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Analysis of DC distribution efficiency based on metered data in a typical Hong Kong office building

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Abstract

This paper aims to analyze the distribution efficiency of DC power distribution power system in commercial building based on measured data from a typical office building in Hong Kong. In this research, a real-scene comparative testbed was built in a Hong Kong office to compare the energy efficiencies of AC and DC power distribution system. Similar load characteristics and use schedules are set and used in the experiment. The distribution efficiency has been found to be affected by load type, voltage level and the loading conditions. The efficiency of this DC power system is derived, considering the PFC model was working in a good condition. For LED loads, the average distribution efficiencies after converter are 77.7% and 51.8 % under the condition of full lightning and normal lightning mode. The main loss in this system is transmission loss and switching loss. The average AC/DC converter efficiencies of LEDs are 92.21% and 88.85% respectively with the load working under full power and normal power, while the average AC power factors of LEDs are 85.31% and 56.22% respectively with the load working under the same as above. The average AC/DC converter efficiencies of the fan coil are 97.41%, 96.03%, 92.74%, 89.10%, 85.71%, 78.72%, 67.61%, 63.57% respectively with the load working under level 8 to level 1 while the average AC power factors of the fan coil are 98.0%, 99.0% and 99.4% respectively with the load working under low middle and high condition. As the PFC circuit does not have ideal power factor correction when the load is small, it is not recommended to add PFC circuit when the load power is low. Using uncontrollable rectifier circuit is going to lead to a better performance.

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Keywords: DC power distribution; Energy efficiency; Load characteristic; System modeling

1. Introduction

The global energy frame characteristics has been changing with the decrease of the conventional fuel energy stock. It has been predicted that the share of renewable energy in total primary energy supply would rise from 14%

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in 2015 to 63% in 2050 [1]. Sustainable energy would play a much more important role in the future world energy pattern definitely. The involvement of these forms would certainly arouse some puzzles when connecting them to traditional power gird. In order to integrate these new energy forms into our main grid with little loss and cost, people have to reconsider the power grid architecture and transmission method properly.

Also, it is no doubt that electricity has become more indispensable due to urbanization process. For example, in 2021, Texas, the power crisis leaded to a $16 billion in unnecessary charges [2]. Photovoltaic solar system is very easy to achieve solar power generation [3,4] and the development of battery charging and keeping technology makes the production of UPS and other energy storage devices simpler and more reliable [5]. Compared to traditional AC power supply system, the PV system and UPS system are much easily integrated into the DC distribution network. Also, straight connecting these parts into DC power distribution grid would also reduce the DC–AC conversion process and then improve the efficiency of overall system [3] We cannot ignore the superiority of direct current (DC) power distribution systems according to all these features [6].

There have been several successful practical applications of DC power systems. When it comes to loads with high power density, such as data center and telecom devices [7]. The systems using direct current save more energy than those using AC. Commercial buildings in the United States currently consume a huge part of their energy in electricity [8,9]. More and more of those commercial buildings tend to use DC power distribution systems, especially in lighting applications, due to the high coincidence of solar generation and commercial end-use loads. The photovoltaic panels provide the bulk of power to lighting, fans and other functions, at times more than 96% of the facility's DC equipment energy needs. [10,11]. Commercial buildings tend to weigh how much electricity can they save when using DC power. And economic effects of DC powered buildings seem to be prospectively. Even by converting only homes' air conditioning condensing units to DC, the costs of direct-DC are greatly reduced and home energy savings of 7%–16% are generated. [12].

However, in real conditions, the measurement data cannot be limited into single load condition such as LED [7]. In order to analysis the feature and efficiency of the DC distribution system more accurately and comprehensively, more kinds of loads and working conditions should be tested. At the same time, the efficiency of the converter also requires the support of real data rather than just simulation verification, in order to have a clearer understanding of the efficiency of the converter in the entire system and the overall efficiency characteristics of the DC power supply.

