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A Grid Connection Mechanism of Large-scale Distributed Energy Resources based on Blockchain

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Abstract: Distributed energy resource (DER) will become the main primary energy in the future Smart Grid. However, it is impossible for DERs to connect to the grid freely and reliably through traditional technology such as micro grid or virtual power plant. As a new distributed computing paradigm, blockchain has the characteristics of security, transparency and decentralization. Consider these characteristics, this paper proposed a blockchain based virtual power plant model for DER's grid connection. The coordinated control method of virtual power plant and the independent grid connected behavior of DERs are organically linked by the incentive mechanism of blockchain, realizing the distributed dispatching calculation of virtual power plant. Results of case study showed that the proposed model could not only effectively reduce calculation costs of VPP, but also make grid connection more freely for DERs.

Key Words: Distributed energy resource, Grid connection, Virtual power plant, Blockchain

1 Introduction

Distributed energy resource (DER) is the primary energy of the future grid due to its high-energy efficiency, low pollution, flexible operation and good economic performance characteristics [1]. DER can connected to the grid directly. In this way, DER has high freedom to decide its grid connection behavior but becomes invisible and uncontrollable for the power system. Power system will be unsafe and unreliable as a large number of DERs connected to the grid directly. DER can also connected to the grid under control via micro grid (MG) or virtual power plant (VPP) [2]. However, DER is strictly constrained by geographical and physical conditions. Because MG is strongly dependent on power electronics technology [3]. VPP is not constrained by these strict conditions, but it costs huge communication and computing resources [4]. The communication and computing resources exponentially increase with the number of DERs connected to the grid. In general, it is difficult to realize the grid connection freely, orderly, efficiently and reliably for DERs with wide distribution, large number, different scales and different behaviors in a single grid connection mode.

The successful applications of blockchain technology [5] in economic, financial, and social systems [6], and the exploratory projects in the energy field [7-12] provide new ideas to solve this problem. The European Union's Scanergy project is based on a blockchain that issues a bitcoin-like NRG coin as a reward for direct green energy trading of end users [7]. The US company Filament has deployed detection devices on the power grid in Australian, and established corresponding communication and information sharing mechanisms for these detection devices based on the blockchain [8]. US energy company LO3 Energy has collaborated with the Bitcoin development company Consensus Systems to build a blockchain-based power interactive platform called TransActive Grid, allowing users to conduct green energy transactions without relying on third parties [9]. Sun Hongbin of Tsinghua University proposed to store power transaction information in the form of smart contracts and perform fund transfer. Traditional power centers conduct security checks and congestion management on these transactions [10]. North China Electric Power University cooperates with China Electric Power Research Institute to review the multi-energy system trading system and key technologies based on heterogeneous blockchain[11]. Zhang Jun of the University of Denver in the United States proposed the concept of blockchain group to provide platforms for distributed distributed power systems such as distributed analysis systems, distributed payment systems, and distributed resource allocation systems [12].

Based on the above researches, our group has proposed a P2P trading system based on blockchain and MG technology to realize the grid connection of small-scale DERs [13]. This article will study the grid connection model for large-scale DERs based on blockchain and VPP technology. Specifically, the proposed model solves two problems. Firstly, under the premise of bidding to grid connection, VPP induces DER to participate in distributed computing based on blockchain which reducing the computational burden of VPP. Secondly, DER optimizes its own grid connection strategy by incentives to improve the freedom of grid connection behavior. The rest of this paper is organized as follows. In Section 2, a grid connection model of DER based on blockchain and VPP is established. Section 3 introduces the distributed optimal scheduling algorithm based on consensus mechanism of improved proof-of-work. In Section 4, a realistic case study is demonstrated and analyzed. Conclusions and future work are given in Section 5.

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2 Modeling

2.1 The Blockchain Model

VPP needs sufficient authority to coordinate, induce and control the grid connection behavior of each DER in order to ensure the safety and reliability of the power system, which makes VPP have centralized node characteristics. VPP and DERs cannot trust each other when DERs participate in distributed computing to obtain incentives. At this time, a decentralized platform is need to ensure fairness. For these contradictions, this paper proposes a semi-center block chain with characteristics of public blockchain and private blockchain, as in Fig. 1 [14].

