RESEARCH ON CONTROL STRATEGY OF HYBRID AC/DC DISTRIBUTED SYSTEM BASED ON MULTIFUNCTION POWER ELECTRONIC TRANSFORMER

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ABSTRACT

This paper mainly focuses on the hybrid AC/DC distributed system with multi-function power electronic transformer (PET) as the core component, and the hierarchical distributed control structure has been proposed according to the analysis about system characteristics. And then the algorithms and control strategies of regional coordination and energy optimization management has been put forward. The reliability and feasibility are verified through simulation eventually.

INTRODUCTION

At present, distributed renewable energy has become an important way to promote energy transformation and has great potential for development in Chinese heavily loaded areas, especially in the southeast coast. Facing the significant demand of distributed renewable energy sources and economical use of DC load, hybrid AC/DC grids have obvious advantages in terms of economy, reliability and flexibility[1]. At the same time, with the development of power electronics and the rise of the concept of "Energy Internet," power flow routing technology, as an emerging control technology, is expected to become an effective solution for future power control[2]. As the trend of routing control of power electronic transformer (PET, also called solid state transformer, SST) or electronic converters, there have been multi-port, multi-directional PET according to meet requirements of enrich voltage levels, followed by the formation of a new AC and DC system topology, and due to the kinds of distributed renewable energy access, it brings great challenges to the hybrid system operation control and energy management[3].

Now, the research of PET mostly focuses on the device topology and its own control technology[4]. However, there are few studies on microgrid and distributed system control technology that contains PET (especially multi-port PET). The [5] proposes a bidirectional droop control method for two PETs, but it only considers a single voltage level. The [6] proposes an autonomous operation control strategy applied to islanding mode, and it only researches on the droop mode operation of multi-port PET, but the hybrid system relevant control strategy about multiple PETs has not been considered.

This paper mainly focuses on the hybrid AC/DC distributed system contained multi-function PET, and the hierarchical distributed control structure has been proposed according to the analysis about system characteristics. And then the algorithms and control strategies of regional coordination and energy optimization management has been put forward. The reliability and feasibility are verified through simulation eventually.

AC/DC DISTRIBUTED SYSTEM[1]

System Introduction

This paper mainly studies on the control strategy of hybrid AC/DC distributed system contained two PETs.

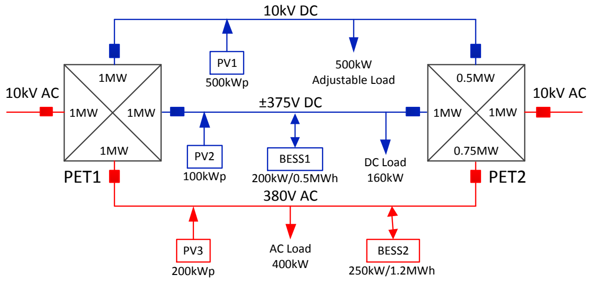

Fig.1 hybrid AC/DC distributed system topology

The Fig.1 is the system topology of hybrid AC/DC distributed system. As it shown, there are two PETs, PV, battery energy storage system (BESS) and loads. The PET have four ports that are 10kV AC, 380V AC, 10kV DC and ±375V DC. The PET1's four ports capacity are same as 1MW, while the PET2's four ports capacity are different that 10kV DC port capacity is 0.5MW and the 380V AC port capacity is 0.75MW.

The PET's 10kV AC ports connect to the distribution network, and the other ports have the PV and load connected. What's more, there are BESSs connected to 380V AC and ±375V DC respectively.

System Operation Modes Analysis

Critical Equipment Operation Modes

The BESS and PETs are the critical equipment in this hybrid AC/DC distributed system.

Table1 PET control modes

No.	PET port	Control mode	Note
1	10kV DC	Constant P	Regulate active power
2		Constant V	Regulate voltage
3		V-I Droop	Voltage & current droop control, droop coefficient
4	±375V DC	Constant P	Same as 10kV DC
5		Constant V	Same as 10kV DC
6		V-I Droop	Same as 10kV DC

1 This work is supported by National Key Research and Development Program of China (No. 2017YFB0903204)

No.	PET port	Control mode	Note
7	380V AC	Constant P&Q	Regulate active & reactive power
8		Constant V&*f*	Regulate voltage & frequency
9		Droop	V-Q and *f*-P droop control droop coefficient
10	10kV AC	Power follow	Regulate power according to three other ports power
11		Power quality adjust	Eliminate the harmonic wave

The PET has flexible control modes, and the detail control modes about each port are shown as above table. If one PET DC port running in constant P mode, and the other PET DC port should running in constant V or V-I droop mode. The constant V and V-I droop mode could form the DC voltage. If one PET AC port running in constant P&Q mode, and the other PET AC port should running in constant V&*f* or droop mode. The constant V&*f* and droop mode could form the AC voltage and frequency. Meanwhile, The BESSs in system have the same control modes as PET.