The efficiency of DC distribution system would influence the overall performance. However, because of the limitation of both equipment and cost, this kind of analysis were usually carried out by simulation instead of experimental data. This paper accessed all measured data from the project of Vicwood Wind Engineering Limited in collaboration with Harbin Institute of Technology (Shenzhen), commissioned by the Electrical and Mechanical Services Department (EMSD) of Hong Kong government.

2. The outline of the DC distribution power system

In this project, two types of power converters will be used: one is a 220 VAC to 400 VDC power converter, and the other is a 220 VAC to 48 VDC power converter as Fig. 1. shown. The first converter (220 VAC to 400 VDC) can provide a high-level voltage output which can reduce a wiring cost by feeding cable diameter narrowing. This is the future of high-capacitance rectifiers, anticipated even as a replacement for large uninterruptible power supplies (UPS), while it may not be suitable for office end-use appliance and need DC/DC converters. The second converter (220 VAC to 48 VDC) are mainly used as direct power supplies for communication devices such as servers, routers, and switching devices for communication carriers.

The system receives AC power as input and outputs DC at voltages suitable for various devices. At present, more and more electronic devices can accept 48 VDC. The current will go through various output circuit breaker, and then each load will be connected to the circuit. The system diagram is drawn in Fig. 1.

2.1. Load characteristics

The efficiency of the system is impacted by the loading condition significantly. The nature of the load would influence the working condition of the system as well. As a matter of fact, setting same type of loading and operating condition for each type of load under the same working conditions makes the overall analysis more precise and meaningful. We can thus understand the rule of the relationship between the efficiency, output power under many

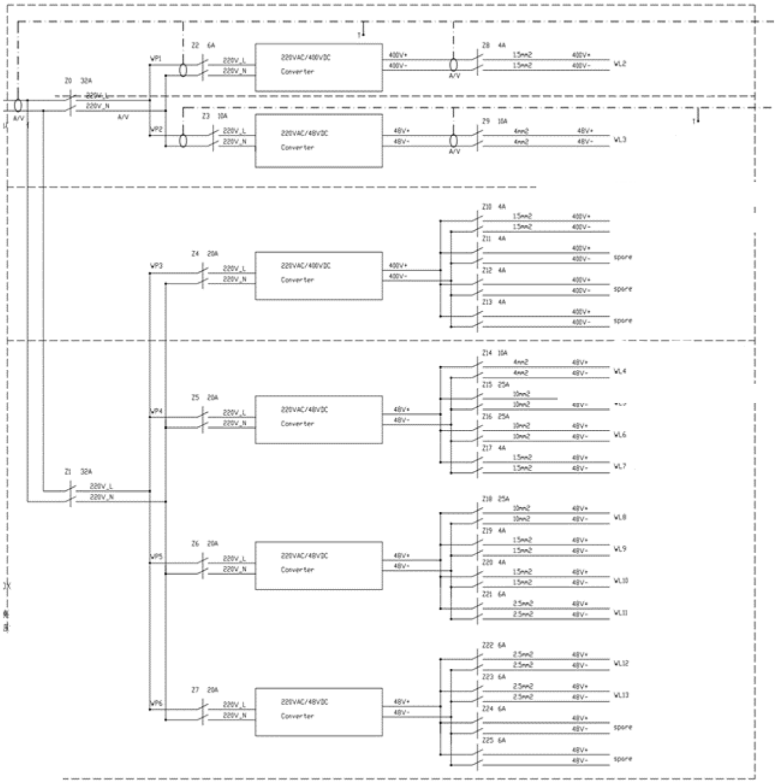

Fig. 1. Schematic diagram of the DC distribution system.

Table 1. Loading settings of different load conditions.

Load name	Setting
LED	Full power, Normal power
AC fan coils	High, Middle, Low
DC fan coils	Level 1 to Level 8

occasions. As LED is the most common lighting equipment in both commercial and residential buildings, we set LED as one of the load types.