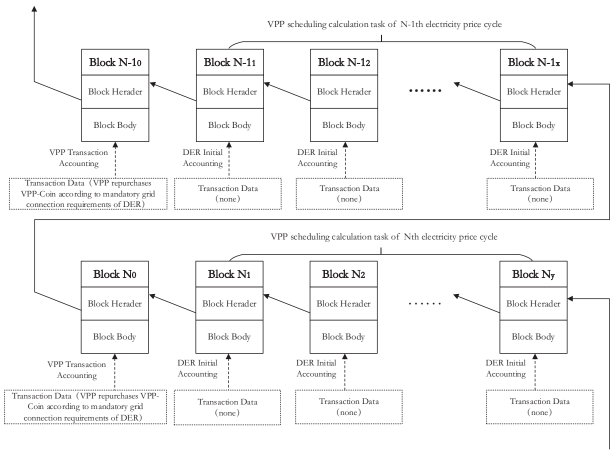

Fig. 1: The blockchain model of grid connection for DER

The blockchain has obvious segmentation characteristics due to the real-time pricing. As can be seen from the figure, y+1 blocks in are generated before the Nth electricity price cycle. In this model, each block corresponds to a certain search neighborhood of the optimal scheduling algorithm, and VPP issues the computing tasks of the block to DERs. It will be written into the corresponding block by VPP after DER completes the distributed computing (mining) process and makes the consensus. When the optimal scheduling calculation in the current electricity price cycle is completed, DERs who make consensus will obtain the virtual currency named VPP-Coin issued by VPP as an incentive. The unit value of VPP-Coin is designed as a rated capacity $Q_{\text{VPP-Coin}}$ for direct grid connection. DER can exchange direct grid connection capacity by VPP-Coin to optimize the grid connection strategy and maximize its own profit. The exchange behavior is written by VPP to block N_0. The circulation of VPP-Coin is determined by VPP according to the current market holdings. VPP can induce DER grid connection behaviors to ensure the safe and economic operation of the power system. When the Nth price cycle begins, VPP coordinately controls the grid connection behaviors of DERs according to the optimal scheduling plan.

2.2 Grid Connection Model of DER

Assume that the real-time pricing period is T, the electricity price update interval is Δt, the real-time electricity price sequence is $price(t_k,n)$ at t_k, the cost price without grid connection of DER in the area during the period from t_k to $t_k+\Delta t$ is $p_o(t_k,1)$. DER develops a grid connection strategy which includes direct mode and biding mode according to $p_o(t_k,1)$.

In direct mode, DER can exchange grid connection capacity by VPP-Coin and VPP must meet the corresponding demand in the next Δt. The direct grid connection capacity trades at a contract price λ, which is the actual cost price of the period from t_k to $t_k+\Delta t$. The direct grid connection profit $\psi(DQ_k)$ of DER k shows in formula (1), where n_k is the number of exchanged VPP-Coin and DQ_k is the direct grid connection capacity of DER k.

$$\psi_k\left(DQ_k\right)=\lambda\cdot DQ_k\cdot\Delta t=\lambda\cdot Q_{\text{VPP-Coin}}\cdot n_k\cdot\Delta t \tag{1}$$

In bidding mode, DER can propose a price-output bidding curve and VPP must determine the corresponding grid connection capacity in the next Δt. The bidding grid connection profit $\varphi_k(BQ_k)$ of DER k shows in formula (2). For DER k, BQ_k is the grid connection capacity, $BQ_{k\min}$ is the minimum output power of the inverter, $BQ_{k\max}$ is the upper limit of grid connection capacity, m_k and n_k are the bidding parameters.

$$\varphi_k\left(BQ_k\right)=\begin{cases}m_k\cdot BQ_k\cdot\Delta t+n_k, & BQ_k\in\left[BQ_{k\min},BQ_{k\max}\right]\\0, & BQ_k=0\end{cases} \tag{2}$$