System Operation Modes

The hybrid AC/DC distributed system could be divided into 10kV DC region, ±375V DC region, 380V AC region and 10kV AC region respectively according to Fig.1. And the regions about 10kV DC, ±375V DC and 380V AC steady control are mainly depend on the PETs. However, the 10kV AC region is formed by distribution network.

The DC region steady control maybe has two methods, one way called master-slave mode is one PET DC port running in constant V mode while another PET DC port running in constant P mode, and another way called peer-peer mode is each PET DC port running in V-I droop mode. What's more, the AC region steady control is similar to DC region.

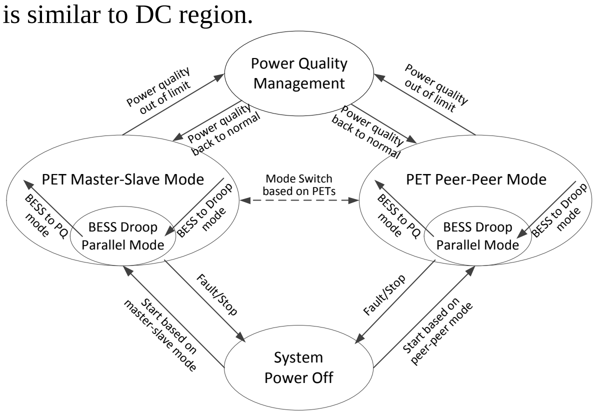

Fig.2 System operation modes switching

Therefore, the hybrid AC/DC distributed system operation modes could be divided into master-slave mode and peer-peer mode based on PETs. Meanwhile, there is a power quality management In addition, the system has the power off mode due to fault and some other reasons. In brief, the hybrid AC/DC distributed system operation modes are as follow:

(1) System power off

This mode means the system power off caused by system fault or stop manually. And then, it could switch to normal operation by system start.

(2) Master-slave mode

This mode means that one PET port running in constant V mode (DC port) and constant V&*f* (AC port) while another PET port running in constant P mode (DC port) and constant P&Q (AC port). What's more, the BESS could operate on constant P (P&Q) and droop mode in master-slave mode.

(3) Peer-peer mode

This mode means that each PET DC port running in V-I droop mode. As well as the AC region steady control is similar to DC region. Therefore, the BESS could operate on constant P (P&Q) and droop mode in peer-peer mode.

The system master-slave mode and peer-peer mode are the normal operation mode. And then, there is mode switching strategy between them.

(4) Power quality management

This mode means that system could improve the PCC (point of common coupling) power quality by PET 10kV AC port power quality management function. On the one hand controller measures the voltage and current, and calculates the harmonic wives. On the other hand the PETs operation mode and output harmonic waves adjusted by controller.

Although the system could operate in master-slave mode and peer-peer mode, the master-slave mode has the defect that the system will be power off when the PET formed grid is fault. However, the peer-peer mode could solve the problem, and the system will continuous operate when one PET is fault.

Hierarchical Distributed Operation Control Structure

The control structure about microgrid and distributed system has been studied in many papers, but the hybrid AC/DC system control structure is researched recently[7]. The hierarchical distributed operation control structure is proposed in this paper according to the system topology, and it is utilized that the hierarchical control structure is based on system operation modes and different regions.

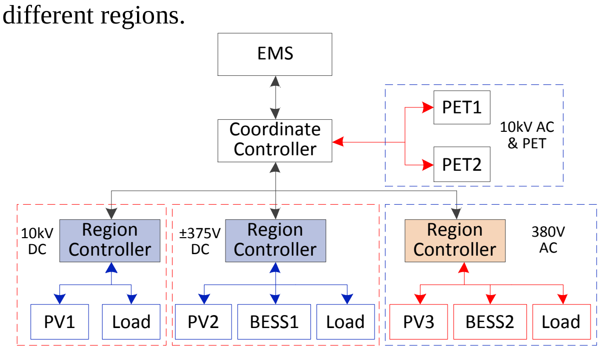

Fig.4 Hierarchical distributed operation control structure

As shown in Fig.4, the control structure is divided into three lays contained region control layer, coordinate control layer and EMS optimization layer. The region control layer is mainly responsible for the steady control in each voltage level region and PETs. As well as the coordinate control layer is mainly responsible for power optimization among different regions. Of course the optimization layer is mainly responsible for the energy management and optimization of the entire hybrid AC/DC system by EMS.

