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Research on Multi-source DC microgrid Distributed Group Control Strategy for Pumping Well Cluste

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Abstract

Due to the pumping units' dual role as alternating loads and new energy sources, multi-source DC microgrid pumping unit well clusters experience increased fluctuation in voltage and power as well as peak and valley values that are superimposed. This work presents a distributed cooperation strategy based on the grouping weighted moving average algorithm for pumping unit well groups in multi-source DC microgrid. Centralized control program is implanted in the RTU of the single well controller of each pumping unit, and the communication of each single well is realized by SCADA system to construct the distributed well group system. The real-time power values of the pumping well group are calculated by grouping the power values and granting weighted weights to each group, using the total power fluctuation threshold of the well group as the control target, and further using a weighted moving average algorithm to predict the next power value and form a table of predicted real-time power spectra. According to the power value in the community power spectrum table, the inverter frequency is proportionally adjusted downward to achieve the power peak before deceleration to reach; after crossing the power peak, the frequency is raised in the same way to accelerate the compensation to achieve the power valley before acceleration to reach, that is, acceleration compensation, and finally achieve the power peak and valley values of the bus system to level off, and further learn to reach the set impulse, and finally form a stable impulse. Through laboratory testing and field application in Shengli XIN-11 block application proved: the group control software module not only effectively suppresses the active power peak and valley values and voltage fluctuations of the bus system, the active power fluctuation rate range decreases by more than 70%, the DC bus voltage fluctuation range decreases by more than 80%, but also reduces active power by about 6% without increasing the cost of new hardware.

Key words: multi-source DC microgrid; pumping unit group control; distributed group control strategy; power weighting; grouping weighted moving average

1. INTRODUCTION

DC microgrid technology is the development trend of the future distributed energy supply system and regarded as an important part of future intelligent power distribution system, which is significant in promoting the energy conservation, emission reduction and sustainable energy development [1-3]. With the implementation of the new energy development strategy, the oilfield production system, as a large consumer of energy consumption, actively implements the new energy strategy. Relying on the oilfield SCADA system (Supervisory Control and Data Acquisition), the oilfield production multi-source DC microgrid is constructed [4-7]. Multi-source DC microgrid for oil production in well

group is incorporated into distributed new energy such as wind power and photovoltaic power generation [8-11]. We formed a well group with multiple pumping units with similar distances and some common attributes. The well group production used DC bus power supply components to form a small DC microgrid, which incorporated several new energy sources such as wind power, photovoltaic power generation and network electricity to form a distributed multi-source DC microgrid. The DC microgrid connects the control cabinets of multiple pumping units in parallel through the DC bus, and the integrated inverter and Remote Terminal Unit (RTU) in the control cabinet can realize the mutual feed-sharing and recycling of the power generated by multiple pumping units [12-15]. The multi-source DC microgrid has commonness and mutual influence among each other [16-19]. Because the pumping unit is an alternating load, it has the superposition of peak and valley, causing a series of hazards, which requires a unified control and management system. Multi-source DC microgrid has commonality and mutual influence, which requires a control management system. This paper proposes a distributed group control strategy for block oil recovery multi-source DC microgrid, and implements it on site to verify the rationality.

2. Multi-source DC Microgrid Group Control Research Status and Current Problems

2.1. Existing problem

The oil production system for the well group's DC microgrid had expanded fast in recent years. By the end of 2020, more than 2000 oil wells in the Shengli Oilfield had transitioned to DC bus power sources, which exhibit outstanding technological and financial advantage. However, the overall condition, which was referred to as "group without control," aimed to get the right feedback and a fair amount of the power generated by each pumping unit. So-called "group control" has a long way to go before its objectives are met [8-10].

