A Energy Balancing Control Strategy for Microgrid with Storage Systems

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Abstract— **In a microgrid, there is usually an energy storage system, while there is no continuous energy supply. The storage system does not only be used as a power supply in islanded state, but also could be taken as the demand side management devices in grid-connected state. In this paper, a system energy managing strategy is proposed. It can balance the energy in autonomous state, and manage power in grid-connected state under time-of-use pricing. Next, the droop control and economic dispatch method are introduced into the power management strategies to improve the power supply reliability and perform peak load shaving for maximum benefits. Finally, a simulation is shown to analyze the benefit from the strategies. And the applications of the economic dispatch method are discussed in the results under different operating conditions and market policies.**

Keywords-microgrid; storage system; energy balancing.

I. INTRODUCTION

For electric loads that are described as the unpredictable fluctuation with obvious difference between peak and off-peak load, power system planners must consider the maximum load in the plan of the electric systems expansion. In order to utilize the existing equipment sufficiently and reduce the distribution equipments investment, electric administrative department usually take measures of 'peak load shaving' (also called time-of-use pricing (TOU), load control and management, etc.) to solve this problem. Now, it is available to store electrical energy on a large scale with the development of energy storage devices and control methods.

Microgrid are the distribution networks comprising various distributed generators (DGs) and storage devices that can operate either interconnected or isolated from the main distribution grid, as in [1]. The microgrid voltage could cover the whole distribution networks, but only the low-voltage is considered in this paper. Storage devices in microgrid can be controlled flexibly to minimize microgrid operation. Some power management strategies are presented, as in [2, 3], for optimal economic operation of the microgrid, including making power and planning, according to the prediction for PV power production and the load forecasting. It could reduce the costs of microgrid and optimise battery charge states. Sortomme and El-Sharkawi [4] used particle swarm optimisation to achieve optimal dispatch of controllable loads and generators as well as effectively utilizing the battery storage of each microgrid. Kim et al. [5] proposed a cooperative control strategy of energy storage system and micro sources for stabilizing the microgrid in islanded operation mode [6-8], consisting of the centralized controller and local controllers interconnected with communication bus [9-11]. Now the storage system has been used to microgrid control, but has not yet been used to energy balancing control.

A detailed analysis of the generic control scheme for energy storage system (ESS) is presented. Based on the analysis, this paper proposes a coordinated control strategy, using a ω-P/V-Q and P-ω/Q-V droop control method, to avoid the real and reactive power coupling problem cased by the high R/X line impedance ratio [12-14]. An economic dispatch method for energy storage systems, under time-of-use pricing, is presented to maximise benefits, and the spare economic benefits of ESS is considered.

In the paper, the control strategies of the ESS in both grid-connected and island mode is proposed. And then, the ESS dispatch method based the control strategies is discussed. At last, the dispatch method is tested in the case study.

II. CONTROL STRATEGIES OF THE ESS

A. The ESS in a microgrid system

ESS plays a vital role in the reliable operation of a microgrid. Figure 1 shows a single-line diagram of a typical distributed ESS in a microgrid. The centralized control system of the ESS comprises local micro source controllers (MCs) and central controller. The MC uses local information to control the voltage and the frequency of the ESS in transient operation.