CONTROL STRATEGIES OF REGIONAL COORDINATION

This paper proposes an improved droop control method under peer-to-peer mode in parallel system contained two PETs and even BESS. The conventional droop control strategy selects a droop characteristic curve similar to that of a synchronous generator to control the converter, and the DC system conventional droop is similar to the AC system.
Although the conventional droop control could restrain the parallel circulation, it is hard to deal with allocated power inconsistent and even make power oscillations, especially in transient circumstance under parallel droop modes. Therefore, some studies proposed improved droop control methods[8]. The improved droop control method considered the rate of change and variable droop coefficient is proposed in this paper according to the characteristic of this hybrid system.
The improved AC droop is mainly focus on the frequency ratio and voltage ratio effects in transient circumstance, as well as the droop coefficient is changed by different factors. And then the PET AC port droop control equation can be expressed as follow:

$$\begin{cases} f - f_0 = -k_p(C,P)(P-P_0) + k_{dp}\dfrac{df}{dt} \\ V - V_0 = -k_q(C,Q)(Q-Q_0) + k_{dq}\dfrac{dV}{dt} \end{cases} \quad (1)$$

The k_{dp} and k_{dq} are frequency ratio and voltage ratio coefficient respectively, and they are the constant. The $k_p(C,P)$ is the function about C (capacity) and P (current active power), and the $k_q(C,Q)$ is the function about C (capacity) and Q (current reactive power). And the equation can be expressed as follow:

$$\begin{cases} k_p(C,P) = k_{p0} \times (1 - P_n / \sum P_j) \times C_{AC}^n / \sum C_{AC}^j \\ k_q(C,Q) = k_{q0} \times (1 - Q_n / \sum Q_j) \times C_{AC}^n / \sum C_{AC}^j \end{cases} \quad (2)$$

The k_{p0} and k_{q0} are the AC region droop constant about active power and reactive power respectively. P_n and Q_n are the device n power, and $\sum P_j$ and $\sum Q_j$ are active power sum and reactive power sum of all droop mode devices in the same AC voltage level region such as 380V AC. As well as C_{AC}^n is the device n capacity, and $\sum C_{AC}^j$ is capacity sum in the same AC voltage level region.
Meanwhile, the AC type BESS droop control equation is same as equation (1), but the droop coefficient is different, and equation the can be expressed as follow:

$$\begin{cases} k_{bp}(C,P) = k_{p0} \times K_{SOC} \times (1 - P_n / \sum P_j) \times C_{AC}^n / \sum C_{AC}^j \\ k_{bq}(C,Q) = k_{q0} \times K_{SOC} \times (1 - Q_n / \sum Q_j) \times C_{AC}^n / \sum C_{AC}^j \end{cases} \quad (3)$$

The K_{SOC} is the function about SOC (State of Charge), and the equation is as follow:

$$K_{SOC} = \begin{cases} (SOC - SOC_{\min}) / (SOC_{\max} - SOC_{\min}) & (P_n \geq 0) \\ (SOC_{\max} - SOC) / (SOC_{\max} - SOC_{\min}) & (P_n < 0) \end{cases} \quad (4)$$

The SOC is the BESS current SOC, and the $SOC_{\max}$ and $SOC_{\min}$ are maximum and minimum BESS SOC.
The improved droop control method in DC region is similar to AC region, and then the DC droop control equation can be expressed as follow:

$$V_{dc} - V_{dc0} = -k_i(C,i)(i_{dc} - i_{dc0}) + k_d \frac{dV_{dc}}{dt} \quad (5)$$

The constant k_d is voltage ratio coefficient. The $k_i(C,i)$ is the function about C (capacity) and i (current), and the equation can be expressed as follow:

$$k_i(C,i) = k_{i0} \times (1 - i_n / \sum i_j) \times C_{AC}^n / \sum C_{AC}^j \quad (6)$$

The k_{i0} is the DC region droop constant. The i_n is the device n current, and $\sum i_j$ is current sum of all droop mode devices in the same DC voltage level region such as ±375V DC.
As well as the DC type BESS droop control equation is same as equation (5), but the droop coefficient is different, and equation the can be expressed as (4).

