Active and Reactive Power Coordinated Control Strategy of Battery Energy Storage System in Active Distribution Network

Wenxi Wang[1], Weiguo He[2], Junzhao Cheng[1], Xiaojian Huang[3], Haoming Liu[3]

1. Yunnan Power Grid Corporation, Kunming 6550011, China
E-mail: wangwenxi@im.yn.csg

2. China Electric Power Research Institute, Nanjing 210003, China
E-mail: heweiguo@epri.sgcc.com.cn

3. Hohai University, Nanjing 210098, China
E-mail: liuhaom@hhu.edu.cn

Abstract: Large penetration of intermittent renewable energy and complex loads in Active Distribution Network (ADN) has aggravated the fluctuation of voltage and increased power loss. Battery energy storage system (BESS) is a critical device in ADN, which are used to provide active power for the system. However, by connected with the grid using converter, battery has the ability to provide reactive power for the grid without other reactive compensation devices. To exploit the potential of BESS to regulate voltage fluctuations in ADN, in this paper, an active and reactive power coordinated optimization of BESS is proposed, with the goal of realizing lowest power loss as well as minimal voltage fluctuations in ADN. Then a specific solution to this optimal problem is given based on particle swarm algorithm. The results of a case study show that, by comparison between active power control strategy and active and reactive power coordinated control strategy, this paper has confirmed that the latter with reactive output of battery can have a better effect on reducing the power loss and stabilizing voltage fluctuation.

Key Words: Active distribution network, battery energy storage system, coordinated control strategy

1 INTRODUCTION

The penetration of intermittent and uncertain renewable energy has increased the requirements for flexibility of active distribution network (ADN). Great challenges have been put on both active power balance and voltage fluctuations regulation. Battery energy storage system (BESS) is gaining increasing population due to the fact that BESS can ramp quickly and can be accurately controlled. Installed in active distribution network, energy storage system contributes to smooth power fluctuations as well as provide ancillary services such as frequency regulation and peak load shifting. In middle and low voltage distribution network, BESS can not only stabilize the fluctuation of active power, but also has the ability to compensate for the reactive power by inverters connected with ADN.

Because of the low-level voltage of ADN, the ratio R/X is relatively larger than large power system, so the calculation of active and reactive power flow in ADN cannot be decoupled. Obviously, using reactive compensation devices merely cannot stabilize the voltage and reduce the power loss effectively simultaneously. So, coordinated active and reactive power control strategies in ADN has gained worldwide attention. In [1], STATCOM and BESS are combined for the use of the wind power systems and network research, which can achieve bidirectional flow of active and reactive power in grid and realize the four-quadrant compensation of the entire system and support the bus voltage. In [2], it proposes a method to improve the voltage stability of the power system by using the voltage stability index of the active power information and reactive power information of the transmission line. In [3], based on the analysis of dynamic mathematical model of doubly-fed motor and its stator-flux oriented vector control model, this paper derived the active and reactive decoupling strategy of doubly-fed motor. In [4], it proposes a robust coordinated dispatch optimization model which simultaneously considers the uncertainties of wind power output and load demand for scheduling the on-load tap changer ratios, reactive power compensators, and charge/discharge power of BESS.

In middle and low voltage distribution network, BESS can not only stabilize the fluctuation of active power, but also has the ability to compensate for the reactive power by inverters connected with ADN. In this paper, we propose an active and reactive power coordinated control strategy by excavating the reactive compensation ability of BESS, which can reduce the switch of reactive compensation devices and the economic cost. The rest of this paper is organized as follows: in section 2, an active power control strategy of BESS in ADN is presented, and in section 3, the active and reactive power coordinated control strategy of BESS is proposed. A particle swarm algorithm based solution is described in section 4, and a case study using a 33 nodes system is discussed in section 5. Conclusions are drawn eventually in section 6.