Due to the pumping units' alternating load characteristics, reverse generation occurs often during their reversing phase, and a superimposed peak-valley phenomenon occurs when the pumping units' DC bus operates as a group. Significant voltage and active power fluctuations occur, and the peak-to-valley ratio of the DC bus power rises. On the one hand, a DC microgrid system might result in feedback overvoltage, undervoltage, and overload. On the other hand, it interferes with the availability of solar, wind, and other emerging energy sources. Harmonics have been a serious concern with the introduction of new energy sources, causing the system to shut down or causing explosions in capacitors, IGBTs (Insulated Gate Bipolar Transistors), and other power electronic equipment, resulting in hazardous events such as a decline in oil well productivity [9-10]. Therefore, it is urgent to conduct unified control and management for the operation of DC bus pumping units in oil wells. This can contribute to coordinating the operation status of each pumping units and suppress the total peak and valley value of the bus and achieve the purpose of stable and safe operation of the system.

2.2. Main research progress

In recent years, the DC microgrid cluster control strategy has been a hot research topic. M Zare and Derbas et al. improved hybrid artificial bee colony algorithm and differential evolution algorithm, as optimization technologies, to solve the problem of optimal energy management of grid-connected microgrid [20-21]. J. Kim, et al., proposes a DC series arc detection algorithm in a photovoltaic (PV) system using an adaptive moving average (AMA) which is effective in the centralized and spread-type of frequency fluctuations [22]. Y. Dong, et al., propose a combined model, i.e., a wind power prediction model based on multi-class autoregressive moving average (ARMA) which has a two-layer structure the wind power data with the logistic function based classification method and the prediction algorithm in each class [23]. Wang J et al. proposed a distributed Kalman filter power prediction algorithm combined with graph theory [24]. T. -T. Nguyen and H. M. Kim proposed a hybrid control method based on the distributed consensus control and the central model predictive control, which could overcome the computational burden in the central control methods or the complexity of the communication network in the decentralized control strategies [25]. Z. Cheng., et al., designed a

modified distributed Kalman filter (KF) based on the mixed phasor measurement unit (PMU) and RTU measurements model, which realized the independently estimating local states by local measurements [26]. M. S. Munsi, et al proposed the use of an algorithm based on the unscented Kalman filter (UKF) to control voltage and current of microgrid against unknown noise [27]. L.Che, M. and Shahidehpour discussed the power flow between DC microgrid and main grid from the perspective of economy, optimization and stability, and designed a three-level control strategy for DC microgrid [28]. However, most of these studies focused on power generation side control rather than DC microgrid internal control, and different user group control objectives require different implementation schemes. At present, there is no special system applied to well group product system [4, 9, 19]. Su J. and Jesse Thornburg, et al., selected the total power output the variance of the well group as control target function, and used the improved adaptive genetic algorithm to calculate the staggered operating time interval of each pumping units, so as to keep the number of the pumping units running in the electric state and the pumping units running in the reverse power state in the well group relatively consistent [10, 15]. To a certain extent, it is positive but unacceptable to change the pumping unite flushing times.

3. Distributed Power Grouping Weighted Predictive Group Control Algorithm

3.1. Application environment

Figure 1 shows the representative control structure of multi-source DC microgrid pumping unit group control system scheme based on SCADA. A control cabinet com-posed of inverter module and RTU is installed on each single well to convert DC into alternating current with variable frequency to realize automatic regulation of the pumping unit motor. The working area of DC microgrid is generally less than 5km.

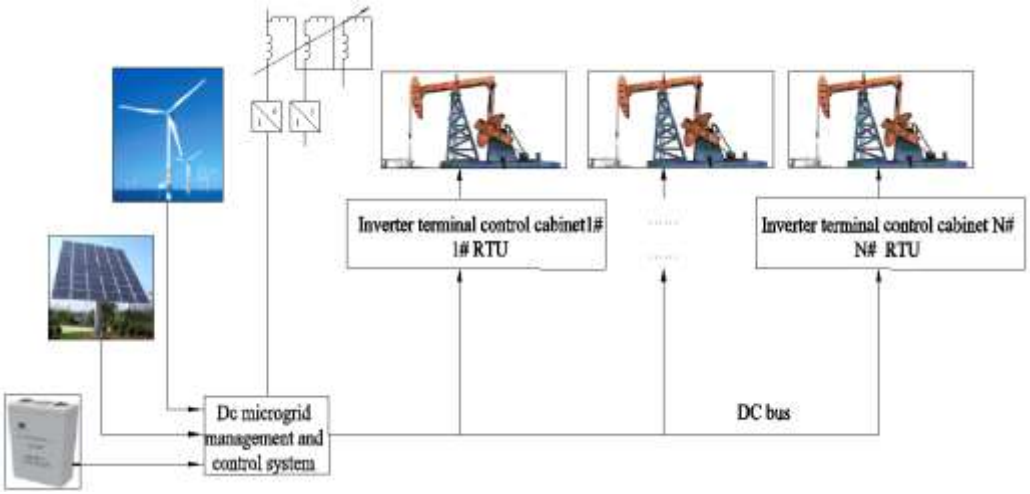


Fig.1 Multi-source DC microgrid pumping unit group control system scheme.

