Distributed energy storage operation optimization model considering demand response

GUO Yuhan[1*], TANG Ren[1], Li Changqing[2], Wang Jintao[2], Wang Ziji[2]

1.Zhejiang Huayun Power Engineering Design Consulting Co.,Ltd.,Hangzhou Zhejiang 310000,China;

2.Hangzhou Henglong New Energy Technology Co.,Ltd.,Hangzhou Zhejiang 310016,China

Abstract: With the rapid development of new energy, wind power, photovoltaic, geothermal and other energy sources are connected to the power grid on a large scale, showing the characteristics of system stability and reliability, complex safety characteristics, imbalance between supply and demand, and insufficient peak shaving capacity. As a flexible demand response resource, distributed energy storage can effectively promote the coordinated and stable operation of power supply and demand resources. Considering the economy and technology of distributed aggregators, an operation optimization model for their participation in demand response is constructed, and a distributed energy storage operation control strategy considering demand response is proposed, which can effectively realize peak load shifting.

1. Introduction

With the increasingly severe global energy crisis and the increasing demand for energy from industrial development and social operation and maintenance, improving energy efficiency and the operating economy of power systems have become the only way for the energy revolution[1].Demand response technology plays an important role in reducing the peak-valley difference of power load and reducing energy consumption by guiding users to change the traditional power consumption mode and adjusting the power contradiction quickly and effectively[2].In order to fully tap the potential of DR, energy storage systems are widely used in the electricity market. By cutting the peak load of the power grid to obtain economic benefits, the stability of the power grid and energy efficiency are improved.

In the face of a large number of emerging load access and the rapid growth of new energy, distributed energy storage technology, as an emerging technical means, has potential application value in delaying the expansion and upgrading of distribution equipment and improving power quality. Firstly, the converter of energy storage system has the ability of four quadrant operation, which can realize the decoupling control of active and reactive power. According to the change of demand side load, the output of energy storage system can be adjusted quickly, so as to optimize the power flow distribution and improve the power quality of the station area. Secondly, the energy storage system can play the role of peak shaving and valley filling, reduce the load rate and safe operation risk of distribution and substation lines during peak hours, play the role of standby power supply, reduce the power outage time of the station area, and improve the power reliability and power supply service capacity of the station area. At the same time, based on its flexible characteristics, multi-point distributed energy storage devices can alleviate the problem of load supply congestion during peak or peak load periods, delay the expansion and upgrading of distribution network, and improve the economy of power grid investment[3].

2. Distributed energy storage charge and discharge model

Distributed energy storage is an excellent resource for participating in demand-side response because of its flexibility and millisecond response capability. First, it is necessary to consider the charging and discharging process of energy storage and its capacity constraints.

*2249832126@qq.com

$$\begin{cases} I_{k,t}^{ch} \cdot \underline{P_k^{ch}} \leq P_{k,t}^{ch} \leq I_{k,t}^{ch} \cdot \overline{P_k^{ch}} \\ I_{k,t}^{dis} \cdot \underline{P_k^{dis}} \leq P_{k,t}^{dis} \leq I_{k,t}^{dis} \cdot \overline{P_k^{dis}} \\ E_{k,t} = E_{k,t-1} + \left[\eta_k^{ch} \cdot P_{k,t-1}^{ch} - \frac{P_{k,t-1}^{dis}}{\eta_k^{dis}}\right] \Delta t, \forall t, \forall k \in R_{MG} \\ \underline{E_k} \leq E_{k,t} \leq \overline{E_k} \\ E_{k,0} = E_{k,T} \\ 0 \leq I_{k,t}^{ch} + I_{k,t}^{ch} \leq 1 \end{cases} \quad (1)$$

In the formula : $P_{k,t}^{ch}$ 、 $P_{k,t}^{dis}$ represent the charging power and discharging power of distributed energy storage respectively ; $I_{k,t}^{ch}$、 $I_{k,t}^{dis}$ are 0 ~ 1 variables, which represent the charging state and discharge state of distributed energy storage respectively; $\overline{P_k^{ch}}$ 、 $\underline{P_k^{ch}}$、 $\overline{P_k^{dis}}$ 、 $\underline{P_k^{dis}}$ respectively represent the upper and lower limits of charging power and discharging power of energy storage ; electricity cycle is T ; η_k^{ch} 、 η_k^{dis} represent the charging efficiency and discharge efficiency, respectively; $E_{k,t}$ represents the charge capacity of energy storage ; $\overline{E_k}$、 $\underline{E_k}$ represent the upper and lower limits of the charge capacity of the energy storage respectively.