There are two working conditions for LED lighting, the first is full lighting and the second is normal lighting. The same lighting equipment is connected after the DC and AC power supply system, measured under the same working condition to make sure the control variable to be the same.

At the same time, we selected fan-coil unit as the second type of load. Fan-coil unit is one of the most important and frequently used HVAC end users in China. Since the output wind speed of the fan can be directly measured, the output can thus be quantified. Since the working principles of DC fans and AC fans are different and their operating gears are also different, we introduce the parameter of wind speed, and record the output wind speed of the fan in different gears as a measure of its working states to settle the problem that its operation cannot be set under the same condition. Figs. 2 and 3 show the system structures of the two different types of fan coils. The details of the load settings are summarized in Table 1.

2.2. AC/DC converter topology

Compared with conventional AC power supply, the transmission loss in DC distribution power supply is low especially under higher voltage level [4]. The higher the voltage is, the more advantages it shows and can reduce a wiring cost by feeding cable diameter narrowing.

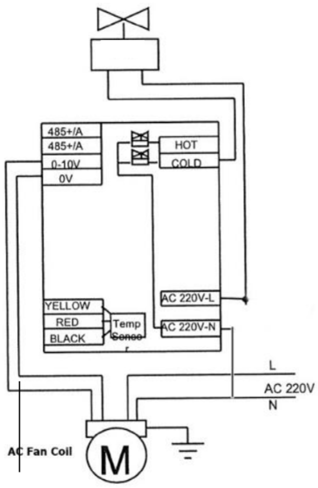

Fig. 2. AC fan coil unit with manually 3 speeds.

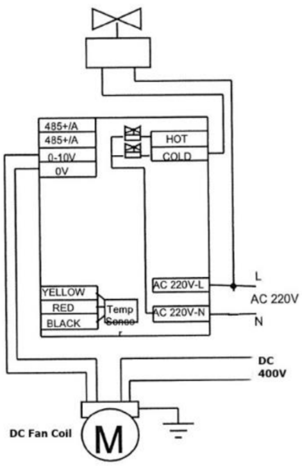

Fig. 3. DC fan coil unit with manually 8 speeds.

The system of the 220 VAC/400 VDC power converter is shown in Fig. 4. The input 220 VAC power is rectified into a DC voltage of about 311 V through a diode rectifier circuit, and then passes through the "BOOST" circuit for active power factor correction (APFC) and outputs the required 400 VDC voltage. Through the first-level isolation topological circuit, 400 VDC voltage is outputted to the load.

The second converter (220 VAC to 48 VDC) is mainly used as direct power supplies for communication devices such as servers, routers, and switching devices for communication carriers.

The system of the 220 VAC/48 VDC power converter is shown in Fig. 5. The method to model the LED lamps and ventilation motors in this project is given. Finally, the design and simulation of photovoltaic hybrid microgrid are realized by Simulink.

2.3. Onsite measurement

Testing devices are installed in the system, and the important node under the high-voltage and low-voltage sets of DC power supply conditions are monitored. Fig. 6 shows the diagram of the measurement points.

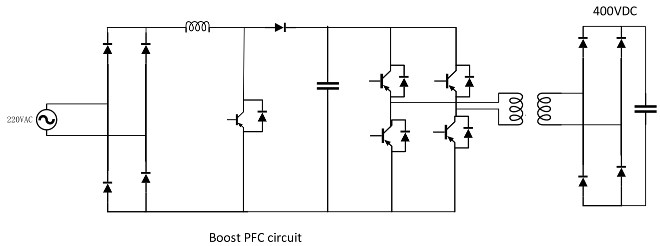

Fig. 4. 220 VAC to 400 VDC power converter topology.