Fig.2 is Scheme diagram of multi-source DC microgrid pumping unit group control system after RTU is implanted with centralized control element. Centralized control software (hereinafter referred to as "group control software") is implanted in the RTU of the single well controller of each pumping unit, and the communication of each single well is realized by SCADA system to construct the distributed well group system. The RTU comes with a central processor and requires no additional hardware costs. Each individual well in the well group communicates with each other through the SCADA system to report real-time production information of individual wells, including real-time power, and to receive production information from other individual wells. Specifically, the group control software module is inserted into the RTU of each single well controller in the well group.

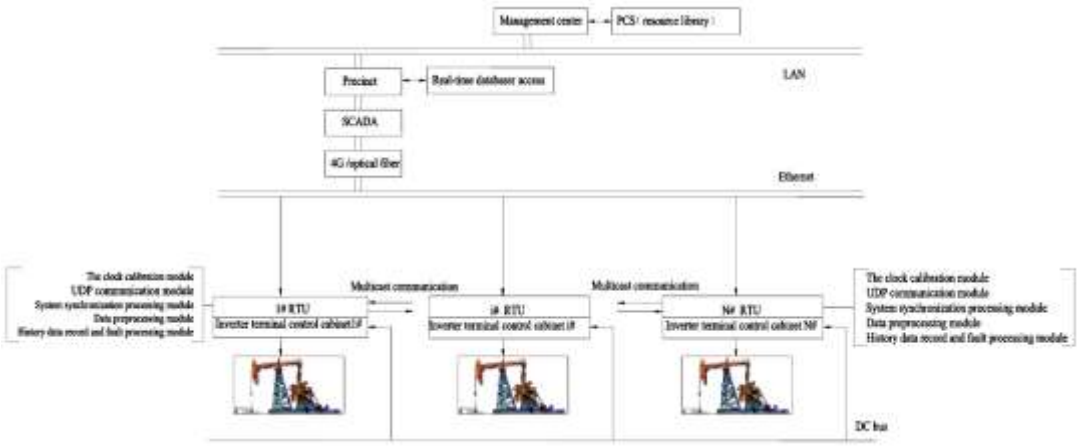


Fig 2 Scheme diagram of multi-source DC microgrid pumping unit group control system after RTU is implanted with centralized control element.

3.2. Group control principle

Due to the power of each individual pumping unit within the well group has periodic fluctuations and the power extremes are deterministic, the real-time power values of the pumping unit well group are calculated by grouping the power values and granting weighted weights to each group. The DC microgrid in question is a distributed system, and the total power fluctuation threshold for the well group is employed as the control objective. In addition, the weighted moving average algorithm is used to predict the next power value to form a predicted real-time power spectrum table in order to locate the pumpers with the largest weight value, that is, the largest impact on power. According to the power spectrum table of the community, the inverter frequency is proportionally lowered to achieve the power peak before deceleration to reach, after crossing the power peak, the frequency is raised in the same way to accelerate compensation to achieve the power valley before acceleration to reach, that is, acceleration compensation, and finally achieve the power peak and valley values of the leveling bus system, and further learning to reach the set impulse, and finally form a stable impulse, effectively coordinating the operating state between the pumpers [30]. The system is designed to achieve smooth and safe operation.

3.3. Group control algorithm and implementation process

The group control software realizes the well group control by embedding RTU of each pumping unit controller in the well group. Taking into account the fact that the real-time pumping power in general shows cyclical fluctuations; multiple pumping power divisions within a certain interval, a grouping weighted moving average is used for the prediction analysis (Refer to Fig5).