Obviously, the profit of DER k can be expressed by formula (3)

$$profit\left(k\right)=\psi_k\left(DQ_k\right)+\varphi_k\left(BQ_k\right) \tag{3}$$

2.3 Optimal Scheduling Model of VPP

The optimal scheduling model based on power demand and grid connection strategy refers to the common optimization targets of commercial and technology VPP, as shown in formula (4).

$$\begin{cases}Cost_1=\varphi_0\left(Q_0\right)+C+\sum_k\varphi_k\left(BQ_k\right)\\Cost_2=\dfrac{1}{2}\sum\dfrac{\left(U_i-U_{i'}\right)^2}{R_{ii'}}\\Cost_3=\dfrac{1}{n}\sqrt{\sum\left(U_i-U_0\right)^2}\end{cases} \tag{4}$$

$Cost_1$ is the operating cost of VPP. Q_0 is the supplying capacity of the centralized power facility and $\varphi_0(Q_0)$ is the corresponding cost for VPP. C is a fixed operating cost such as VPP communication and calculation, which can be equivalent to a constant. $Cost_2$ is the active power loss. U_i－$U_{i'}$ is the voltage difference of branch ii', $R_{ii'}$ is the branch impedance. $Cost_3$ is the voltage deviation of VPP. U_i is the node voltage and U_0 is the voltage of reference node.

Normalization of the multiple optimization objectives is based on fuzzy theory. The membership function of $Cost_i$ shows in formula (5). The closer A ($Cost_i$) is to 0, the closer $Cost_i$ is to the optimal value。The Normalized objective function shows in formula (6). Solving the minimum value of formula (6) makes all $Cost_i$ close to the optimal value.

$$A\left(Cost_i\right)=\frac{Cost_i-Cost_{i\min}}{Cost_{i\max}-Cost_{i\min}} \tag{5}$$

$$Cost=\max\left(A\left(Cost_1\right),A\left(Cost_2\right),A\left(Cost_3\right)\right) \tag{6}$$

The physical condition constraints must be met when VPP solves the optimal scheduling problem. Formula (7) is the supply and demand balance constraint and $\sum LQ$ is the total load capacity of the regional power system. Formula (8) shows the branch capacity constraint and $p_{k\max}$ is the upper limit of the branch capacity.

$$Q_0 + \sum_k BQ_k > \sum LQ \tag{7}$$

$$BQ_k \le p_{k\max} \tag{8}$$

3 Blockchain-based Distributed Algorithm

The combination algorithm based on multi start and variable neighborhood descent algorithm (MS-VND) and local search algorithm (LS) proposed in author's previous studies can solve the VPP optimal scheduling problem, although the grid connection models are different [15]. VPP optimal scheduling calculation takes 2.47h based on Intel(R) Core(TM) i5-4590 CPU @3.30GHz processor. The power flow calculation takes 99.85% of the total time by analyzing the calculation process parameters. In this case, a distributed computing framework based on blockchain can improve the computational efficiency. A large number of DERs can calculate the power flow using standard calculation program. VPP only needs to run the upper-level scheduling algorithm and collect the results of power flow calculation in real time to reach a consensus. The flowchart of distributed algorithm shows in Fig. 2.