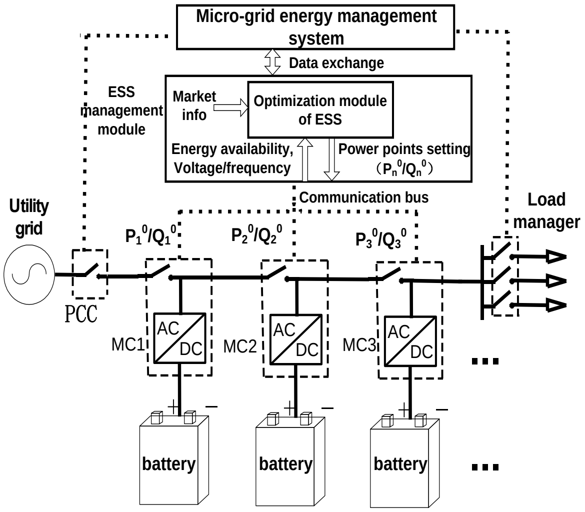

Figure 1. Typical ESS structure in a microgrid

The MC also follows the demands from the central controller to optimize the operation. The decentralized control method for the parallel operation of inverters working in island mode is the frequency and voltage droop method, and the power management strategies are based on local measured signals without communications assistance. The ESS management module is responsible for the dispatch of the ESS and the maximization of the ESS's value. The dispatch method is related to the structure and operation modes of the microgrid, and has an effect on the microgrid stability. The proposed hierarchical control system of ESS is shown in Figure 1. The battery storage inverter with island detection function changes the control scheme based on the microgrid mode of operation, i.e. islanded or grid-connected, and the ESS management module sends dispatch commands to the local controllers according to the amount of available energy, electricity price and system electric parameters.

B. *Control methods of the ESS in grid-connected mode*

In the grid-connected mode, the utility grid is expected to supply the difference in real/reactive power. Similar to a conventional utility system, each DG unit can be controlled to generate pre-specified real and reactive power components (PQ-bus) or generate pre-specified real power and regulate its terminal voltage (PV-bus). Optimization power management of the ESS can help to minimize the tie line power (peak shaving), and maximize the ESS's value under TOU price.

Figure 2 shows a block representation of a generic control system of the ESS inverter in grid-connected mode. A signal processing block and a phase locked loop (PLL) block are used to process the measured currents and voltages of the ac-bus and to estimate the local frequency. The frequency estimation is used to synchronization and to track relative angle of the inverter reference frame. Controls of the real/reactive power are implemented in a dq0 reference frame that determines d- and q-axis components of the ac-side currents. The power set-point is determined by the ESS power management module.

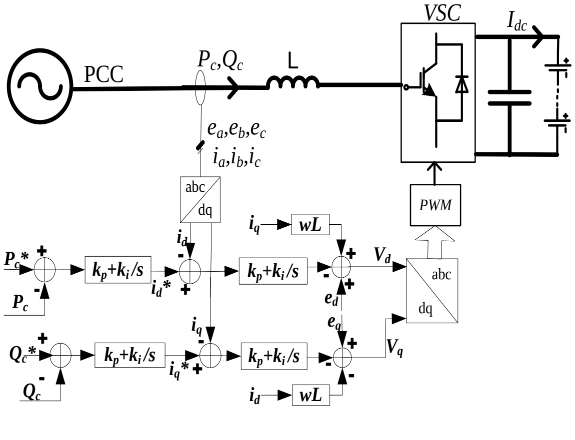

Figure 2. P-Q control scheme for the ESS

The dispatch method of ESS power management module in grid-connected mode is based on electricity price, to achieve economic benefit maximization of ESS and load peak shaving. A ω-P/U-Q droop method of ESS control is shown in Figure 3.

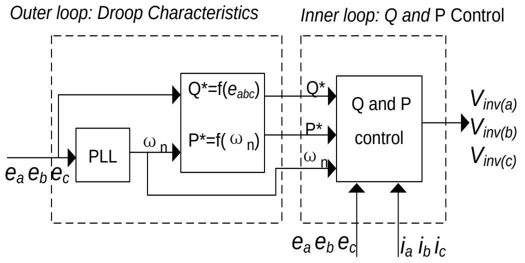

Figure 3. ω-P / V-Q droop controller for ESS in grid-connected mode

The method in Figure 3 improves the microgrid stability. The outer loop determines the set points for P*and Q*, according to the frequency measured by PLL and voltages of ac-side. The droop characteristics can be mathematically represented as

$$\begin{aligned} P_n &= -1/K_{wn}(w_n - w_0) + P_n^0 \\ Q_n &= -1/K_{Vn}(U_n - U_0) + Q_n^0 \end{aligned} \qquad (1)$$

where K_{wn} and K_{Vn} are the droop characteristic slope for the *nth* battery unit, ω_0 and U_0 are the reference frequency and reference voltage of the microgrid, respectively, and the P_n^0 and Q_n^0 represent the initial real/reactive power generation assigned to the unit, respectively. The inner loop utilizes independent real/reactive power control method to ensure the output power to be the pre-specified *P** and *Q**. The control method is similar to the one used in conventional power systems for the correct load sharing among generators feeding to ac system, and can help to support the frequency and voltage of the microgrid.