Informational connection is created between each well node in the well group, after which the system will periodically correct the time. System clock calibration and group control error are closely related.

The following issues: UDP (User Datagram Protocol) software realizes the group sending of RTU after power-on, including grouping, clock, distribution of hashtag, IP, marking clock, member list, etc. It will further achieve the increase/decrease of members. The management right is automatically promoted. The address size in the network is sorted. The former is the manager and the management right is transferred automatically.

The RTU is connected to the inverter, first extracts the stored data area code, then extracts the data in each area code, and finally extracts the data in the inverter, including real-time power, voltage, current, impulse, etc., and stores it in the form of database file. After the well number is obtained, the RTU that is not powered on is sent to the group, and the members of the group are retrieved. Members of the group who are absent for an extended period of time will receive separate notifications, and the database will create and store the group table file group.jq.

Calculate the real-time power spectrum power.dt of the machine, calculate and assign the power weight. The real-time power spectrum of each pumping units is determined and the power weight is given, and then the power weighting is calculated to judge the contribution value of different single well model power to the bus. RTU data is re-read at a certain interval to recalculate the real-time power spectrum of each pumping units. The weighted calculation formula of real-time power value is as follows:

$$Q_j = \frac{\sum_{i=1}^{n_1} P_{i,j} \times k_1) + \sum_{i=1}^{n_2} (P_{i_2 j} \times k_2) + \ldots + \sum_{i=1}^{n_n} (P_{i_n j} \times k_n)}{\sum_{i}^{n} k_i} \tag{1}$$

where Q_j is the actual real-time power value of a single well is reported after weighting;

k_i , grouping weight, $k_i = i / n$; i, group number; n, number of pumping units;

P_{ij} is real-time power value of pumping unit i at time j;

$$\vdots$$

$P_{i_1 j} = \left\{ P_{i_1 j} : \min \le Value \le S1, n_1, k_1 \right\}$, $P_{i_1 j}$, Real-time power value, n_1 , number of $P_{i_1 j}$;

$P_{i_2 j} = \left\{ P_{i_2 j} : S1 \le Value \le S2, n_2, k_2 \right\}$, $P_{i_2 j}$, Real-time power value, n_2 , number of $P_{i_2 j}$;

$P_{i_3 j} = \left\{ P_{i_3 j} : S2 \le Value \le S3, n_3, k_3 \right\}$, $P_{i_3 j}$, Real-time power value, n_3 , number of $P_{i_3 j}$;

$$\vdots$$

$P_{i_n j} = \left\{ P_{i_n j} : S(n-1) \le Value \le Sn, n_n, k_n \right\}$, $P_{i_n j}$, Real-time power value, n_n , number of $P_{i_n j}$;

Establishing a real-time community power spectrum table for a cluster of wells and predicting it using a grouping weighted moving average based power prediction model.

$$Q_{j+1} = \frac{\sum_{i=1}^{n_1} P_{i,j} \times k_1) + \sum_{i=1}^{n_2} (P_{i_2 j} \times k_2) + \ldots + \sum_{i=1}^{n_m} (P_{i_n j} \times k_n)}{\sum_{i}^{n} k_i} \tag{2}$$

$$(Q_{j+1} - Q_j) / Q_j \le A \tag{3}$$

Where A is the prediction error threshold, set at 5% or less than 5%.

Adjusting the inverter to level out the power peaks and valleys of the bus system accorded to the predicted values.

Update relevant data, including torque and speed, rotational inertia, angular acceleration, predictions, post-action prognosis.

Input a certain time initial data, training; after self-learning to reach a set number of impulses, forming a stable impulse table, continuous operation.

4. Implement

4.1. Hardware support

Without the need for additional hardware resources, RTU hardware realizes the group control software. An ARM11 embedded CPU processor powers RTU. Software Development Kit (SDK) for LINUX embedded systems is offered by ARM11. The specific development software is a Windows 10 system and a Linux kernel 3.15. The ARM11 platform supports the TCP/UDP/IP and MODBUSRTU protocols and has RS485, ZIGBEE, and ETHERNET communication interfaces. The device address, connection parameters, and well group data can all be changed online with ARM11.