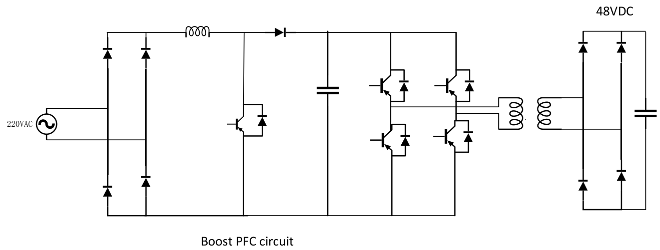

Fig. 5. 220 VAC to 48 VDC power converter topology.

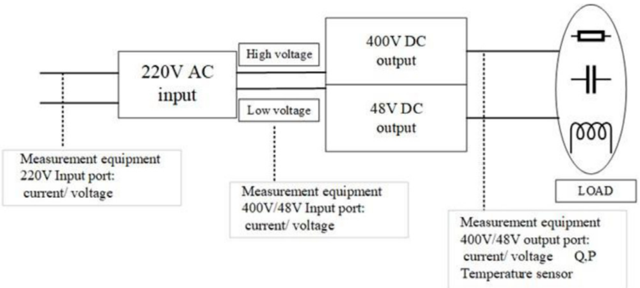

Fig. 6. The measurement points diagram.

Fig. 7. The DC instrument cabinet at site.

The DC instrument cabinet is the core component of the DC distribution system. The 220 VAC/400 VDC converters and 220 VAC/48 VDC converters were installed at the same cabinet but in separated compartments to improve electrical safety. The cabinet is divided into compartments of High voltage and Low voltage as shown in Fig. 7. Each component of the DC power distribution unit is connected to the main electrical ground. Incoming and outgoing wires are set at the bottom of the cabinet. Values of parameters measured from the DC and AC distribution systems are shown on the display of the DC instrument cabinet. A computer module is installed to store the metered data.

For DC power supply part, all the parameters below are measured.

Fig. 8. Loading control panels of the fan coil units.

Fig. 9. LED lighting control panels (full power and normal power).

Table 2. Average values of test data of DC LED.

Setting	AC input voltage (V)	AC input current (A)	Power factor	DC output power (W)
Full power	220.38	0.63	0.84	107.82
Normal power	220.67	0.34	0.58	39.41

Table 3. Average values of test data of DC fan coils.

Set	Before converters				After converters		
	Voltage (V)	Current (A)	Power factor	Power (W)	Voltage (V)	Current (A)	Power (W)
8	220.9275	0.462125	0.82	83.3625	401.235	0.202	81.435
7	220.8325	0.3805	0.805	67.445	401.2175	0.1605	64.9225
6	220.8225	0.3135	0.7725	53.705	401.225	0.12175	49.795
5	220.84	0.260625	0.7375	41.2375	401.2375	0.091	36.72
4	220.755	0.22125	0.6425	31.23	401.1925	0.068125	26.645
3	220.7475	0.18575	0.58	23.7125	401.19	0.048375	18.8875
2	220.6525	0.1615	0.4425	15.6725	401.215	0.02825	10.585
1	220.525	0.156875	0.4	13.72	401.22	0.021	8.73

1. Online current and voltage at 220 VAC input side;
2. Online current and voltage at each 400 VDC and 48 VDC load feedback terminal;
3. Online temperature of 220 VAC/400 VDC and 220 VAC/48 VDC converters in the Cabinet

2.4. Analysis and results

We firstly log the data as the standard of each setting and working conditions of two kinds of loads. All these data are used to filter the specific and correct data from the overall dataset (the loading control panels of LEDs and fan coils are showcased in Figs. 8 and 9). This process would eliminate the error of setting and recording errors. The average data would be used as our final data to analyze and compare.

The Tables 2 and 3 below show the filtered average test data results:

We first calculated the distribution efficiency of this system. As the converter supplied most of the system loss, the tables below demonstrated the efficiency before and after the converter.

Table 4. The average converter efficiency of LED lighting (DC).

DC led lighting Setting	Input power (W)	Output power (W)	Efficiency
Full power	116.93	107.82	0.9221
Normal power	44.36	39.41	0.8885

Table 5. The average power factor of LED lighting (AC).

