Research on energy efficiency management method of AC/DC hybrid distribution system

Juan ZHOU¹, Wenjing XIE¹, Yunfeng XIA¹, Feng XUE¹, Junni SU¹

1 Dongguan Power Supply Bureau of Guangdong Power Grid Corporation, Dongguan, China
E-mail: zhou_juanjane@126.com

Abstract. With the increasingly serious problems of fossil energy crisis and environmental pollution, vigorous development of Distributed Renewable Energy has become an important means of energy structure reform and energy consumption transformation. On the distribution side, AC/DC hybrid distribution system has been widely studied for its advantages of accessing multiple types of energy, satisfying diversification energy demand, realizing multi-energy complementation and improving grid security. The energy efficiency evaluation and management of AC/DC hybrid system are of great guiding significance to the planning and design of AC/DC system. However, traditional energy efficiency management mainly reduces primary energy consumption by saving electricity. For AC/DC systems with multiple distributed energy sources, it is difficult to reflect the efficiency level of the whole system by considering a single technology or a single part of energy efficiency management. Aiming at the characteristics of AC/DC hybrid distribution system, this paper studies the energy efficiency management method of the system. Firstly, combined with energy efficiency evaluation and system economic analysis, energy efficiency evaluation index of AC/DC hybrid distribution system are formulated. Secondly, the energy efficiency management method is studied through the study of adjustable load, transferable load and different types of load overall management method. Then the method of combining power quality and energy efficiency is studied. Finally the interaction between source and load is studied to improve the energy efficiency of the system. The energy efficiency management method proposed in this paper can fully tap the potential of load adjustable and energy saving, improve the comprehensive energy utilization efficiency of the system, which provides a basis for the engineering application of AC/DC hybrid power grid.

1. Introduction

In recent years, with the changes of the social environment such as energy security, climate crisis and environmental protection, many countries have implemented the changes of energy structure and energy consumption[1-3]. Energy internet, which is a integrated energy system with multiple energy sources has become the trend of energy development. As an important unit of energy internet, AC/DC distributed system not only contains multiple types of energy input to meet the diversified energy needs, but also promotes the matching of supply and demand within the system and enhances the security of power grid. With the improvement of power market and the widespread application of communication and measurement facilities, load optimization brought by demand-side participation has become an important factor that cannot be ignored in the planning and operation of energy interconnected AC/DC distributed system[4]. Considering the multi-energy coordination and optimization of energy supply and demand, AC/DC distributed system can not only achieve multi-energy complementation, but also give full play to the comprehensive regulation potential of demand.
response and energy storage equipment, promote the absorption of Distributed Renewable energy, and achieve high coupling between supply and demand[5]. The traditional energy management of distribution network usually achieves the goal of energy saving and consumption reduction by means of the transformation of process and equipment[6-8]. This method only pays attention to the energy saving of partial process technology, and lacks the scientific management of the energy efficiency of the whole system. According to the common energy use scenarios of AC/DC hybrid distribution network and the characteristics of multi-energy interaction, this paper proposes a calculable and replicate energy efficiency management method for AC/DC hybrid distribution system[9-12]. It includes the design of indicators for energy efficiency evaluation, system energy efficiency management method and energy efficiency management platform. This scheme can realize the efficient utilization of Distributed Renewable Energy and multiform energy storage, optimize the allocation of resources and improve economic efficiency, and help to alleviate the situation of increasing scarcity of traditional fossil energy, make full use of green energy and realize energy transformation.

2. Architecture design of AC/DC hybrid distribution system

This paper designs an AC/DC hybrid distribution system. As shown in Figure 1, the system includes photovoltaic system, wind power generation, photothermal power generation and thermal utilization system, and storage system. Through multi-port power electronic transformer, the distribution system has formed four voltage levels: 10kV AC and 10kV DC, 380V AC and ±375V DC. The structure has the following advantages:

- It improves the reliability, flexibility and economy of operation and facilitates redundancy expansion through parallel expansion of power electronic transformers.
- On the power side, distributed renewable energy can flexibly select different voltage levels according to the size of capacity, which is conducive to renewable energy.
- On the load side, the generalized DC energy equipment represented by IT load, frequency conversion air conditioning, DC lighting and electric vehicle can be directly connected to the DC power grid, which reduces the loss of the converter link and improves the energy efficiency of the system.

![Figure 1. Architecture of AC/DC Hybrid Distribution System](image)

3. Design of energy efficiency evaluation index
3.1. Energy efficiency evaluation index for each part of AC/DC hybrid distribution system

AC/DC distributed energy system can be divided into three parts: energy supply side, energy transmission channel and energy consumption side. According to the characteristics of these three parts, this paper formulates corresponding energy efficiency evaluation index[13].