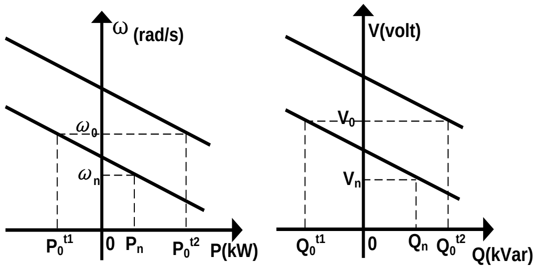

Figure 4. Frequency and voltage droop control characteristics

This droop method of ESS can also be applied in islanded microgrid with a slack bus to minimize the dynamics and system oscillations. The frequency and voltage droop control characteristics are shown in Figure 4.

C. *Control method of the ESS in islanded mode*

In grid-connetcted mode, the ESS power management discussed in this paper can be applicable to other controllable sources as well, and the unstable sources are controlled based on optimal power generation schemes to deliver maximum available power. Whereas in islanded mode, the microgrid central controller is responsible to the regulation of the charge and discharge power of ESS, output power of DG units, and load shedding, to match generation and load demand. The objective of the ESS control system is to maintain the system frequency and the voltage magnitude, rather than load peak shaving.

The power control system of ESS encompasses real power generation control and the reactive power control block. The *P-f* and *Q-V* droop characteristic is introduced as the primary control to share load and regulate the voltage without communication among the fast acting inverters. This cooperative control method of ESS and micro sources is chosen because none of the inverters can dominantly support the frequency and voltage of the system in islanded microgrid. Base on mainly inductive line impedance between the inverters, the frequency control is coupled with the real power flow control, and the inverter voltage is controllable through Q.

Figure 5 shows a block representation of a generic control system of the ESS inverter in islanded microgrid. The control structure of parallel voltage sources converter adopted droop method encompasses two control loops, as shown in Figure 6. The outer loop determines the reference ω^* and E^*, and expressed as in (2).

$$\begin{aligned} w_n &= -K_{wn}(P_n - P_n^0) + w_0 \\ E_n &= -K_{Vn}(Q_n - Q_n^0) + E_0 \end{aligned} \qquad （2）$$

where K_{wn} and K_{Vn} are the droop characteristic slope for the *n*th battery unit, ω_0 and U_0 are the reference frequency and reference voltage of the microgrid, respectively, and the P_n^0 and Q_n^0 represent the initial real/reactive power generation assigned to the unit, respectively. The inner loop controls the ac-bus frequency and the voltage of converter according to ω^* and E^*. In islanded microgrid, the output real/reactive power of ESS inverters is vary depending on the ω_n and E_n, not pre-specified, and the cardinal control objective is reliability of power supply, rather than the economic dispatch of ESS.