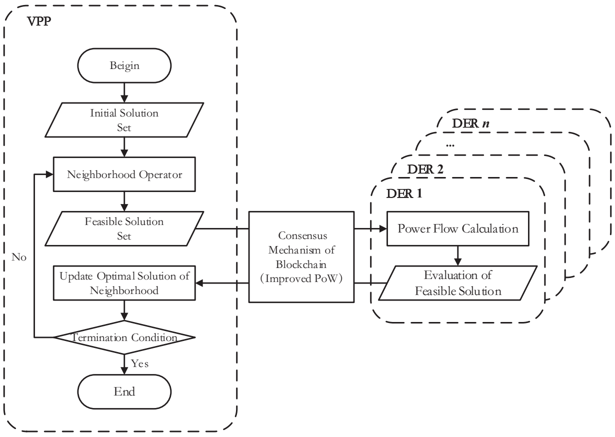

Fig. 2: Flowchart of distributed algorithm

In the blockchain designed in this paper, DER may provide false results of power flow calculation for obtaining more VPP-Coins. DER may also provide incorrect results of power flow calculation due to calculation errors. Consensus mechanisms such as PoW (Proof of Work) are badly needed to avoid trust problems between VPP and DERs. In PoW, the certifier needs a huge amount of calculation to produce the calculation results, but it is easy to verify the calculation results. Due to the particularity of power flow calculation, both the calculation and verification of the results will take a lot of computing resources and time. VPP cannot easily verify the calculation results and reach a consensus; otherwise, the distributed algorithm is meaningless. Therefore, this paper designs an improved POW consensus mechanism. VPP assigns the same power flow calculation to multiple DERs, and reaches a consensus by verifying the consistency of these DERs' calculation results. The data communication between VPP and DER is unicast, and the assignation of power flow calculation is random, so that the information between DERs is not equal. Under these designs, VPP has a certain guiding effect on generating blocks which can reduce the probability of Byzantine failures and avoid the fork attack caused by the double spend problem. The consensus process shows in Fig. 3. The response states of VPP and DER for different excitations show in table 1.

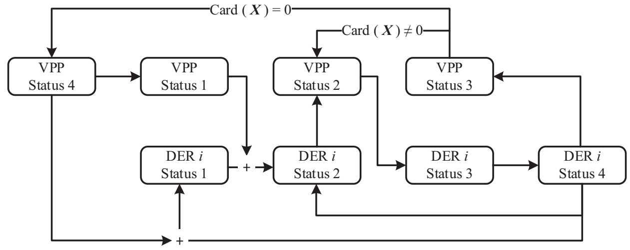

Fig. 3: Improved POW consensus mechanism

Table 1: Status of VPP and DER

Status	Description
VPP Status 1	(1) VPP changes the searching neighborhood. (2) VPP updates the feasible solution set $\boldsymbol{X}$ to be evaluated. $\boldsymbol{X}$ includes feasible solutions that have not been power flow calculated or feasible solutions of unverified power flow results. (3) VPP resets the proof of work sequence *pow*(N) which records the number of the correct power flow calculation for each DER. (4) VPP broadcasts to all DERs that distributed computing of this searching neighborhood begins.
VPP Status 2	VPP sends a feasible solution X_j in $\boldsymbol{X}$ to DER*i* to evaluate via a unicast mode. X_j must be randomly selected and has never been evaluated by DER*i*.
VPP Status 3	(1) VPP updates the evaluation set $\boldsymbol{F}(X_j)$ of the feasible solution X_j according to the result of power flow calculation $F(X_j, i)$ submitted by DER*i*. (2) VPP removes X_j from $\boldsymbol{X}$ when X_j is correctly evaluated. X_j is considered to be correctly evaluated when there is more than one element in the $\boldsymbol{F}(X_j)$ and more than half of the calculation results are consistent under a certain precision. Only the correct results of power flow calculation consider valid. (3) VPP updates *pow*(N) based on the valid proof of work in $\boldsymbol{F}(X_j)$ when X_j is correctly evaluated.
VPP Status 4	The computing of current neighborhood is complete. VPP maintains the current block based on *pow*(N) and broadcasts to all DERs.
DER Status 1	DER*i* stands by for the next searching neighborhood.
DER Status 2	DER*i* is idle and applies for power flow calculation from VPP.
DER Status 3	DER*i* calculates the power flow in condition of X_j.
DER Status 4	DER*i* finishes the power flow calculation and sends the result $F(X_j, i)$ as the proof of work via a unicast mod.

4 Case Study

4.1 Parameters of the Case

As shown in Fig. 4, the IEEE-118 standard test system is used to simulate a regional power system. Load parameters and line topology parameters of the standard test system will not show in detail.