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2 ACTIVE POWER CONTROL STRATEGY OF BESS IN ADN

The reactive distribution in ADN can influence on the system's voltage recovery and underpower when the distribution network is fault. Similarly, the imbalance of reactive power can contribute to the voltage instability, and then cause the collapse of power grid. In order to keep the system safe, stable and economic, the optimal control to the voltage/reactive of ADN can not only improve power quality and optimize power flow, but also reduce the detrimental impact on ADN due to the penetration of renewable energy. So, the reactive control strategy, which is the coordination of a variety of reactive compensation devices, can minimize the active power loss of distribution network and stable the voltage by means of controlling the switching number of capacitors and SVC and the reactive output of PV inventors.

According to the strong coupling of active and reactive power, active power can stabilize the fluctuation of node's voltage by controlling the output of DGs [5], loads of demand side [6-7] and charge/discharge power of BESS [8-9]. In comparison, using storage devices to adjust active power could be a better method because they can be controlled more accurately and switched more easily. What's more, it poses little influence on users.

2.1 Object Function

In middle and low voltage system, battery energy storage system can reduce the power loss to some extent by changing power flow distribution in distribution network. With the goal of minimizing power loss, we establish an active optimal model of BESS, which can be expressed as:

$$F = \min P_{loss} \tag{1}$$

where, P_{loss} is the active power loss in distribution network, which can be expressed as:

$$P_{loss} = \sum_{i,j\in N} g_{ij}(U_i^2 + U_j^2 - 2U_i U_j \cos\theta_{ij}) \tag{2}$$

where, N is the number of nodes in ADN, U_i and U_j are the voltage amplitude of node i and j, g_{ij} is the branch admittance between node i and j, θ_{ij} is the difference of voltage phase angle.

2.2 Constraints

Constraints of active control strategy comprise equality constraints and inequality constraint. The equality constraints are active and reactive power flow constraints, which is:

$$\begin{cases} P_i = U_i \sum_{j\in i} U_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \\ Q_i = U_i \sum_{j\in i} U_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \end{cases} \tag{3}$$

where, P_i, Q_i are respectively the active and reactive injected power in node i, G_{ij} and B_{ij} are respectively the conductance and susceptance between node i and j.

The constraint of battery storage output power at time t can be expressed as:

$$P_E^{\min} \le P_E \le P_E^{\max} \tag{4}$$

where P_E^{min} and P_E^{max} are the lower and upper active output power of battery, respectively.

3 COORDINATED CONTROL STRATEGY OF REACTIVE AND REACTIVE IN ADN BASED ON BESS

BESS is usually considered to provide active power for the grid, however, its reactive output ability cannot be neglected. The reactive output power comes from the converter connected BESS with ADN.

3.1 Object Function

When taking the reactive power of BESS into consideration, the voltage of ADN can be regulated as well. In order to testify the potential reactive power compensation ability of BESS, we establish the active and reactive coordinated optimization model with the goal of lowing power loss and minimizing node voltage fluctuations simultaneously. The object function can be expressed as:

$$F = \min(P_{loss} + \lambda U_r) \tag{5}$$

where, U_r is the sum of average voltage deviation which is:

$$U_r = \sum_{i=1}^{N} \left| \frac{V_i - \frac{V_{\max} + V_{\min}}{2}}{V_{\max} - V_{\min}} \right| \tag{6}$$

where, V_i is the current voltage of node i, V_{min} and V_{max} represent the minimum and maximum voltage of each node. Considering the dimensions between P_{loss} and U_r, we use a coefficient λ to eliminate the difference.

3.2 Constraints

1) The constraint of node voltage

Reactive power will influence on the voltage of each node, so in the coordinated active and reactive power control strategy, constraint of nodes' voltage should be added, which is:

$$V_{\min} \le V \le V_{\max} \tag{7}$$

where the meaning of V_{min} and V_{max} are mentioned in equation (6).

2) The apparent output power constraint of BESS

As the reactive power of battery storage is considered as a controllable variable, the constraint of apparent power output should be satisfied, which is:

$$S_{\min} \le S \le S_{\max} \tag{8}$$

where, S_{min} and S_{max} are the minimum and maximum apparent output power of BESS.

3) The constraint of reactive power output BESS

In principle, the output reactive power from BESS can be the same with apparent power, but to ensure the power factor of ADN reasonably, the reactive power is supposed to be constrained as:

$$Q_{\min} \le Q \le Q_{\max} \tag{9}$$

where Q_{min} and Q_{max} are the minimum and maximum reactive output power of BESS.