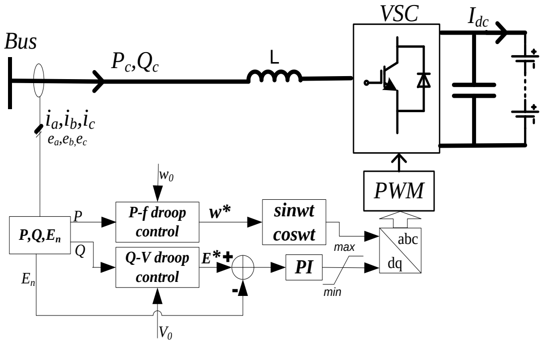

Figure 5. V-f control scheme for the ESS

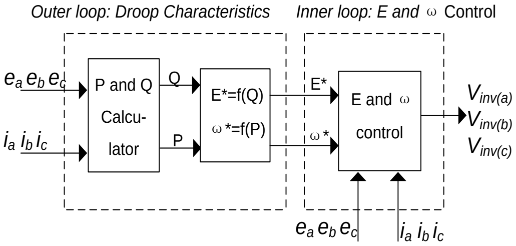

Figure 6. P-ω/ Q-V droop controller for ESS in islanded mode

However, when the traditional droop method is implemented in a low voltage microgrid, the different inverter output impedances and the high R/X line impedance ratio lead to severe real and reactive power control coupling and system stability concerns. So the droop method should be improved. This paper presents the combination control strategy of ω-P/V-Q droop and P-ω/Q-V droop method to solve the real/reactive power coupling problem and improve the stability performance. In the distributed storage system structure shown in Figure 1, the MC1 adopts P-ω/Q-V droop control method after the transition from grid-connected mode to islanded mode, while the other MCs adopts ω-P/V-Q droop control regardless of the microgrid mode of operation. This combination control strategy uses the system frequency and voltage as a communication means without causing real/reactive power coupling problem in islanded operation.

III. ECONOMIC DISPATCH OF THE ESS

The objective of the microgrid energy management module is to generate suitable set-points for the storages and micro sources in such a way that economically optimised power dispatch will balance the certain load demand. The output of the ESS management module defines the direction and amount of the power flow between storages, especially in grid-connected mode, to realize the maximum economic benefits of the ESS. The economics of the ESS in islanded microgrid are particular complex, because it related to other controllable sources and loads. But in grid-connected mode, the ESS can be dispatched according to the TOU price. Thus, the energy stored in the ESS is used as the state variable. Time stages are calculated with unit 1h, and most stage more than 1hour. Energy stored in the batteries is expressed as follows.

$$Q_{n,t+1} = \begin{cases} Q_{n,t} + A_n * P_{n,t} * \Delta T & (\text{ if the ESS is charging }) \\ Q_{n,t} - A_n * P_{n,t} * \Delta T & (\text{ if the ESS is discharging }) \\ Q_{n,t} & (\text{ if the ESS is idle }) \end{cases} \qquad （3）$$

$$A_n = \begin{cases} 1/\eta_C \\ 0 \\ \eta_D \end{cases}$$

where $Q_{n,t}$ is the energy stored in the *n*th storage units at hour *t*, $P_{n,t}$ is the real power of the *n*th storage units output at hour *t*, A_n is the nth storage units charging/discharging efficiency(η_C:charging factor, η_D:discharging factor).

The ESS sells stored energy at high price and shaves the peak loads of the large system, and stores it when the electricity is abundant and cheap. The objective function for each hour intervals and the physical constraint are expressed as in (4), and it aimed at maximizing the generation benefit.

$$MaxF(P_{n,t}) = \sum_{t=1}^{T} \sum_{n=1}^{N} {*c_t} * P_{n,t} * \Delta T$$

$$s.t. \begin{cases} Q_{\min} \le Q_{n,t} \le Q_{\max} \\ P_{\min} \le P_{n,t} \le P_{\max} \\ V_{\min} \le V_{n,t} \le V_{\max} \\ f_{\min} \le f_{n,t} \le f_{\max} \end{cases} \qquad (4)$$

Where c_t is the electricity price at time t, $\triangle T$ is the time stage, T is total number of hours, and N is total number of storages. The constraints in optimization module includes unit capacity, rated power, and the variation of the V and f of the system, because of the applied of droop control.

