \tag{2}$$

Where γ_n is the connection fee at the substation/feeder n, and α and β are the coefficients of the connection fee.

2.2 Carbon intensity and low carbon incentive

In addition to conventional regional carbon intensity tracing methods which evaluate carbon emissions caused by electricity generation only, our research considers the carbon intensity of electricity consumed in each substation/feeder. Evaluating the carbon intensity of electricity consumed in each substation/feeder requires to model the power flows and incurred carbon intensities between substations and feeders. The procedures of evaluating the carbon intensity of electricity consumed in each substation/feeder are introduced in the following subsections.

2.2.1 Regional carbon intensity

The power generation at a substation/feeder is the sum of generation from all generators connected to this substation/feeder as

$$g_n = \sum_{i=1}^{I} g_{n,i}, \tag{3}$$

Where g_n is the total electricity generation at the substation/feeder n, $g_{n,i}$ is the electricity generation from the generator i connected to the substation/feeder n, and I is the index set of buses.

The carbon emissions generated from a substation/feeder are the sum of carbon emissions from all generators connected to this substation/feeder as

$$e_n = \sum_{i=1}^{I} g_{n,i} \cdot \rho_i, \tag{4}$$

Where e_n is the carbon emissions generated from the substation/feeder n, and ρ_i is the carbon intensity of the generator i connected to the substation/feeder n.

Hence, the carbon intensity of each substation/feeder is calculated as

$$\rho_n = \frac{e_n}{g_n}, \tag{5}$$

Where ρ_n is the carbon intensity of the substation/feeder n.

2.2.2 Power exchange

The power exchange, i.e., power imbalance, of a substation/feeder is calculated by the difference between the electricity generated from this substation/feeder and electricity consumed by this substation/feeder as

$$p_n = g_n - d_n, \tag{6}$$

Where $\mathrm{p_n}$ is the power imbalance of the substation/feeder n, and d_n is the demand of the substation/feeder n. The positive value of power imbalance p_n indicates that the generation is greater than demand, and thus the substation/feeder can export electricity to other substations/feeders. The negative value of power imbalance p_n indicates that the generation is lower than demand, and thus the substation/feeder has to import electricity from other substations/feeders.

2.2.3 Carbon intensity of power flow

To evaluate the carbon intensity of the power flow, the power flow analysis needs to be firstly performed. Assume a power network with $|B|$ buses and $|L|$ lines. This power network can be described by a $|L| \times |B|$ incidence matrix, denoted as A. If the line l ends at the bus s, we have $A_{l,s} = -1$; If the line l ends at the bus r, we have $A_{l,r} = -1$; *If* $w \neq s \neq r$, we have $A_{l,w} = 0$. The AC power flow analysis can be expressed by the following power equations in a polar form as

$$p_s = |v_s| \sum_{x=1}^{B} |v_r| \cdot |y_{sr}| \cos(\delta_s - \delta_r - \theta_{sr}), \tag{7}$$

$$q_s = |v_s| \sum_{x=1}^{B} |v_r| \cdot |y_{sr}| \sin(\delta_s - \delta_r - \theta_{sr}), \tag{8}$$

Where $|\mathrm{y}_{sr}|$ is the admittance, $|v_s|$ and $|v_r|$ are the voltages of the bus s and bus r, respectively, δ_s and δ_r are the phase angles of the bus s and bus r, respectively, and θ_{sr} is the angle difference between the bus s and bus r. This research uses the Newton Raphson iteration for the power flow analysis.

Based on the calculated power flow, the carbon intensity of power flow can be obtained. The carbon intensity of the power outflow from a bus equals to the weighted average of carbon intensity of the power inflow to this bus.

2.2.4 Carbon intensity of consumption

Once the carbon intensity of power flow is calculated, the carbon intensity of the electricity consumption at each substation/feeder can be evaluated. If a substation/feeder exports electricity, the carbon intensity of the electricity consumption equals to the carbon intensity of electricity generation at this substation/feeder; If a substation/feeder imports electricity, the carbon intensity of electricity consumption equals to the weighted sum between the on-site generation and the power flows from lines transmitting electricity to this substation/feeder.

Therefore, if the connection of a generator would contribute to reducing carbon intensity of consumption of a substation/feeder, this generation company or prosumer would receive the monetary compensation, i.e., negative low carbon incentive, for carbon reduction. If the connection of a generator would increase the carbon intensity of consumption of a substation/feeder, this generation company or prosumer would have to purchase the low carbon incentive. This research assumes a linear relationship between the low carbon incentive and the change of carbon intensity of electricity consumption as

$$\pi_n = \epsilon \cdot (\rho_n^{d\prime} - \rho_n^d) + \sigma, \tag{9}$$

Where π_n is the low carbon incentive at the substation/feeder n, ϵ and σ are the coefficients of the low carbon incentive, and $\rho_n^{d\prime}$ and ρ_n^d are carbon intensity before and after connecting a new generation capacity to the substation/feeder n, respectively.