4.2. Software overall structure and module interface design

As shown in Figure 2, the UDP communication module, inverter control module, clock calibration module, data preprocessing module, history data record and fault processing module, well group of parameters of the stored file system module, and system synchronization processing module are all classified as seven functional modules in total. RTU multicast communication proved successful in enabling barrier-free information transfer between a single well. The system synchronization processing module realizes the synchronization function with the oilfield SCADA system, and the data preprocessing module achieves the functions of weighting, denoising, and interpolation after frame loss

of power values under various pumping units. The group control software adopts an innovative design on.

4.3. Laboratory tests

As shown in Figure 3, an integrated development platform and test platform were set up in the laboratory, which included desktop computers, raspberry PI 4B, 4 250W AC electric motor, 4 intelligent monitoring modules for oil and water Wells dedicated to oilfields of well group RTU, 4 inverters and DC power supply. Test the functionality and dependability of the RS485 communication program, as well as the frequency selection, in a stand-alone communication environment. Test for calibration program: Run constantly for 10 days, watch each RTU's time, and ensure that the time inaccuracy is within 0.3 milliseconds. Test the multicast communication on each machine that sends and receives data. Test for power trend prediction: Predict the power trend in the following minute with less than 5% variance. Bus total power test: when the automatic control software was implemented, the bus total power fluctuation was decreased by 85% in comparison to the original system, and the desired result was obtained.



(3a) (3b)

Fig.3 Laboratory test site. (3a) Panorama of experiment platform; (3b) RTU and AC electric motor s implanted with centralized control element**.**

4.4. Field application test

A portion of the test well site is shown in Figure 4. The Shengli Oilfield's DXX11 well group, which has a relatively high concentration of 29 wells, was chosen as one of the test locations for the DC micro power grid group control test. According to the relative position, it is separated into three groups that are fairly concentrated: well group 1 has four wells, well group 2 has eleven wells, and well group 3 has 14 wells. After the transformer, the grid power is the main power supply, the maximum photovoltaic power is 50×2kW, and the lithium energy storage is 70kW. Since the photovoltaic power generation at full load is not enough to maintain the power supply of the system, it is used as the supplementary power supply. Well groups 1 and 2 are connected to 50kW solar energy, while well group 3 is connected to 50kW solar energy. Well group 1 was selected for experimental analysis. Table 1 shows detailed information of the 4 Wells.

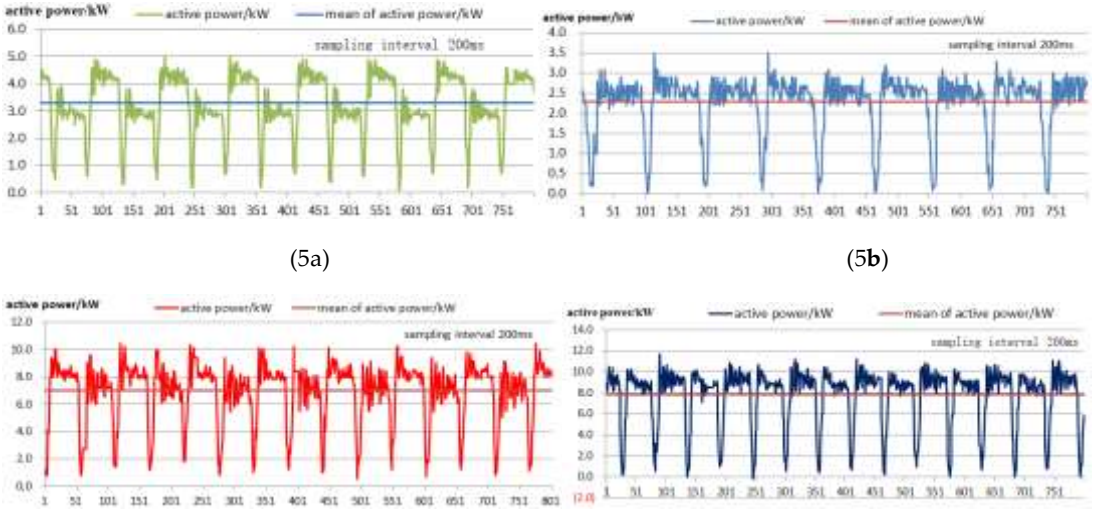
•Table 1. Parameter list of pumping units in DXX11 well group.

