Research on Coordinated Control of PV-Storage Microgrid and Distribution Network

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Abstract—In order to solve the problems brought by the PV-storage microgrid embedded to distribution network, this paper proposes a hierarchical coordinated control scheme to alleviate negative effect. First, the characteristic of distribution network with microgrid is analyzed, the model of PV-storage microgrid is built and the interactive optimization objective function of microgrid and distribution network is proposed. Second, interactive model between microgrid and distribution network is established and coordinated control strategies are proposed and digitally simulated. Finally, the proposed scheme is implemented in a real-world PV-storage system and tested physically. The test results validate the proposed scheme and show the excellent performance in feasibility and reliability.

Keywords-Hierarchical coordinated control; microgrid; distribution network; PV-storage; Scheduling optimization

I. INTRODUCTION

The rapid development of new clean energy and energy related technologies makes the microgrid technology widely promoted and applied. As a new type of electric power access technology, through the construction of distributed generation system, microgrid provides an effective technical means for comprehensive utilization of solar, wind and other renewable and environment-friendly energy and the battery storage system [1]. In last decades, many domestic and foreign scholars have carried on research in this area, and a variety of microgrid laboratories and projects have been approved and constructed in China, Europe, United States, Japan and other countries around the world [2-3].

Along with the new distributed energy resources (DER) connected to distribution network and the development of smart grid, the original characteristics of the distribution network have been changed. The original dispatch management mechanism and the operation automation level of distribution network seriously restricted the distributed generation access and optimal operation of microgrid. In view of this situation, the active distribution network (ADN) technology came into being, and become an important development mode of the future smart distribution grid [4-6]. Active distribution network is designed to solve the issues of grid compatibility and application of the large scale intermittent renewable energy, enhances the utilization rate of green clean energy, and optimizes energy structure [7-8]. Microgrid connected to network, as a form of active distribution network, will have an impact on the steady distribution of power flow and transient fault characteristics for distribution network, and bring new problems in planning and design, dispatch and operation, protection and control, and emergency control scheme for distribution network [9].

This paper researches on the interactive coordinated control of microgrid with access to distribution network, and verifies the proposed scheme through digital simulations and field tests. The rest of the paper is organized as follows. In section II, a general hierarchical coordinated control architecture is proposed; and a model of PV-storage microgrid and its optimal operation scheme is put forward in section III. In section IV, the issues of stability is analyzed and the strategies of frequency control is explained in detail. In section V, the digital simulations and field experiments are conducted to validate the correctness and effectiveness of the proposed scheme, and concluded our paper in section VI.

II. HIERARCHICAL DISTRIBUTED COORDINATED CONTROL

A. Background

Recently, many literatures talk about distributed energy resource (DER) connected to distribution network, and mainly focus on sitting and sizing of DER, programming algorithm of power source configuration, and coordination of protection and control [10-12]. But the study of coordinated control between DER and distribution network is less, and the coordinated control of microgrid connected to distribution network is more limited. In traditional dispatch mode, power sources in public grid are actively controllable, and the operators dispatch the power sources to satisfy the load demand directly. However, due to the access of DER or microgrid, power flow in public gird changes tremendously, so the interactive coordination control is an inevitable choice after microgrid connected to distribution network. For the configuration of distribution network with microgrid connection described in section II, a hierarchical distributed coordination control scheme is put forward and well illustrated in this paper.

B. General Interactive Control Architecture

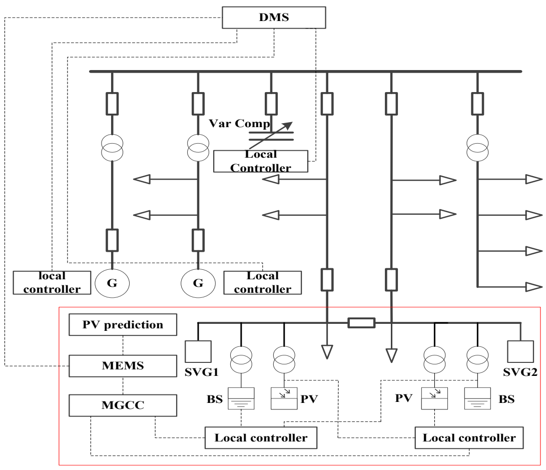

Figure 1. Diagrammatic sketch of hierarchical distributed control structure of microgrid and distribution network