AC led lighting Setting	Apparent power (W)	Active power (W)	Power factor
Full power	158.57	135.28	0.8531
Normal power	72.65	40.85	0.5622

As the data shown above, the distribution efficiencies of DC system after converter are 77.7%, 51.8%, respectively with the LED working under full power and normal power. And the distribution efficiencies after converter are 79.76%, 77.26%, 71.93%, 63.80%, 54.55%, 46.06%, 29.70%, 25.23% respectively under the flow level from 8 to 1 of fan loads. As we can see, the distribution efficiency is impacted by the working load conditions and features.

We also calculated the converter efficiency of this DC system, which deals with the output stage only instead of the whole distribution system and here are the results.

As the data shown above in Tables 4 and 5, the AC/DC converter efficiencies are 92.21% and 88.85% respectively with the load under full power and normal power. The AC power factors are 85.31% and 56.22% respectively with the load working under full power and normal power. The AC/DC converter output power is 107.82 W, which is lower than active power of AC system (135.28 W) with the normal load of LED, saving about 6.9% energy, and with the full power load of LED the efficiency saving would be about 1.7%. Therefore, the DC power is much more efficient than AC power, but the difference in power change is impacted by the loading working conditions. In the full power condition, the DC system saves less than AC system which means the DC system is much more perfect under normal power condition.

Table 6. The average power factor of fan coil (AC).

AC fan speed setting	Input power (W)	Output power (W)	Power factor
Low	28.14	28.69	0.9807
Middle	51.82	52.31	0.9907
High	98.96	99.51	0.9945

The power factors of AC system are 98.07%, 99.07% and 99.45% respectively with the load working under low, middle and high conditions as shown in Table 6. The AC/DC converter efficiencies are 97.41%, 96.03%, 92.74%, 89.10%, 85.71%, 78.72%, 67.61%, 63.57% respectively with the load from level 8 to level 1. The converter efficiency decreases significantly when the fans work under level 1 and level 2. Thus, in order to gain higher efficiency of the converters, low speed of fan coil is not recommended due to energy efficiency.

Therefore, the AC power factor seems to keep stable no matter what load conditions are. In DC system, the converter efficiency is significantly influenced by the fan coil speed.

We also measured the relationship between the speed and the power consumption of AC and DC fans. When having the same speed output wind, the DC coils consume more power than AC coils commonly. This could be caused by the structure of the fans and if possible, AC fans could be much more perfect if we care about the efficiency a lot.

3. Limitations

The power load scale is not large enough and the power distribution scale is small as well. The conversion efficiency on the converter cannot be ignored, and the no-load loss is comparatively large. If the power distribution scale is larger, the efficiency of the high-power rectifier will be higher surely, which would then make up for the base loss in rectifiers and converters. The load form is not diverse, and the load characteristic is both single and limited. We only set LED and DC fans as our load so the result would be more accurate if more kinds of electronic devices are included. As all the products are produced with a parameter tolerance, we may not be able to exclude uncertainties caused by the product manufacturing.

4. Conclusions

To study the DC distribution power system efficiency in commercial buildings, a real running DC and AC circuit systems is built in a typical Hong Kong office. Two sets of load categories are equipped, and different working conditions are set. The simulation models are built with Simulink as the comparing groups.

After analyzing the results, we find that the distribution efficiency could vary because of loading category, voltage level and the loading conditions. It is found that for different types of loads (LED and fan-coil), DC distribution efficiency is higher than the AC ones. For fan-coil loads, the difference in efficiency performance of the mid-high operation speed is due to the motor being used, the nature of the different structure of the DC and AC fan coils plays a key role in this phenomenon. The AC power efficiency is higher than DC power efficiency with the load of fan coils, and the AC power efficiency remains stable no matter what load conditions are. As the PFC circuit does not have ideal power factor correction when the load is small, it is not recommended to add PFC circuit when the load power is low. Using uncontrollable rectifier circuit is going to lead to a better performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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