4 SOLUTION PROCEDURE BASED ON PARTICLE SWARM OPTIMIZATION ALGORITHM

Particle Swarm Optimization (PSO) algorithm has been successfully used in a lot of optimization issues for its strong global searching capability and fast computing speed. But PSO may easily trap in local optimum for some optimization problems with discrete variables. In this paper, since there are no discrete variables in active power control strategy and active and reactive power coordinated optimization model, PSO is an effective method to solve the proposed optimization models. The process to solve the optimization problem using PSO can be seen in Fig.1.

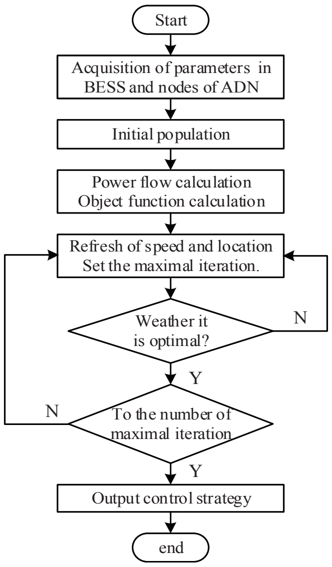

Fig. 1. Flow chart of proposed coordinated optimal strategy based on PSO.

Supposing that in an objective searching space with m dimension, the number of particle swarm is N, and each particle is in the upper and lower limit of the solution vector. To speed up the calculation of power flow, we form the vector X_i as the particle i and V_i is its refresh rate, which is:

$$\begin{cases} X_i = (P_{i1}, P_{i2}, ..., P_{im}; Q_{i1}, Q_{i2}, ..., Q_{im}) \quad i=1,...,N \\ V_i = (V_{pi1}, V_{pi2}, ... V_{pim}; V_{qi1}, V_{qi2}, ... V_{qim}) \; i=1,...,N \end{cases} \tag{10}$$

When using active power control strategy, Q_{it}=0, V_{qit}=0, (t=1, 2, …, m).

The searched optimal position of particle i till now is denoted as pbest, which is:

$$pbest = (P_{i1}, P_{i2}, ..., P_{im}; Q_{i1}, Q_{i2}, ..., Q_{im}) \quad i=1,...,N \tag{11}$$

The searched optimal position of all the particles till now is denoted as gbest, which is:

$$gbest = (P_{g1}, P_{g2}, ..., P_{gm}; Q_{g1}, Q_{g2}, ..., Q_{gm}) \tag{12}$$

Each particle in the optimization can refresh its speed and location as:

$$\begin{cases} V_{i+1} = w \times V_i + c_1 \times rand \times (pbest - X_i) \\ \qquad + c_2 \times rand \times (gbest - X_i) \\ X_{i+1} = X_i + V_{i+1} \end{cases} \tag{13}$$

where, c_1 and c_2 are the non-negative constant which can accelerate the process. V_i is the speed of particles which is between the minimum speed v_{min} and maximum speed v_{max}. Usually, v_{min}=0.1 and v_{max}=0.2. *rand* is the random number between 0 and 1. w is the inertial coefficient which can be set or regulated by adaptive strategy as:

$$w = w_{\min} + (w_{\max} - w_{\min}) \times (T_m - T_n) / T_m \tag{14}$$

where, w_{min} and w_{max} are the lower and upper limit, T_m and T_n are the maximum and current iterations.

5 EXAMPLE SIMULATION

The example simulation in this paper is based on IEEE 33 nodes distribution network, where the rated voltage is 12.66kV and the reference capacity is 10MVA. The topological structure of ADN with PV is shown in Fig.2, where storage device is connected with node 15, and its volume is 1000kWh. The rated power of BESS is 500kW and the volume of its converter is 600kWh. To verify the strategy proposed in this paper, we set 3 scenarios.

Scenario 1: There is no storage device connected in ADN;

Scenario 2: There is a storage device in node 15 of ADN, and only its active power output is controllable.

Scenario 3: There is a storage device in node 15 of ADN, and both its active and reactive power output are controllable.