	Well number	Motor	Pumping units	P /kW	Day-power consumption/kW·h	Flushes times/min	IP
1	11XN9	Y225M-8	belt	30	90.17	2.3	192.168.97.124
2	11X173	Y225M-8	belt	30	69.42	3.5	192.168.97.126
3	11X161	YE3-250M-8	belt	37	178.67	2.2	192.168.97.129
4	11X195	Y225M-8	belt	37	192.25	2.1	192.168.97.128



(4a) (4b)

Fig.4 Test site of DXX11 well group. (4a) Partial panorama of the well site; (4b) Participated in testing 4 wells**.**



(5a) (5**b**)

(5**c**) (5**d**)

Fig.5 Active power diagram of 4 pumping units after installation of group control software:(5a) –(5d) Active power diagrams of No. 1-4 pumping units respectively.

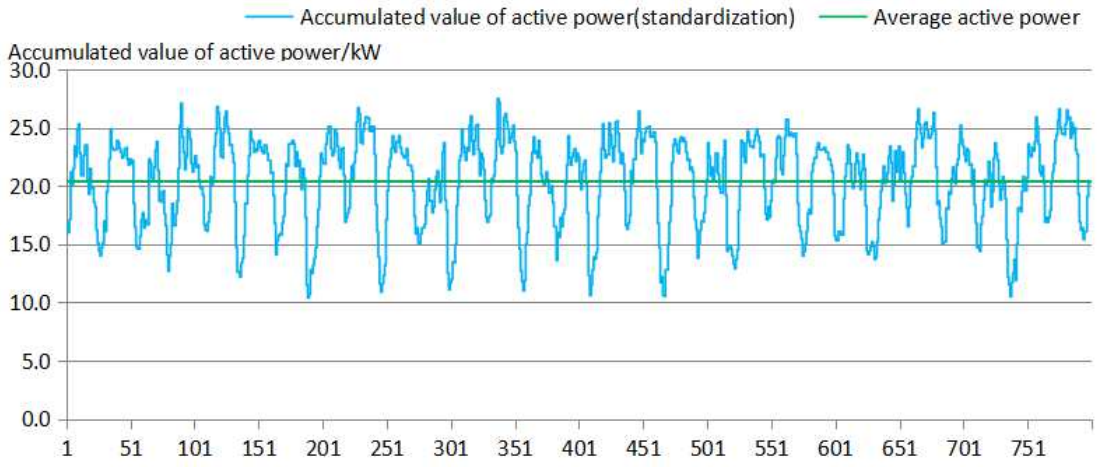


Figure 6. Active power diagram of test bus after installation of group control program.

The SCADA system of the Shengli Oilfield was used to test the active power and collect the parameters of every single well (10:00 a.m, on October 23, 2021). The test sampling interval was 200ms, with a total of 800 groups of test data and a total length of 160s. As shown in Figure 5, the active power of the four pumping units fluctuated from 0.1 to 5.0, 0.0 to 3.5, 0.5 to 10.4 and -0.2 to 10.7kW, respectively. It could be seen that the active power of a single well fluctuates greatly. The

mean square error of active power was 1.09, 0.73, 2.26 and 2.7kW. The fluctuation of active power mainly lies in the sharp reduction of active power during the reversing process, and some of them even appear "reverse power generation phenomenon". The group control software cannot change the original power characteristics of the pumping units. As shown in Figure 6, the cumulative DC busbar active power of the 4 pumping units fluctuated in the range of 10.4~27.5kW, with the mean active power of 20.38kW and the mean-variance of the active power of 3.76kW. It could be seen that the fluctuation range of active power of the bus bars of the four pumping units decreases obviously. The overall strokes of the four pumping units remain the same, but different strokes correspond to different cycles, such as unit 1. At the same time, there were periodic fluctuations, mainly due to program adjustment of the peak power. In addition, No.1 pumping units, there were problems with the balance adjustment of up and downstroke, and the power difference was quite large.