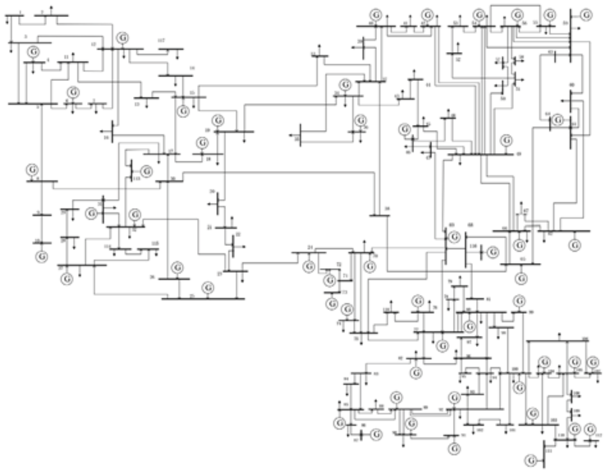

Fig. 4: Topology of IEEE-118 standard test system

Assume that the node 69 (balance node) in the IEEE-118 standard test system is a controllable thermal power plant with a total generating capacity of 1500 MW. The actual generating capacity is 594.226 MW during the last period of Δt, and the power generation cost function is referenced in [16]. In the next period of Δt, the capacity of the thermal power plant Q_0 will be 1298.358 MW and the generation cost will be 54477 USD if the energy supply is concentrated. Therefore, the reference price of grid connection $p_o\left(t_k,1\right)$ is $41.96\,\$/\mathrm{MW}\cdot\mathrm{h}$.

Table 2: DER's grid connection strategy data and calculation power data

DER	DQ_k MW	$DQ_{k\min}$ MW	$DQ_{k\max}$ MW	m_k	n_k	Computing Power
6	1.031	3.21	4.469	55.67	-57.12	0.43
8	0.748	2.89	6.482	18.04	97.32	0.61
9	1.048	2.87	5.562	34.45	50.33	0.27
10	0.851	2.82	5.209	26.62	64.89	0.19
13	0.831	3.05	3.699	57.03	-27.22	0.56
17	0.481	2.31	3.889	63.75	-49.42	0.51
20	0.676	2.58	3.364	70.97	-97.56	0.49
21	1.425	2.36	7.185	46.19	-27.52	0.61
24	0.832	2.93	6.138	52.21	-24.56	0.73
25	1.221	2.96	5.039	45.93	-17.93	0.9
28	0.773	3.22	4.257	37.12	22.84	0.55
29	0.531	2.86	4.319	63.49	-59.33	0.83
34	1.038	2.83	5.512	43.06	-4.96	0.18
37	0.958	2.03	6.612	56.97	-42.83	0.77
39	0.537	3.68	3.773	116.23	-287.8	0.34
41	0.795	1.97	4.755	60.66	-57.26	0.07
42	0.643	4.08	5.277	56.46	-54.07	0.42
45	0.744	2.67	3.266	80.92	-120.7	0.84
46	1.006	2.43	5.834	22.81	69.41	0.05
48	0.783	3.28	4.807	45.43	-11.77	0.04
49	1.376	3.66	6.534	63.92	-114.4	0.25
50	0.635	3.49	4.975	71.08	-105.3	0.89
51	0.999	3.23	5.411	42.37	29.46	0.82
52	0.871	2.98	3.989	63.14	-76.06	0.26
53	0.834	2.62	4.546	51.55	-28.83	0.35
54	0.617	2.95	4.213	48.56	0.62	0.68
55	1.172	2.98	5.218	57.22	-42.32	0.47
56	0.734	3.03	6.566	63.2	-85.65	0.77
57	0.901	3.43	4.509	36.76	33.13	0.72
58	0.694	2.7	5.746	43.83	5.84	0.74
60	0.747	3.55	4.753	89.63	-206.1	0.68
62	1.028	3.07	5.072	39.31	39.01	0.8
64	0.74	2.32	6.46	61.13	-63.48	0.77
65	0.92	3.32	5.2	47.62	7.48	0.83
67	0.627	3.47	4.333	75.42	-114.9	0.11
70	0.524	2.29	4.616	54.93	-45.16	0.36
72	1.013	2.92	4.817	71.95	-115.0	0.21
73	0.926	3.44	4.884	32.51	61.76	0.9
74	0.863	2.64	4.267	71.68	-99.56	0.06
78	0.725	2.99	5.455	60.08	-81.23	0.25
79	1.406	2.68	5.864	53.72	-58.23	0.88
80	0.618	2.41	5.132	32.96	35.4	0.24
81	0.71	2.93	5.09	33.8	53.88	0.83
83	0.475	2.15	3.325	70.16	-78.61	0.47
84	0.612	2.79	4.618	20.74	59.19	0.8
85	0.662	2.99	3.948	40.12	-19.83	0.28
86	0.778	2.93	4.832	69.91	-100.9	0.65
87	0.864	3.17	5.666	69.73	-118.1	0.33
88	1.087	2.61	6.433	42.11	8.29	0.14
90	0.844	3.67	6.956	52.3	-65.49	0.4
93	0.682	3.11	5.198	11.88	124.6	0.39
95	0.854	3.8	4.826	26.44	92.13	0.57
96	0.909	1.93	5.911	41.46	9.28	0.47
98	0.982	2.53	5.508	40.83	-19.55	0.82
99	1.276	3.11	5.494	68.05	-108.2	0.45
100	0.945	2.45	5.835	50.66	-31.39	0.76
101	0.847	3.42	3.673	24.1	57.43	0.32
102	1.073	1.75	5.467	50.84	-28.81	0.65
104	0.743	2.58	5.167	31.8	43.85	0.51
105	1.042	3.54	4.198	90.41	-202.5	0.45
108	0.79	2.42	4.52	41.5	1.74	0.09
110	1.181	3.18	6.099	45.33	-7.28	0.02
111	0.755	3.51	4.435	29.43	71.59	0.52
114	0.867	3.81	3.893	73.49	-137.3	0.79
115	1.13	2.82	5.08	46.49	5.05	0.36
116	1.075	4.13	6.935	51.86	-18.22	0.84
117	0.731	2.76	5.299	69	-101.5	0.22