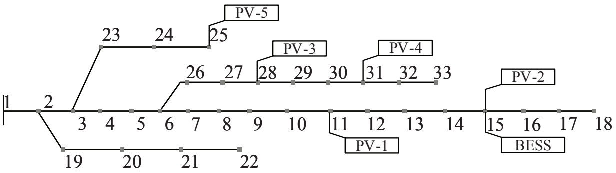

Fig. 2. Topological structure of 33 nodes system.

In this paper, when optimizing the object function, which is the minimizing power loss in ADN, PSO algorithm is used, and some parameters of PSO are set in Table 1.

Table1. Parameters of PSO

Parameter Name	Value
Size of particle swarm/ N	80
The maximal number of iteration/ T_m	100
The dimension of particle/ m	6
Inertial coefficient/ w	0.729
Learning factors/ c_1	1.49445
Learning factors/ c_2	1.49445
Multi-objective coefficient/ λ	0.8

Table2. Simulation result when the BESS charges

Parameter Name	Scenario 1	Scenario 2	Scenario 3
Active of Storage/kW	0	-106.25	-96.02
Reactive of Storage/kvar	0	0	-45.49
Active power loss/kW	17	16.561	16.438
Voltage deviation/p.u.	9.434	7.9307	7.2351

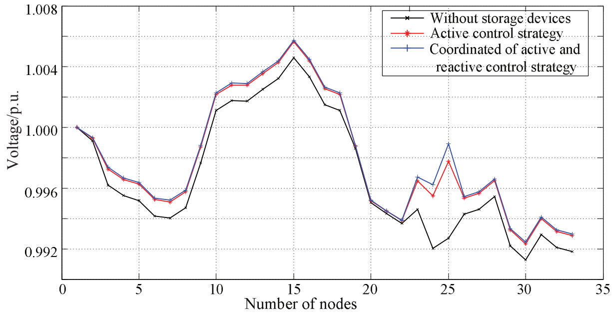

Fig. 3. Voltage distribution curves

As is shown in Table 2, since the power loss and voltage deviation has been small thanks to other regulating equipment, in scenario 2, when energy generation is less than load demand and battery energy storage system at node 15 is dispatched to discharge, power loss in ADN can be reduced for a small-scale adjustment from 17kW to 16.561kW. In scenario 3, from Table 2, it can be seen that the power loss is also reduced from 17kW to 16.438kW compared with that in scenario 1 when BESS is not dispatched. In addition, power loss in scenario 3 is even less than that in scenario 2, implying that when active power and reactive power of BESS is coordinated controlled, it exerts better and more noticeable impact on reducing power loss.

In scenario 3 where active and reactive power coordinated control strategy is applied in BESS, voltage fluctuations in ADN is regulated to some extent. From Table 2, the voltage deviation index can be small than in scenario 1 and scenario 2.

What's more, we can obviously see in Fig. 3 that voltage fluctuations of nodes close to node 15 is smoothed in scenario 3, compared with original node voltage curve, whilst little changes in node voltage deviations of nodes that are relatively far away from node 15 can be found. Voltage fluctuations of nodes close to node 15 is regulated through proposed coordinated optimization model while node voltage deviations of nodes that are relatively far away from node 15 almost stay unchanged.

Thus we can come to the conclusion that, utilizing the active output of BESS can help to reduce the power loss, but reactive of BESS is often neglected. In fact, this 'FREE' reactive power of BESS can be made full use of to reduce both power loss and voltage deviation, but the effect on voltage deviation of nodes relatively far away is not that significant.

6 CONCLUSION AND EXPECTSTION

To exploit the potential ability of battery energy storage system in regulating voltage deviations in active distribution network, a coordinated active and reactive control strategy of BESS is proposed in this paper, with the goal of reducing power loss and smooth voltage fluctuations simultaneously. The case study demonstrated that, through coordinated control of active and reactive power of BESS, power loss in active distribution network can be decreased more remarkably compared with that when active power of BESS is dispatched only. Besides, node voltage deviations of nodes close to BESS's location can be smoothed, though effect on regulating voltage deviations of nodes far away is not significant. Through optimal control, BESS does contribute to regulate voltage fluctuations in active network, and its ability still need to be studied further.

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