ENERGY OPTIMIZATION MANAGEMENT

In terms of long-term scale, the rolled economic optimization operation strategy is proposed in this paper based on ladder price. Now the PV and load forecasting have been matured. At the same time, the electricity price that hybrid system output is a constant, while the electricity price that hybrid system consumed has been set at a ladder price. Therefore, the interactive economic benefit function is established between hybrid system and distribution network, and the function equation can be expressed as formula (6).

$$\begin{aligned} F = & [\sum P_{pv}(t) + \sum \beta(t) P_{pv\_pre}(t)]\gamma \Delta T \\ & - [\sum (P_L(t) - P_b(t)) + \sum (\delta(t) P_{L\_pre}(t) - P_{b\_pre}(t))]\lambda(t)\Delta T \end{aligned} \quad (6)$$

The ΔT is time interval; $P_{pv}(t)$ and $P_{pv\_pre}(t)$ indicates that PV average output power and forecasted power respectively. The $\beta(t)$ represents the prediction accuracy function about $P_{pv\_pre}(t)$, and it could be set 1 for simplified calculation. As well as $\delta(t)$ is similar to $\beta(t)$. γ is PV electricity price. $P_L(t)$ and $P_{L\_pre}(t)$

indicates that the load average power and forecasted power. $\lambda(t)$ is the function about electricity ladder price that system consumed. $P_b(t)$ and $P_{b\_pre}(t)$ indicates that the BESS average power and forecasted power respectively.

If the economic benefits would be maximized according to formula (6), and the target function is $\max(F)$. However, there are charging and discharging power constraint condition for BESS in the full-day. Therefore, the interactive target function between hybrid system and distribution network can be expressed as follows:

$$\begin{cases} \max(F) \\ \sum P_b(t) + \sum P_{b\_pre}(t) = 0 \end{cases} \tag{7}$$

The $P_{b\_pre}(t)$ result would be obtained by PSO (particle swarm optimization) according to equation (7), and then the control command is performed according to the $P_{b\_pre}(t)$ sequence. What's more, the next optimization calculation should be carried out after a calculation and optimization control, so as to realize the rolled economic optimization control based on the ladder price.

SYSTEM SIMULATION

The simulation of hybrid AC/DC system is built according to the Fig.1, and the control strategies are verified.

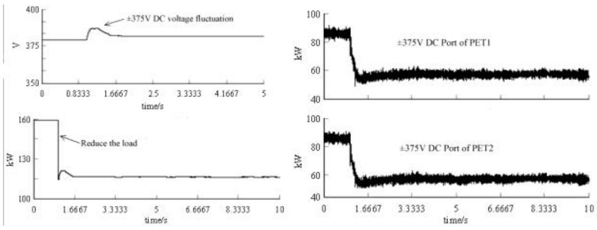

Fig.5 DC region parallel operation curves

As shown in Fig.5, it is the ±375V DC region parallel operation curves by improved droop strategy proposed in this paper. There is a minor fluctuation when the load reduced, and the two DC port are consistent in changed power.

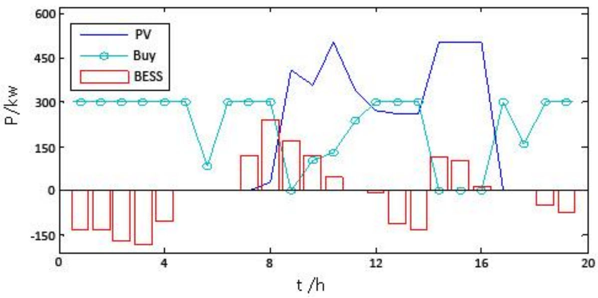

Fig.6 Rolled economic optimization curves

As shown in Fig.6, it is the simulated result about system rolled economic optimization. It can be concluded that the battery is charged at a low electricity price and discharged at a high electricity price in order to reduce the cost of the entire system and improve system economic efficiency. What's more, the system would buy electricity when the grid electricity price is low, and the system would consume its own electricity firstly when the grid electricity price is high.

CONCLUSION

This paper mainly focuses on the hybrid AC/DC distributed system contained multi-function PET, and system operation modes have been analyzed. And then the hierarchical distributed control structure has been proposed. What's more, The improved droop control method considered the rate of change and variable droop coefficient is proposed according to requirement of region control layer, and the rolled economic optimization operation strategy is proposed according to requirement of EMS optimization layer. Finally, the reliability and feasibility are verified through simulation eventually.

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