A three-layer distributed coordinated control scheme is proposed in this paper, and Fig .1 shows the general diagrammatic sketch. The bottom layer is local control layer, which consists of different kinds of distributed generation (DG) controllers and is responsible for control and management of one or one kind of distributed resources, such as small hydropower, PV, battery storage (BS), diesel generators, etc. The middle layer is regional management layer, which mainly consists of power prediction system, microgrid energy management system (MEMS) and microgrid central controller (MGCC), and is responsible for management of a region in distribution network containing several local controllers. The top layer is distribution management system (DMS) layer, which implements the coordination and optimal management of the whole distribution network.

As depicted in Fig .1, PVs, BSs, Var compensators and other DGs are controlled by local controllers respectively. The devices shown in bottom red frame form a microgrid, and equipped with PV power forecast system, MGCC and MEMS. MEMS can send optimal control command to MGCC according to the output of power prediction system, send running information of the microgrid to DMS, and receives dispatch command from DMS. DMS realizes the inter-regional optimal scheduling through load forecast, optimal power flow analysis etc. The proposed scheme can greatly reduce the burden of distribution management, improve the flexibility of distributed power connected to distribution networks, realize the plug and play function, and improve the stability and the reliability of distribution network.

III. MODELS OF INTERACTIVE COORDINATED CONTROL

A. PV-Storage of Microgrid Model Based on Bata Distribution

Interactive scheduling refers to the measurement and control system based on the smart grid, with grid scheduling, coordinate the generation and demand side scheduling resources realized power interactive distributed wide area, in order to obtain the optimal economic and environmental benefits [13,14]. As well as the coordinated scheduling microgrid connected to distribution network, the paper [15] focuses on the complementary of different area of microgrid DER (Distribute Energy Resource) output. In this paper the study of interactive system proposed optimization coordination model based on Beta distribution.

The power of PV-storage microgrid is closely related with the solar irradiance of solar irradiance during daytime. Solar irradiance is a random variable according to statistics over a period of time, and it has obeyed the Beta distribution [16,17], therefore the power of photovoltaic power in the microgrid could be considered as the Beta distribution. Microgrid energy storage is used to charging during daytime, so the PV-storage microgrid total generate power has also obeyed Beta distribution, and the probability density is written as:

$$f(P_t^{DG}) = \frac{1}{B(a_1,b_1)}\left(\frac{P_t^{DG}}{P_{\max}^{DG}}\right)^{a_1-1}\left(1-\frac{P_t^{DG}}{P_{\max}^{DG}}\right)^{b_1-1} \quad (1)$$

where P_t^{DG} is the total generate power of microgrid at t moment; $P_{\max}^{DG}$ is the maximum generation power of microgrid; $B(a_1,b_1)$ is Beta function.

Microgrid load that is uncertainty can be used to normal distribution [18]. The generate power of PV-storage microgrid can be divided into two modes(day and night), and the energy storage is only satisfied with the microgrid load demand in night, so microgrid power in night is also obeyed the normal distribution, the probability density is written as:

$$f(P_t^{DG}) = \frac{1}{\sqrt{2\pi}\sigma_{DG}} \exp(-\frac{(P_t^{DG} - \mu_{DG})^2}{2\sigma_{DG}^2}) \tag{2}$$

where μ_{DG} and σ_{DG} is the expected value and standard deviation of microgrid power respectively.