3.1.1. Energy supply side

The power supply of AC/DC hybrid distribution network includes photovoltaic, wind, photothermal, storage, heat storage, generator, lithium bromide absorption chiller and other distributed power sources. Its energy efficiency index can be divided into two categories: process energy efficiency index and economic energy efficiency index[14]. The process energy efficiency index includes primary energy utilization rate and energy conversion efficiency, which can be obtained by optimizing energy saving of equipment and reducing multiple AC/DC converter links. Economic energy efficiency index includes initial investment cost, operation and maintenance cost and life expectancy, which can be optimized by means of energy efficiency management.

3.1.2. Energy transmission channel

AC/DC hybrid distribution network system realizes energy transmission and distribution through power electronic transformer and distribution line[15]. The energy efficiency evaluation object of energy transmission channel mainly focuses on the loss index of distribution line and power electronic transformer.

3.1.3. Energy consumption side

The energy efficiency evaluation index of the energy consumption side is embodied in the aspects of power consumption and power quality.

3.2. Comprehensive energy efficiency evaluation index

For a highly coupled system with multiple distributed energy sources and purchased electricity input, convert, consumption and storage, the energy efficiency of a single technology or link alone is not enough to reflect the efficiency level of the whole system, and the whole system needs to be considered as a whole to examine its energy efficiency level.

Considering that the whole AC/DC system, input can be divided into two types: outsourced electricity and distributed primary energy. The outsourced electricity includes fossil energy generation and renewable energy generation[16]. Distributed primary energy is mainly consist of solar energy and wind energy. The output power includes heat energy and cold energy. The comprehensive energy efficiency evaluation index of AC/DC distribution system can be defined as the ratio of total cold, heat and electricity to fossil energy input, the higher the energy efficiency.

The energy conversion path of AC/DC distribution system is shown in Fig. 2. The energy input of the system can be divided into two types: outsourced electricity and distributed primary energy. The outsourced electricity includes fossil energy generation and renewable energy generation. Distributed primary energy is mainly consist of solar energy and wind energy. Many kinds of energy, such as photovoltaic, wind power, photothermal and so on, are transformed into cold, heat and electricity which directly consumed by users through AC-DC hybrid distribution system. In the figure, Characters on the upper and left sides of the energy streamline represent the energy input or power input through the path. Characters on the lower and right sides of the energy streamline represent the efficiency of energy conversion through the path.
Figure 2. Energy Conversion Path Map

Considering such factors as energy storage loss, solar energy utilization and outward supply, the cooling \( D_c' \), heat \( D_h' \) and electricity \( D_e' \) required by the system can be expressed by equation (1) to equation (3)

\[
D_c' = D_c + X_c
\]
\[
D_h' = D_h + H_s(1 - N_{h,s}) + X_h - R_h
\]
\[
D_e' = D_e + E_s(1 - N_{e,s}) + X_e
\]

Where \( D_c, D_h, D_e \) are the system demand of cooling, heat and electricity; \( X_c, X_h, X_e \) are the outward supply energy; \( E_s, H_s \) are the capacity of energy storage; \( N_{h,s}, N_{e,s} \) are the conversion efficiency of energy storage; \( X_h, X_e \) represents direct utilization of heat.

The energy supply and demand balance equation of distributed energy system is shown in equation (4) to (6)

\[
E_i = E - S_e - W_e - R_e
\]
\[
E = E_h + E_c + E_e
\]
\[
E_e = D_e'
\]

Where \( E_i, S_e, W_e, R_e \) are outsourced electricity, photovoltaic energy, wind energy, photothermal energy; \( E, E_h, E_c, E_e \) are the total energy, cooling, heat and electricity required by the system.

The comprehensive energy efficiency of multi-energy complementary distributed energy system is defined as the ratio of total demand for cold, heat and electricity to fossil energy input (converted into equivalent standard coal). Its comprehensive calculation formula is shown in equation (7).

\[
\eta_c = \frac{D_c + D_h + D_e - H_s(1 - N_{h,s}) - E_s(1 - N_{e,s}) - R_h}{E + E_h + E_c - S_e - W_e - R_e \theta_e}
\]

4. Research on energy efficiency management method

From the energy efficiency evaluation index, we can see that the main way to improve the energy efficiency of the supply side is to increase the output of distributed energy, and to ensure that the
network is fully absorbed as far as possible. [18-20] The main way to improve the energy efficiency of the supply side is to improve the energy efficiency of the equipment; the energy loss of the distribution side is mainly determined by the distribution lines and power electronic transformers; therefore, this paper focuses on the energy efficiency management of energy consumption side. The typical application scenarios of distributed distribution network include data center, industrial user and resident user. In this paper, by analysing the load situation in three kinds of power consumption scenarios, the energy efficiency promotion methods on the user side are excavated to form the energy efficiency management strategy.