3. BLOCKCHAIN SMART CONTRACTS FOR MANAGING GIRD CONNECTIO

This section provides details on how to use standardized Blockchain smart contracts for managing the grid connection. The Blockchain smart contracts can support a platform under which the connection proposal from generation companies or prosumers, connection fee determined by power system operators, and carbon incentive determined by policy makers are integrated and exchanged. The contents and execution of smart contracts are recorded in a block. Blocks are chronologically chained by including the hash of the previous block into the next block, forming a Blockchain.

A standardized form of smart contracts is designed for the generation companies and prosumers which are willing to connect with new generation capacity. The detailed procedures of the designed smart contracts are given as follows:

Step 1): Generation company or prosumer who is willing to connect new generation capacity calls the smart contract by providing the information of energy type, capacity, and location.

Step 2): System examines the eligibility of connection, and evaluates corresponding connection fee and low carbon incentive for eligible generation company or prosumer.

Step 3): Receiving the published connection fee and low carbon incentive, the generation company or prosumer confirms its connection decision. If the generation company or prosumer is still willing to connect to the proposed generation capacity, it needs to deposit the connection fee and low carbon incentive to the smart contract (for the monetary compensation, the power system operator and policy maker need to deposit)

Step 4): Once the new capacity is built, the smart contract deduces the deposit.

4. CASE STUDIES

Case studies have been performed on the IEEE 33-bus distribution system. The comparison of capacity margin for each bus before and after the connection of new capacity is presented in Fig. 1, and the comparison of the carbon intensity before and after the connection of new capacity is presented in Fig. 2. It can be seen from these figures that the buses with low or negative capacity margin and high carbon intensity would be the most prior buses to be connected by generation companies or prosumers.

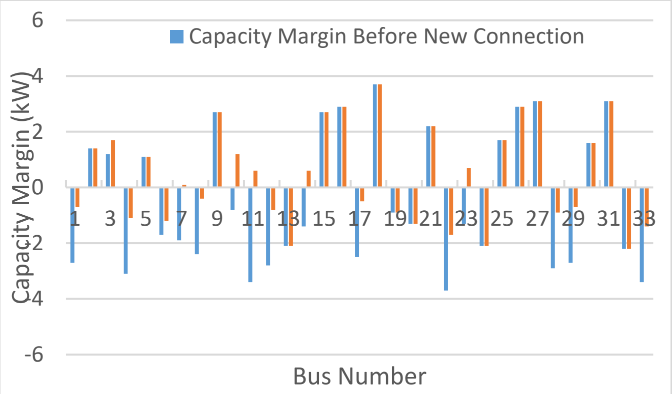

Fig. 1. Comparison of the capacity margin before and after the connection of new capacity. The *x*-axis is the bus number and *y*-axis is the capacity margin.

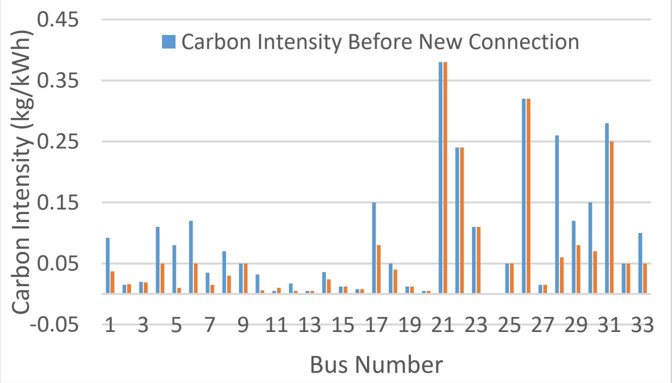

Fig. 2. Comparison of the carbon intensity before and after the connection of new capacity. The *x*-axis is the bus number and *y*-axis is the carbon intensity.

5. CONCLUSIONS

This paper proposes a Blockchain based platform to manage the grid connection for both generation companies and prosumers. Through evaluating the capacity margin and carbon intensity of each substation and feeder in power networks, the corresponding connection fee and low carbon incentive are formulated to encourage the generation companies or prosumers to invest in the substation/feeder with low or negative capacity margin and high carbon intensity. The standardized connection procedures are automatically self-enforced by the designed smart contracts. Case studies with IEEE 33-bus distribution systems validate the effectiveness of the proposed model for carbon reduction and local energy balance. As a future work, other factors which affect the grid connection, e.g., expansion factors, security factors, and local tariffs could be investigated.

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