PV-storage microgrid load is different during day and night, but it is stable, and it can be approximated as two values, so the PV-storage microgrid output power probability density is quite similar to its total power probability density, so the probability density of PV-storage microgrid can be described as:

$$f(P_t^{MG}) = \begin{cases} \frac{1}{B(a,b)} (\frac{P_t^{MG}}{P_{\max}^{MG}})^{a-1} (1 - \frac{P_t^{MG}}{P_{\max}^{MG}})^{b-1}, (t \in [T_s, T_e]) \\ \frac{1}{\sqrt{2\pi}\sigma_{MG}} \exp(-\frac{(P_t^{MG} - \mu_{MG})^2}{2\sigma_{MG}^2}), (t \in [T_e, T_s^{'}]) \end{cases} \tag{3}$$

where P_t^{MG} is the output power of microgrid at t moment; $P_{\max}^{MG}$ is the maximum output power of microgrid; $B(a,b)$ is Beta function; μ_{MG} , σ_{MG} is the expected value and standard deviation of output power respectively; $[T_s, T_e]$ is day time and $[T_e, T_s^{'}]$ is night.

B. *Interactive Coordination Scheduling Optimization*

Coordinated scheduling between PV-storage microgrid and distribution network based on price of microgrid, not considering the output power uncertainties factors of DER in microgrid, realizes the optimization of micro based on the whole distribution network. The goal of interaction coordinated operation is maximum ratio (referred to as profit rate) between the difference and the distribution network load (without and with load within the microgrid). the difference is that the profit of power sale profit deduct purchasing cost and operate cost. the goal function is written as:

$$\max \Omega = (\lambda_t P_t^{MG} + \alpha P_t^{DN} - \gamma R_t^{DN}) / P_t^L \tag{4}$$

where P_t^{MG} is the output power of microgrid at t moment; P_t^{DN} is the demand power of distribution network at t moment; R_t^{DN} is the reserved power; α and γ is the price coefficient; λ_t is the difference price between sale and purchase of microgrid at t moment. If $\lambda_t = \lambda_1$, then $P_t^{MG} > 0$, and microgrid can be considered as generator; If $\lambda_t = \lambda_2$, then $P_t^{MG} < 0$, and microgrid can be considered as generator. What's more, λ_1 and λ_2 demand the equation $\lambda_2 = (2 : 3)\lambda_1$ in this paper. P_t^L is the distribution network load without PV-storage microgrid at t moment.

The constraint conditions of interaction coordination function mainly have power balance constraint, microgrid power constraint, reserved capacity constraint and energy storage power constraint. The power balance constraint condition with distribution network line loss ignored is written as:

$$P_t^{MG} + P_t^{DN} = P_t^L \tag{5}$$

The microgrid power constraint is written as:

$$P_{t\min}^{MG} \le P_t^{MG} \le P_{t\max}^{MG} \tag{6}$$

where $P_{t\max}^{MG}$ is the maximum power output of microgrid at t moment; $P_{t\min}^{MG}$ is the minimum output power of microgrid at t moment. $P_{t\min}^{MG}$ has been met with $P_{t\min}^{MG} = -(P_t^{ML} + P_t^{BAT})$, where P_t^{ML} is microgrid load. P_t^{BAT} is the energy storage charging and discharging power, that negative stands for discharge, and positive stands for charge. What's more, energy storage constraint is written as:

$$SOC_{\min} \le SOC_t^i \le SOC_{\max} \tag{7}$$

where SOC_t^i is the SOC (State of Charge) of battery *i*; $SOC_{\max}$ and $SOC_{\min}$ represent the energy storage battery upper limit and lower limit respectively.

IV. STABILITY ANALYSIS AND FREQUENCY CONTROL

The operation reliability and key quality index of new distribution network that contains microgrid have been studied deeply in domestic and foreign literatures. The impact of microgrid power type, capacity and other factors on the distribution network reliability have been analysis by Monte Carlo simulation [19]. Reference [20] conducted research on the voltage effects of microgrid connected to distribution network. This paper will study on the stability and reliability after the high permeability PV-storage microgrid connected to distribution network.

In this paper, it is assuming that the frequency fluctuation of distribution network is big (between 47Hz ~ 52Hz), the response speed of photovoltaic inverter is slow, and the response speed of energy storage is very fast. This assumption is often the real case. Therefore, the energy storage could be utilized to control frequency. In actual operation, the lifetime of energy storage is affected greatly by charge and discharge times, so it is not suitable for real-time frequency control, so it can be used to realize the emergency difference frequency control, and it should exit after frequency recovery.