Assume that there are 67 nodes in the power system with DER participating in the grid connection. The strategy data and calculation power data (relative to VPP's calculation power in section 3) of DER are shown in Table 2.

4.2 Results and Analysis

Under the same conditions, case 1 simulates the power system without any grid connection of DERs, case 2 simulates the situation of common VPP model, and case 3 simulates the situation of the blockchain based VPP model. All the results are shown in Table 3.

Table 3: Results of Case Study

	Case 1	Case 2	Case 3
Capacity of Centralized Energy Supply (MW)	1298.358	979.91	958.626
Cost of Centralized Energy Supply (USD)	54477.08	24939.62	23442.55
Total Winning Bid of DER (MW)	-	279.994	241.05
Total Capacity of Direct Grid Connection (MW)	-	-	57.836
Total Capacity of Grid Connection (MW)	-	279.994	298.886
Cost of Bidding for VPP (USD)	-	12608.55	10694.17
Total Operating Cost (USD)	54477.08	37548.17	35782.44
Active Power Loss (MW)	104.208	65.752	63.359
Voltage Deviation	0.021562	0.021366	0.021395
Cost of Electricity (USD /MWh)	41.96	29.8	28.45
Computing Time (s)	-	8892.90	540.46

Compared with case 1, the operating cost of case 2 is reduced by 31.08%, the active loss is reduced by 36.9%, and the voltage deviation is reduced by 0.9%. Compared with case 1, the operating cost of case 3 is reduced by 34.32%, the active loss is reduced by 39.2%, and the voltage deviation is reduced by 0.8.%. All the three indicators have significantly improved than the centralized power generation in case 2 and case 3. It can be seen that the distributed energy supply mode can effectively improve the power quality, reduce the power generation cost and the power loss than the centralized energy supply mode.

Compared with the simulation 2, the centralized energy supply capacity of simulation 3 decreased by 2.172%, and the corresponding cost decreased by 6.003%. The total capacity of DER grid-connected network increased by 13.909%, reaching 75.05% of the DER grid-connected capacity demand. The operating cost of VPP decreased by 4.703%, the average cost price decreased by 4.53%, the active network loss decreased by 3.64%, but the voltage deviation increased by 0.136%. In general, except for the slight decrease in power quality, the other indicators have improved significantly.