3. Operation optimization model participating in demand response

Distributed energy storage resources are equivalent to a special commodity being introduced into the electricity market for trading, which has its own uniqueness and the generality of commodity trading. In this paper, the economic benefits of distributed energy storage aggregators are taken as the main objective of optimization, and the technical objectives of participating in demand response are considered to ensure the stability of system operation.

3.1 Objective function

Taking the maximum profit of demand response day and the minimum variance of load curve as the objective function, the formula is adopted.

$$\begin{cases} \max F_1 = B_1 + B_2 - C_1 - C_2 \\ \min F_2 = \frac{1}{T}\sum_{t=1}^{T}\left(P_{load}(t) + P_d(t) - \frac{1}{T}\sum_{t=1}^{T}\left(P_{load}(t) + P_d(t)\right)\right)^2 \end{cases} \quad (2)$$

In the formula : B_1 represents the price arbitrage income ; B_2 represents the response compensation income ; C_1 represents the compensation cost of energy storage users ; C_2 indicates the cost of battery loss ; $P_{load}(t)$ represents the baseline load demand of the power grid at time t ; $P_d(t)$ represents the total output of energy storage resources after aggregation at time t.

3.2 Constraint condition

3.2.1Net load power balance constraint

Energy storage resources need to meet the power balance of the system when they are connected to the power grid for demand response.

$$P_{act}(t) = P_{load}(t) + P_c(t) - P_d(t) \quad (3)$$

In the formula : $P_{act}(t)$ represents the actual load after the response at time t ; $P_{load}(t)$ denotes the user 's baseline load at time t ; $P_c(t)$ represents the charging power of energy storage after aggregation at time t ; $P_d(t)$ represents the discharge power of energy storage after polymerization at time t.

3.2.2State of charge,SOC

During the operation of the energy storage day after the polymerization, the residual energy at t + 1 moment is related to its residual energy at t moment and its charge-discharge state. Therefore, the state of charge of energy storage at any time needs to meet the following two constraints.

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (4)$$

$$SOC(t+1) = SOC(t) + \frac{P_c(t)\eta_c\Delta t}{E_R} - \frac{P_d(t)/\eta_d\Delta t}{E_R} \quad (5)$$

In the formula : Δt represents the continuous charging and discharging time of energy storage after non-polymerization.

3.2.3Power and capacity constraints

When the aggregated energy storage resources participate in demand response, they need to meet power constraints and capacity constraints.

$$\begin{cases} P^- \leq P(t) \leq P^+ \\ E_{min} \leq E(t) \leq E_{max} \end{cases} \quad (6)$$

In the formula :P^+、P^- represent the upper and lower limits of the power of the energy storage after polymerization, respectively ;E_{max}、E_{min} represent the upper and lower limits of the capacity of the energy storage after polymerization, respectively.

3.2.4 Charge and discharge state constraints

The distributed energy storage device cannot charge and discharge at the same time at a certain time, and it needs to be in one of the three states of charging, discharging and no charging and discharging. Therefore, the constraints on the charging and discharging state of the energy storage device are as follows.

$$P_c(t) \cdot P_d(t) = 0 \qquad (7)$$

3.2.5Demand response constraints

Satisfy the maximum load constraint that the baseline maximum load is greater than or equal to the agreed response period.

$$\max\left(P_{load,j} + P_{c,j} - P_{d,j}\right) \geq \max\left(P_{load,k} + P_{c,k} - P_{d,k}\right) \qquad (8)$$

In the formula : $P_{load,j}$ represents the baseline load of the response period j corresponding to the five days before the demand response day ; $P_{c,j}$ 、 $P_{d,j}$ respectively represent the charging and discharging power of the aggregated energy storage in period j ; $P_{load,k}$ represents the load participating in demand response in the free period ; $P_{c,k}$、$P_{d,k}$ respectively represent the charging and discharging power of the energy storage after polymerization in k time period.

Average load constraint in response period:

$$\max\left(P_{load,j} + P_{c,j} - P_{d,j}\right) - \max\left(P_{load,k} + P_{c,k} - P_{d,k}\right) \geq 0.8P_{dsm} \qquad (9)$$

In the formula :P_{dsm} represents the optimal response power reported.

The range of the agreed response power is constrained. Generally, the agreed response capacity is 5-20 % of the maximum power load of all users in the previous year :

$$0.05P_{max}^{pre} \leq P_{dsm} \leq 0.2P_{max}^{pre} \qquad (10)$$

In the formula : P_{max}^{pre} represents the maximum peak load of users in the previous year.