The microgrid energy storage emergency frequency control in distribution network should meet with the rapid and real-time demand, but it should exit slowly after frequency recovery to reduce unnecessary impact. Therefore the PID control algorithm with inertia link is adopted.

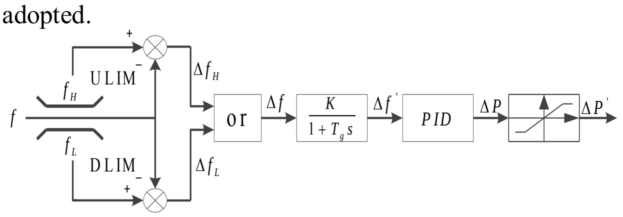

Figure 2. Microgrid emergency frequency control structure

The high and low frequency limit (f_H, f_L) in emergency frequency control has been set. When frequency is out of the range $[f_L, f_H]$, Δf can be calculated by high or low frequency minus current detected frequency. Then $\Delta f^{'}$ is obtained via inertia link, and the amount of energy storage power change is calculated through PID algorithm. Finally, the amount of output power change $\Delta P'$ calculated by limiter, plus current energy storage power to calculate energy storage total power reference.

According to the emergency frequency control structure, discrete inertia link is the formula about Δf and $\Delta f'$.

$$\Delta f_k' = \frac{T_s}{T_g}(K\Delta f_k - \Delta f_{k-1}') + \Delta f_{k-1}' \quad (9)$$

where T_s is sample time; T_g is inertia time constant; K is inertia proportion coefficient; Δf_k is frequency deviation at moment k; $\Delta f_k'$ is inertial frequency deviation at moment k; $\Delta f_{k-1}'$ is inertial frequency deviation at moment k-1.

The PID control algorithm can be divided into position type PID (also known as absolute PID) and incremental PID, however microgrid energy storage frequency control output is incremental power. Therefore it is suitable to use incremental PID algorithm. Its formula is written as:

$$\Delta P_k' = K_p \Delta f_k' + K_i \Delta f_{k-1}' + K_d \Delta f_{k-2}' \quad (10)$$

The following formulas are the specific calculation formula of three parameters in PID.

$$K_p = K_c(1 + \frac{T_s}{T_i} + \frac{T_d}{T_s})$$
$$K_i = -K_c(1 + \frac{2T_d}{T_s}) \quad (11)$$
$$K_d = K_c \frac{T_d}{T_s}$$

where K_c is proportional coefficient; T_i is integration time constant; T_d is differentiating time constant.

V. EXPERIMENT RESULTS AND ANALYSIS

A. *Configuration of Experiment System*

The configuration of the PV-storage microgrid experiment system is shown in Fig .3.

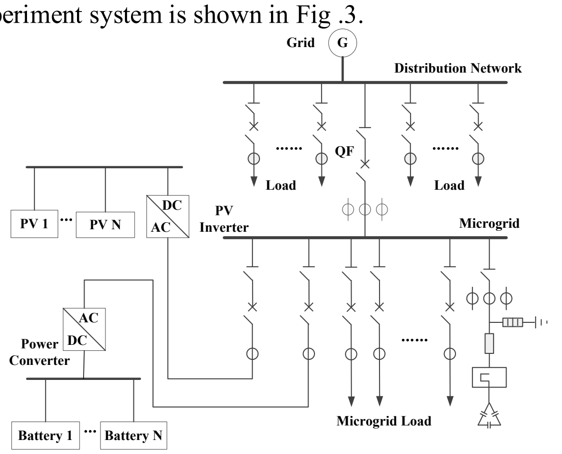

Figure 3. Illustration of the PV-storage microgrid experiment system

B. *Simulation and Analysis of Interactive Coordination*

According to the proposed interactive coordination scheduling model, RTDS (Real Time Digital Simulation) simulation test and the data analysis have been carried out based on distribution network load. During the simulation, the parameter values were set according to the microgrid and distribution network system shown in Fig .3, and specified values are λ_t=0.75, α=0.5, γ=0.1.