The one-week test was carried out from November 21 to November 28, 2021, in order to more effectively test the DC bus active power and voltage fluctuation. The sampling interval was 10 minutes, and the sampling time was 167T. A sample of 1000 different data sets was taken. The comparative data consisted of the active power and voltage values of the bridge rectifier power supply output measured prior to installation, the test voltage being the bus voltage. It was sunny during the test, with little variation in lighting. From Figure 7, it can be seen that the average active power of the DC bus has decreased from 18.30kW to 17.22kW before and after installing the group control software, a decrease of 5.90%, or an energy saving of 5.90%. The fluctuation range of the active power of the DC bus has decreased from 3.6 to 40.5kW to 12.4 to 23.1kW, with a reduction of 71.01% in the fluctuation range. Figure 8 shows that before and after installing the group control software, the fluctuation range of DC bus voltage decreased from 684.0-518.6 to 546.1-524.8, the voltage fluctuation range decreased by 87.12%, and the mean square deviation of the fluctuation decreased by 77.93% from 14.09V to 3.11V. At the same time, before and after installing the group control software, the average voltage of the DC bus decreased significantly from 545.28V to 534.28V. Especially, significant voltage singularities are removed, which has a substantial impact on the DC microgrid, as the DC bus voltage in the singularity area is much higher than the input voltage of new energy, which has a significant negative impact on the integration of new energy into the DC microgrid, that is, new energy sources such as photovoltaics cannot be integrated into the DC microgrid.

The analysis of the above data shows that the installation of group control software not only effectively reduces the active power range by more than 70% and the DC bus voltage fluctuation range by more than 80%, but also saves energy by 5.90%. The reason analysis is as follows: due to the use of bridge rectifiers and braking resistors when connected to the grid, the braking resistor consumes some electrical energy when the specified voltage value is exceeded. After installing the group control software, the voltage fluctuation is small, especially after the removal of singular voltage high points, the braking resistor does not consume electricity.

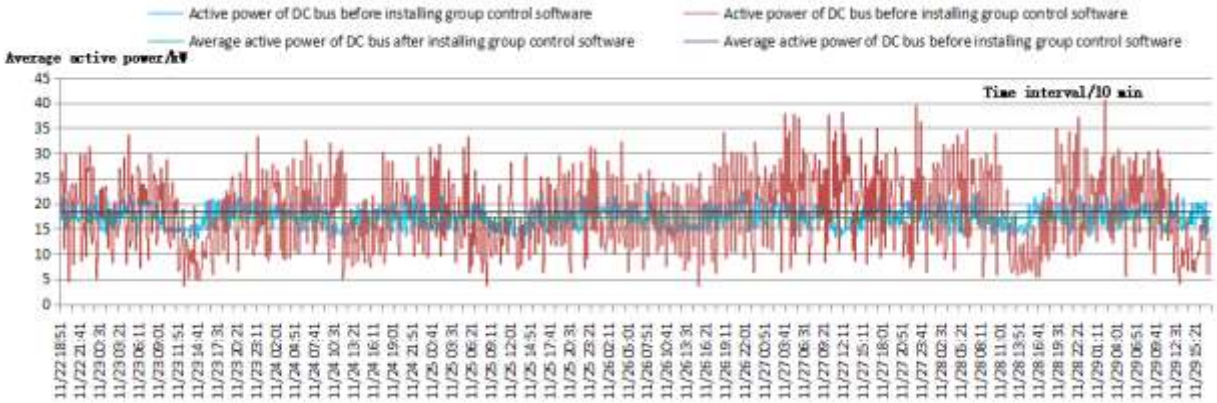


Fig.7 Comparison diagram of active power fluctuation of DC bus before and after installation of group

control software.