3.3 Solution method

The daily operation optimization model of demand response established above belongs to mixed integer programming, which has the characteristics of high dimension, nonlinearity and randomness. In order to improve the efficiency and accuracy of the solution, the mature Particle Swarm Optimization (PSO) algorithm is used to solve the above optimization model. The idea of PSO algorithm is to treat each potential solution of the optimization problem as a particle in the multidimensional space. Starting from the random solution, the fitness function of the particle is calculated to meet the solution standard, and the global optimal solution is obtained by updating iteration.

The calculation process of the PSO algorithm is as follows : In the D-dimensional space, the position of each particle i can be described by a vector. The position vector is $X_i = (x_{i1}, x_{i2}, \dots, x_{iT})^T$, and the velocity vector is $V_i = (v_{i1}, v_{i2}, \dots, v_{iT})^T$.Each particle i moves in the D-dimensional space to find the fitness value of the objective function. In this process, the local optimal position (pbest) that it has reached is recorded, and the global optimal position (gbest) of all particles is explored. On this basis, the update iteration is performed by adjusting the speed and direction of its own motion until the optimal solution satisfying the stopping condition is found. The update formula of the position and velocity of each particle i is :

$$v_{id}^{t+1} = \omega v_{id}^t + c_1 r_1 (pbest_{id}^t - x_{id}^t) + c_2 r_2 (gbest_d^t - x_{id}^t) \qquad (11)$$

$$x_{id}^{t+1} = x_{id}^t + v_{id}^{t+1} \qquad (12)$$

In the formula :x_{id}^t、 v_{id}^t represent the position of the i th particle after t iterations and the component of the velocity vector in the D dimension respectively ; c_1、 c_2 represent the acceleration factor, which is usually a constant greater than zero. By selecting the appropriate value, the convergence speed can be accelerated and the local optimal solution can be avoided. ω is the inertia weight factor ;r_1 、 r_2 represent two random numbers, which satisfy the uniform distribution of [0,1]. $pbest_{id}^t$ represents the individual extreme point of the t-th iteration of particle i in the D-dimensional search space ; $gbest_d^t$ represents the global extreme point of the tth iteration of the whole population in the D-dimensional search space.

The main steps of using PSO algorithm to optimize the solution are as follows :

1) Initialization : initialize the population number N, input the maximum number of iterations, learning factors and other parameters, and randomly assign the initial position and speed of each particle in the D-dimensional search space.

2) Evaluation particles : For each particle, the fitness of the D-dimensional optimization function is evaluated to find the individual optimal position and the global optimal position of each particle.

3) Updating the optimal position : Firstly, the particle fitness is compared with the individual extreme point. If the result is better than pbest, the individual optimal position will be updated to the current particle position. Secondly, the particle fitness is compared with the global extremum point. If it is better than gbest, the global optimal position will be updated to the current particle position.

4) Update the velocity and position of particles : update the velocity and position of all particles according to Formulas (11) and (12). After updating, it is judged whether the velocity and position of the particles exceed the limit boundary. If the limit boundary is exceeded, the upper or lower limit is taken.

5) Termination condition : It is necessary to determine whether the iteration is completed. If it is not completed, go to step 2 until the termination condition is satisfied and the global extreme point gbest is output. The general termination condition is to meet the fitness and the maximum number of iterations.

Based on the above steps, the flow chart of PSO algorithm is as follows :

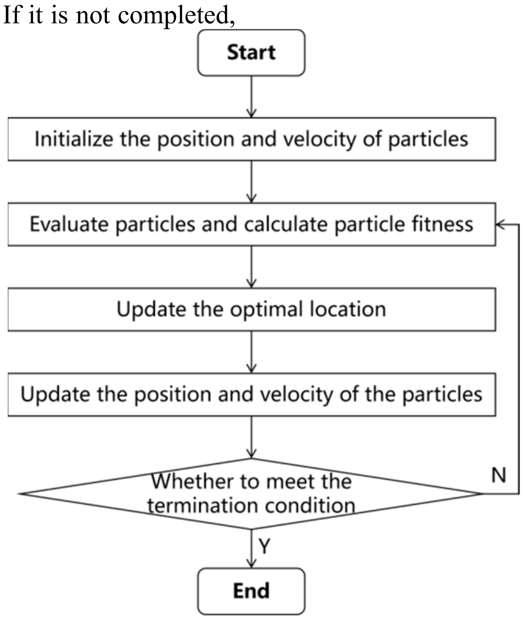

Figure 1. PSO algorithm flow chart

4. Example analysis

The validity of the model is simulated and analyzed by an example of an industrial park. Because the model is aimed at the daily operation strategy, a day of the park is selected as a typical day to calculate and analyze the model. Based on the day-ahead load forecasting results, the typical daily maximum load is 5367.40 kW, and the minimum load is 2791.36 kW. The peak shaving demand response period is 9 : 00-11 : 00 and 18 : 00-20 : 00 ; the compensation price of the quota demand response is 3.75 yuan / kWh. The SOC of 100 energy storage devices in the park is set to be 0.1 at the beginning of charging, 0.9 at the beginning of discharging, and the charging and discharging efficiency is 0.95. The rated discharge depth is 50 %, and the corresponding number of cycles is 3000.