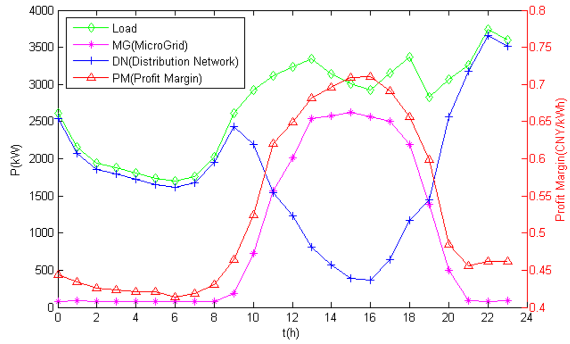

Figure 4. Simulated curve of generation and profit rate

Results have been obtained as shown in Fig .4 through the simulation and analysis. of the output and economic benefit of the simulation curve. It not only can obviously improve economic profit rate, but also reduce supply plenty of spare capacity from Fig .4.

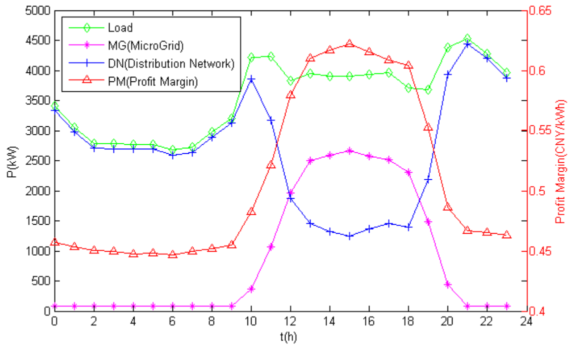

Figure 5. Experimental curve of generation and profit rate

In addition, in order to verify the feasibility of interactive coordination between microgrid and distribution network, experiment has been carried out. By experiment as shown in Fig .5, the economic benefit of distribution network is improved, especially when microgrid supplied power to distribution network.

C. *Analysis of Emergency Frequency Experiment*

According to the proposed microgrid emergency frequency control strategy, it has taken experiment to verify the feasibility and stability of strategy. Considering the frequency fluctuation range, energy storage charge and discharge times, and so on, high and low frequency limit were set to 51Hz and 49Hz respectively. The fault recorder has been used to storing related data, and the energy storage emergency frequency action curve is obtained in Fig .6 by data analysis.

Fig .6 shows the energy storage power is A phase active power, and the negative value is stand for battery discharging. It can be seen from Fig .7 that appears low-frequency limit, and the lowest frequency was 48.581Hz. Meanwhile, the storage of A phase active power change is 95kW, the whole process of emergency frequency control has taken about 1.5s, and then the system frequency rapid return to normal. Therefore, according to experiment, it can be comprehensive to see that emergency frequency control strategy has played a positive role to the frequency stability of distribution network.

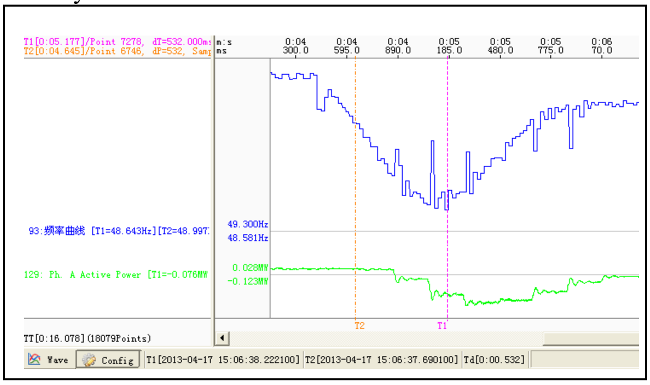

Figure 6. Experimental curve of emergency microgrid frequency control

VI. CONCLUSIONS

This paper analyzes the PV-storage microgrid with access to distribution network, establishes microgrid model according to the characteristics of PV-storage microgrid, and puts forward an economic optimization model of interactive coordination between microgrid and distribution network. In addition, through the RTDS simulation test and field experiment, the feasibility and stability of the control strategy is proved, it provides reference of coordinate control of the microgrid access to distribution network, and plays an active role in promoting the research of coordinated control of DGs in active distribution network.

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