4.1. Energy efficiency management method for controllable load
From the management point of view, the load on the energy consumption side can be divided into adjustable load, transferable load, uncontrollable load and important load. The first two kinds of terminal adjustable load and transferable load are the key contents of energy efficiency optimization management. The adjustable load power is variable and the working time cannot be moved. The power of the transferable load is fixed and the working time is controllable. Through the analysis of load characteristics of key equipment in AC/DC hybrid distribution system, adjustable load equipment mainly includes lithium bromide refrigeration unit, DC air conditioning, charging pile, LED lamp, elevator, and transferable load mainly includes production line equipment of industrial enterprises.

4.1.1. Lithium bromide refrigeration unit and DC Air conditioning
Air conditioning load accounts for 10% of grid load in summer. Reasonable setting of minimum startup temperature of air conditioning can reduce energy consumption. When the temperature is lower than the limit, the system can automatically shut down; and the start and stop of air conditioning units can be considered by setting appropriate intervals.

4.1.2. Charging pile
Electric vehicle charging is managed according to peak and valley electricity price and SOC status of electric vehicle battery, and charging pile is arranged to charge during load Valley period.

4.1.3. LED lamp
Intelligently adjust the brightness of the lamp and turn it on or off by sensing the intensity of illumination and the daily activity time of the staff.

4.1.4. Elevator
According to the statistics of the elevator's running load, the most frequently used elevator and the period of high frequency use, combined with the staff's working time, the most reasonable use time is planned for different elevators, so as to reduce the energy waste of no-load or less-load elevators.

4.1.5. Production line equipment of industrial enterprises
The production line of industrial enterprises consists of different processes, which have different atmospheric loads. The energy consumption of each process can be analysed by collecting the electricity consumption data of the production and processing products. Under the condition that the production process is unchanged, the high energy consuming process can be adjusted in the valley period. The low energy consuming processes are produced in peak or peacetime periods. By rationally adjusting the production time, time and manpower of each process, we can achieve the purpose of saving production costs by staggering peak power consumption, help users to calculate the cost of electricity consumption, realize economic electricity consumption, and improve the level of energy saving and emission reduction.

4.2. Energy efficiency management in peak load period
There is a kind of high energy consuming enterprise in AC/DC hybrid distribution system, whose power consumption accounts for a large proportion of the total power consumption. When the power
supply of the system is insufficient during peak load period, if the effect of power limitation is obvious, and the overall energy efficiency of the system can be significantly improved. The optimal management strategy of load limitation in peak load period can be divided into two stages: In the first stage, considering the gap allocation scheme of energy efficiency during peak load period, and taking the scale competition mechanism as the basis, the energy efficiency maximization model is constructed to determine the interruptible capacity allocation scheme of each high energy consuming enterprise. The second stage is the real time operation stage, which divides users into uncontrollable high energy users, terminal control loads through smart meters and important loads of continuous power outage. Aiming at maximizing energy efficiency, minimizing switching operation times and minimizing important loads and interruptible outages, an optimization model of load management is constructed to form an optimal power limit sequence. Under the condition of ensuring the safety of power grid, the number of blackouts should be reduced, the power supply of important loads should be guaranteed, and the overall energy efficiency of the system should be improved.

5. Economic Analysis of Energy Efficiency Management

In AC/DC hybrid distribution system, the power sources in the system are renewable energy sources, and the output energy is partly controllable. On the premise of maximizing the output of distributed energy, the optimization of system economy is considered as the purpose of energy efficiency management.

5.1. Distributed power generation

In addition to the demand for load in the system, when the load in the system can not be absorbed, it can also sell electricity to the external network, which can directly obtain economic benefits.

5.2. Heat storage and power storage

Energy storage system can absorb electricity at low price, release electricity at high price, and transfer electricity to create economic value through time domain.

5.3. Adjustable load

Adjustable loads such as lithium bromide absorption refrigerators and charging piles can obtain economic compensation or preferential tariffs by interrupting load, reducing load or transferring peak load, and reduce electricity consumption expenditure.

5.4. Additional economic value of the system

As an important part of the distribution network, the system can participate in the competition of the power market as a whole after integrating resources, including demand-side response, ancillary service market, open spot electricity market and so on, so as to obtain greater economic value.

6. Conclusion

This paper presents an energy efficiency evaluation method and an energy efficiency management method for AC/DC hybrid distribution system. Firstly, an AC-DC hybrid distribution system based on power electronic transformer is introduced, which can meet the demand of power side and user side. Then, the energy efficiency evaluation methods of each part of the AC/DC system and the comprehensive energy efficiency evaluation methods of the system are analyzed. By analyzing the characteristics of energy consumption of different loads, the energy efficiency management of energy consumption side is mainly studied. Finally, from the economic point of view, the interaction between source and load is studied to improve the energy efficiency of the system. The energy efficiency management method proposed in this paper promote the effective interaction between the source network and energy storage, improve the comprehensive energy utilization efficiency of the system,
and provide a solution for energy efficiency management of multi-energy complementary AC/DC distribution system. In the future, energy efficiency management software will be developed according to the energy efficiency management scheme proposed in this paper.