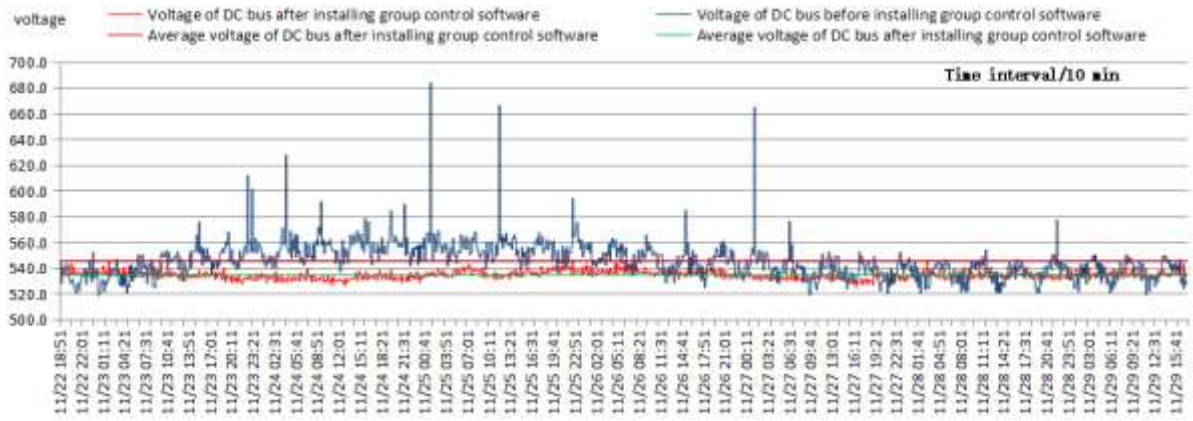


Fig.8 Comparison diagram of voltage fluctuation of DC bus before and after installation of group control software.

After analysis of the test data of 11 Wells in group 2, compared with group 1, the fluctuation range of active power of DC bus decreased by 78.80%, the voltage fluctuation range of DC bus decreased by nearly 88.92%, and the mean value of active power of bus decreased by 6.06%.

5. RESULTS

Due to the access of multiple new energy sources and the inherent alternating load characteristics of the pumping units, there is a peak-to-valley superposition phenomenon in the operation of the DC bus cluster of the pumping unit well set multi-source DC microgrid, resulting in serious fluctuations of the microgrid bus voltage and active power, which must be controlled by the cluster.

In view of the periodic fluctuation of the power of each single pumping unit in the well group and the deterministic characteristics of the power extremes, this paper proposes a control strategy for distributed multi-source microgrid well groups, using a group moving average group control algorithm, taking the total power fluctuation threshold of the well group as the control target, further using a weighted moving average algorithm to predict the next power value, forming a predicted real-time power spectrum table, achieving decelerated arrival before the power peak and accelerated compensation after crossing the power peak by regulating the inverter, effectively smoothing the power peaks and valleys of the bus system, and further learning the set impulse of stable arrival afterwards.

Develop group control software module, through laboratory testing and field application, it is proved that: the group control software module not only achieves to level out the power peaks and valleys of bus system, the active power fluctuation range decreases by more than 70%, the DC bus voltage fluctuation range decreases by more than 80%, the DC bus active power and voltage fluctuation range decreases significantly, increases the incorporated DC bus photovoltaic power generation, the DC bus active power decreases by about 6% after rectification, the energy saving function has obvious effect.

As a distributed group control software system, RTU implants an embedded program to realize the control of the pumping wells group, without increasing the system additional hardware costs. At the same time, the effective suppression of the DC bus voltage fluctuation range is conducive to new energy access. Therefore, the project has a great promotion advantage in the optimization management of multi-source microgrid. It improves the ratio of electricity and green energy in the oilfield and saves energy.

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resources and data curation, Senior Engineer LiFengming and Wang Zhenjie.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results".

Availability of materials and data： We encourage: All data are collected and collated for field testing to ensure the authenticity and reliability of the data. All test data is available if required.The datasets used and/or analysed during the current study available from the corresponding author on reasonable request. All data generated or analysed during this study are included in this published article [and its supplementary information files].For additional clarity, the project team's data collection efforts greatly outstripped the information included in the "Paper field test data and data analysis" submission. To create a remote real-time data collection and monitoring system for the pumping well cluster, the project team builds upon the SCADA (Supervisory Control and Data Acquisition) system. Data is gathered and saved in the cloud by putting RTUs (Remote Terminal Units) in each individual well, photovoltaic substation, maximum power point tracking (MPPT) controller, rectifier power source, etc.

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