In case 3, VPP released a total of 49,109 power flow calculation tasks, which took 554.49s to complete the optimal scheduling calculation, and the calculation speed increased by 1501.42% compared with case2. Fig. 5 shows the frequency of each DER node participating in block calculation and achieving valid consensus. Under actual circumstances, the results of power flow calculations may not reach consensus at a minimum cost due to various factors such as computer power, accuracy, communication congestion, and subjective causes of nodes. The node failure is simulated by setting the calculation error rate. In case 3, the vast majority of consensus process can be completed by two nodes' power flow calculation. At most, the consensus process is completed by five nodes' power flow calculation (the 1890th, 10303rd, 13352nd, 13557th, 16148th, 33881st, 41712nd and 46085th power flow calculation tasks issued by the VPP).

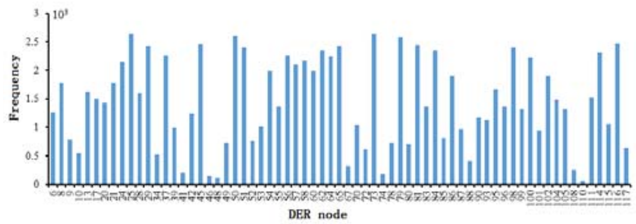

Fig. 5: The valid frequency consensus of each DER

Fig. 6 is a time curve of the effective consensus times for DER 62 (smaller computing power) and DER 38 (larger computing power). DER 62 participates in the power flow calculation for 554.5s, in which the consensus succeed 59 times and fail once(at 258.9s). DER 38 participates in the power flow calculation for 546.8s, in which the consensus succeed 2632 times and fail 28 times (at 3.29s、33.7s、47.49s、53.66s、56.13s、58.59s、65.38s、134.03s、139.78s、177.20s、193.24s、272.99s、293.96s、301.98s、305.69s、328.10s、349.68s、362.02s、393.07s、404.79s、421.42s、473.66s、480.24s、494.62s、513.09s、513.51s、535.49s、540.43s). In general, the greater the computing power, the more valid consensus, and the number of consensus failures increases.

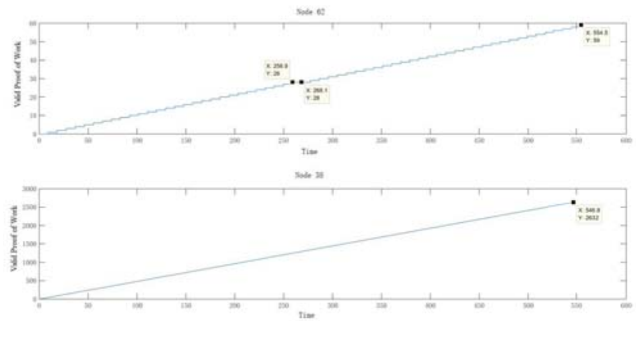

Fig. 6: Valid consensus for DER with smaller and larger computing power

The sum of all the DERs' computing power in Case3 is 33.56 times of the VPP's. Assume that the computing power of each DER is the same, which is 0.5009 times of the VPP's. Under the same conditions, VPP releases a total of 48505 power flow calculations, which takes 540.46s to complete the optimal scheduling calculation. If the computing power of DER increases proportionally to 68.6 times of VPP's computing power, VPP releases 47785 power flow calculations to complete the optimal scheduling calculation with a time of 260.59s. It can be inferred that the computational time of optimal scheduling based on blockchain is strongly related to the sum of computing power and weakly related to the distribution of computing power. In order to reduce the optimal scheduling time more effectively, VPP can stimulate DER to improve the computing power by increasing incentives of blockchain.

5 Conclusions

In general, the blockchain based grid connection model of DERs and the improved PoW based distributed algorithm can not only effectively reduce the VPP optimal scheduling time by appropriate distributed redundancy calculation. but also allow DER connect to the grid more freely through the blockchain incentive mechanism. Simulation results show that the proposed model is effective. The study will focus on achieving the trading of VPP-coin between DERs next.

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