7. References

[1] Loh P C, Li D, Chai Y K, et al. Hybrid AC–DC Microgrids With Energy Storages and Progressive Energy Flow Tuning[J]. IEEE Transactions on Power Electronics, 2013, 28(4): 1533-1543.

[2] Jin C, Loh P C, Wang P, et al. Autonomous operation of hybrid AC-DC microgrids[C]// Sustainable Energy Technologies (ICSET), 2010 IEEE International Conference on. IEEE, 2011.

[3] Guerrero J M, Vasquez J C, Matas J, et al. Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization[J]. IEEE Transactions on Industrial Electronics, 2011, 58(1): 158-172.

[4] Xie Ning, Zeng Jie, Xu Qi, et al. Overview of AC/DC hybrid distributed renewable energy system[J]. Southern Power System Technology, 2017, 11(9): 30-35(in Chinese).

[5] Eneko U, Barrena A J. Hybrid AC/DC microgrids-part I: review and classification of topologies[J]. Renewable and Sustainable Energy Reviews, 2015(52): 1251-1259.

[6] Eneko U, Jon Andoni B. Hybrid AC/DC micro grids-part II: review and classification of control strategies[J]. Renewable and Sustainable Energy Reviews, 2015(52): 1123-1134.

[7] Eghtedarpour N, Farjah E. Power control and management in a hybrid AC/DC microgrid[J]. IEEE Transactions on Smart Grid, 2014, 5(3): 1494-1505.

[8] Nejabatkhah F, Li Y W. Overview of power management strategies of hybrid AC/DC microgrid[J]. IEEE Transactions on Power Electronics, 2015, 30(12): 7072-7089.

[9] Zhao Chuanhong, Weiss M, Mester A, et al. Power electronic transformer (PET) converter: Design of a 1.2MW demonstrator for traction applications[C]. Proceedings of 2012 International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion. Sorrento, Italy: IEEE, 2012: 855-860.

[10] Huang A Q, Crow M L, Heydt G T, et al. The Future Renewable Electric Energy Delivery and Management (FREEDM) system: the energy internet[J]. Proceedings of the IEEE, 2011, 99(1): 133-148.

[11] Li Zixin, Wang Ping, Chu Zunfang, et al. Research on medium- and high-voltage smart distribution grid oriented power electronic transformer[J]. Power System Technology, 2013, 37(9): 2592-2601(in Chinese).

[12] Gao Fanqiang, Li Zixin, Wang Ping, et al. Prototype of smart energy router for distribution DC grid[C]. Proceedings of the 17th European Conference on Power Electronics and Applications. Geneva, Switzerland: IEEE, 2015: 1-9.

[13] Suzuki A, Akagi H. HVDC Circuit Breakers Combining Mechanical Switches and a Multilevel PWM Converter: Verification by Downscaled Models[J]. IEEE Transactions on Power Electronics, 2018, PP(99): 1-1.

[14] MA Zhao. R&D status and prospects of HVDC circuit breakers[J]. Smart Grid. 2013, 1(01): 12-16.

[15] Wen W, Wang Y, Li B, et al. Transient Current Interruption Characteristics of a Novel Mechanical DC Circuit Breaker[J]. IEEE Transactions on Power Electronics, 2018, PP(99): 1-1.

[16] CHEN Zhengyu, YU Zhanqing, LÜ Gang, et al. Researches on 10 kV DC hybrid circuit breaker based on IGCT series[J]. Proceedings of the CSEE, 2016, 36(2): 317-326.
[17] QU Ru, ZHANG Xiangyu, CHEN Zhengyu, et al. IGCT series voltage-sharing technology for DC breaking[J]. High Voltage Engineering, 2018, 44(02): 409-416.

[18] ZHANG Fan, YANG Xu, REN Yu, et al. Voltage balancing circuit for series-connected IGBTs in solid-state breaker[J]. Proceedings of the CSEE, 2016, 36(3): 656-663.

[19] Dong Zhaoyang, Zhao Junhua, Wen Fushuan, et al. From smart grid to energy internet: basic concept and research framework[J]. Automation of Electric Power Systems, 2014, 38(15): 1-11.

[20] Ma Zhao, Zhou Xiaoxin, Shang Yuwei, et al. Exploring the concept, key technologies and development model of energy internet[J]. Power System Technology, 2015, 39(11): 3014-3022.

Acknowledgments
Funding organisation: Supported by National Key Research and Development Program 2017YFB0903205.