The ESS increases the reliability of power supply by supporting certain loads demand in microgrid, when the utility electric grid is unavailable. Thus, the benefits of the emergency reserve of the ESS should be calculated. The benefits encompass the spinning reserve capacity $C_{rsc,n}$ and the reserve electricity $C_{rsp,n}$. The spinning reserve capacity benefit is related to both the remaining capacity of the battery and the rated power of the ESS inverters. And it can be expressed as in (5).

$$C_{rsc,n} = Q_{rsoc} * P_{rp} * \rho_{rp,n} \tag{5}$$

P_{rp} is the rated power of the ESs inverter, $\rho_{rp,n}$ is the price of the spinning reserve capacity. Consumers that chose the reserve services should pay the reserve capacity fee according to the load no matter grid failures occur or not. When the grid failures occurs, the consumers should pay the reserve electricity benefit as

$$C_{rsp,n} = \rho_{rsp,n} * Q_{rsoc} * \eta_D \tag{6}$$

Thus, the total reserve benefits of the ESS is expressed as

$$C_{r,n} = C_{rsc,n} + P_{rh}\% * C_{rsp,n} \tag{7}$$

Where $\rho_{rsp,n}$ is the price of the reserve electricity, $P_{rh}\%$ is the probability of the grid failure happens. The objective function of the ESS dispatch module taking account of the reserve benefits is expressed as

$$MaxF(P_{n,t}) = \sum_{t=1}^{T}\sum_{n=1}^{N} c_t * P_{n,t} * \Delta T + C_{r,n} \tag{8}$$

IV. CASE STUDY

In this section, it takes a 500Ah/600V lithium batteries system rated power 100kW as a study case to analyse the economic dispatch in the paper. The energy management of a distributed storage system in a grid-connected microgrid is formulated as a linear programming problem. The market prices of a day is given in Table 1, and the parameters is set as follows, η_C=η_D=0.9, Q_{min}=90kWh，Q_{max} =300kWh, P_{max} =100kW, and the initial remaining energy of the batteries is Q_s =90kWh. Ignoring the reserve benefits, it can be noted that benefits can be made only if ESS efficiency is greater than the off-peak/peak price ratio, i.e.

$$\eta_D * \eta_C > P_{off-peak} / P_{on-peak} \tag{9}$$

TABLE I. Electricity TOU PRICE

Time/h	0-8	8-12	12-14	14-18	18-22	22-24
Price	25%	100%	50%	100%	75%	50%

When 1kWh power is stored from the grid in the off-peak, no more than 1 kWh can be return to the grid in the peak, because of the convert loss. So, the benefit ratio for the storage should be higher than the loss.

TABLE II. POWER SETTINGS OF THE ESS

Time/h	0-8	8-12	12-14	14-18	18-22	22-24
P_t/kW	29.2	-47.2	100	-40.5	0	0

According to formula 4, the power set points of the ESS of the day are given in Table 2, and the benefits of the ESS is 192.7 standard kWh per day calculated as follow.

$$MaxF(P_{n,t}) = \sum_{t=1}^{T} c_t * P_{n,t} * \Delta T = 192.7kWh\cdot$$

TABLE III. POWER SETTINGS OF THE ESS INCLUDING RESERVE SERVICE

Time/h	0-8	8-12	12-14	14-18	18-22	22-24
P_t/kW	18.7	-37.5	75	-37.5	0	0

If the reserve benefits is considered, the parameters is set as follows, $\rho_{rp,n}$=0.1%, $\rho_{rsp,n}$=150%, $P_{rh}\%$=0.5%, Q_{rsoc} =60kWh, and the available capacity for dispatch under market price is $Q_a = Q_{max} - Q_{rsoc} - Q_{min}$. According to formula 8, the power set points of the ESS of the day is given in Table 3, and the benefits of the ESS offering reserve service is 151.4 standard kWh per day calculated as follow.

$$MaxF(P_{n,t}) = \sum_{t=1}^{T}\sum_{n=1}^{N} c_t * P_{n,t} * \Delta T + C_{r,n} = 151.4kWh$$

V. CONCLUSION

In this paper, the detailed control method analysis of the ESS is presented in island and grid-connected mode. The droop control method can be applied in both modes operation to improve the grid transient performance. Mathematic model for analyzing the economic effect of the energy storage system is proposed under the TOU price. Also, the reserve benefits of the ESS are also taken into account in this model. The ESS management module can make an optimal dispatch schedule according to the electricity price to maximize benefits.

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