The time-of-use electricity price table for the location of the park is as follows :

Table 1. Time-of-use electricity price table

	time interval	electrovalence
overshoot	17:00-19:00	1.2552
peak	08:00-12:00、19:00-21:00	1.0086
Flat	05:00-07:00、12:00-17:00、21:00-23:00	0.6837
low ebb	23:00-05:00	0.3587

The relevant parameters of the PSO algorithm are set as follows :

Table 2. PSO algorithm parameters

parameter	numerical value	parameter	numerical value
iteration times N	500	accelerin c_1	1.0
population size	100	accelerin c_2	2.0
ω	0.8	speed limit	[-1,1]

The effective charging and discharging times of energy storage are set to 2 times. The optimization results of the load curve before and after the installation of energy storage are shown in the figure when the demand response is obtained through the simulation of the example.

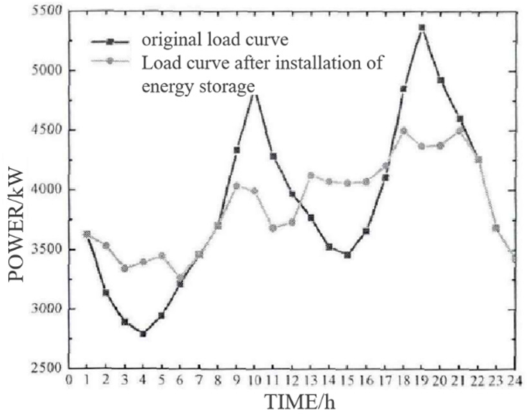

Figure 2. Load curve trend chart

Through the comparison of the optimization results, the load curve after the installation of energy storage is relatively flat compared with the original load curve, effectively reducing the peak-valley difference by about 1340kW, reducing the peak-valley difference rate by about 21% and achieving the purpose of smoothing the load curve.

When participating in demand response, the optimization results of charging and discharging power and state of charge of energy storage in each period are shown in the following figure.

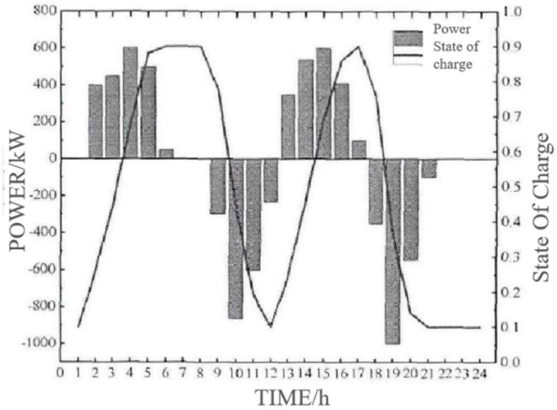

Figure 3. Charging and discharging power and state of charge at each time period

According to the optimization results, the maximum load reduction at 19 : 00 in the demand response is 1000kW.

Further, the economic benefits of energy storage participating in demand response are obtained through model solving. Among them, the total income is 12386.25 yuan, the profit is 6848.22 yuan. The following table shows :

Table 3. PSO algorithm parameters

Amount (yuan)	income		cost			profit
	Electricity price arbitrage	demand respond	purchasing electricity	battery loss	User compensation	
	1080.76	11305.49	2102.05	45.66	3390.32	6848.22

5. Conclusion

Under the trend of large-scale integration of new energy sources such as wind power and photovoltaics, the cost of energy storage technology is reduced and the installed capacity is increasing year by year. As an important energy regulation component, distributed energy storage becomes crucial in demand response side resource management and regulation. In this paper, the objective is to maximize the daily profit and minimize the mean square error of the load. Considering the operation constraints of energy storage, the effective demand response conditions, the compensation cost of energy storage users and other factors, the particle swarm optimization algorithm is used to solve the optimization model and the effectiveness of the model is verified by an example analysis. It not only realizes the peak load shifting, but also improves the utilization rate of energy storage resources and the economic benefits of users.

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