The Interruptible Load Control Strategy of Distribution Network in Integrated Energy Service System

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Abstract. In the integrated energy service system, distribution network shall manage to settle its own power balance issue. The market competition that grid corporations open the sale services of electricity to the society and interruptible load is encouraged to participate in ancillary services becomes a development tendency. At this time, a corresponding control strategy was required to instruct interruptible loads scheduling. In this paper, a control strategy using discrete Fourier transform is proposed in combination with the requirements of the electricity market. Under the constraint of the new evaluation criteria, different types of resident interruptible loads were on-demand dispatched in different periods. The root mean square error (RMSE) of the feeder daily forecast could improves the power load control capability of distribution network as well as the quality of power supply.

1. Introduction

There are a lot of interruptible loads (IL) [1] in the distribution network, such as air conditioning, refrigerator and electric vehicle. From the perspective of system operation, these IL are important power balance resources, which can smooth the load curve of the distribution network. In the traditional distribution network, due to the lack of consideration of how to play the role of adjustable load and lack of technical means in planning and design, the load only passively absorbs power from the grid according to its own needs, and does not play a role. Now, users can choose to sign power supply guarantee agreement, IL agreement and other contracts with distribution network managers voluntarily based on their own load characteristics, stipulate their rights and obligations of auxiliary services, bear necessary auxiliary service costs, or get corresponding economic compensation according to their contributions. At present, limited by the power reserve service market is not fully open in China, there are still many issues worthy of discussion such as IL scheduling control.

The peak load of power grid can be restrained only by integrating the air conditioning load [2]. Therefore, a double-layer optimal scheduling model of air conditioning is proposed to control the start and stop of air conditioning so as to adjust the power and maintain the room temperature in a comfortable range. In [3], based on the priority and cycle scheduling algorithm, the air conditioning cluster control scheme is established. According to the random sampling theory, an instruction algorithm for group tracking active power control of air conditioning load is proposed in [4]. In [5], it is considered that controlling multiple residential loads is an important measure to implement demand
response in distribution network, and the control model is designed based on the actual power shortage and different IL physical characteristics. The fuzzy neural network designed in [6] can learn the electricity habits of smart home appliances in advance, and then automatically respond to the demand. In [7], the dynamic priority of household appliances is calculated online according to their real-time state, and the load control decisions are carried out according to the priority order. In reference [8], the electrical appliances and key devices in the home are abstracted mathematically, and the demand response control architecture model is constructed in the home domain network. In [9], a household energy management system was established to obtain an IL optimization model. The above research has carried on the multi-angle analysis to the IL control in the distribution network, provided the constructive opinion, but still needs to consider the following several questions: 1) the reasonable classification and time-sharing scheduling of the IL in the distribution network can improve the utilization efficiency, accurately track the demand change; 2) in meeting the requirements of the distribution network operation, the IL control times should be as few as possible to reduce the impact on the user's electricity consumption; 3) The control strategy of IL control standard needs a set of standards that meet the actual needs of the power market to guide the IL scheduling control; 4) the IL control strategy should be as simple and effective as possible for practical application.

This paper focuses on IL control under the premise that grid companies have signed interruption contracts with enough users. According to the requirements of distribution network guiding IL to provide auxiliary services in the power market environment, an IL control strategy using discrete Fourier transform (DFT) is proposed. Based on the regulation response time, the strategy classifies different IL according to the frequency domain. According to the deviation between the load power and the planned value, it can calculate the auxiliary reserve regulation quantity in different frequency bands, dispatches the corresponding IL power to suppress the fluctuation of the load power, reduces the prediction deviation of the feeder power in the distribution network with less regulation cost, and improves the service ability of the power selling enterprises.

2. The demand of interruptible load control

The early implementation of interruptible load is mainly for industrial users, but its production continuity is strong, the machine is not easy to start and stop, and it is not suitable for distribution network standby. With the development of economy and the improvement of residents' living standards, the electricity consumption of the tertiary industry and residents has increased dramatically. Intelligent and controllable household appliances such as air conditioning are gradually popularized, which can be used as the main regulatory resources of distribution network IL.

| Sequence | Time  | Equipment     | Interruptible load/kW | Response time | Response frequency |
|----------|-------|---------------|-----------------------|--------------|--------------------|
| 1        | Immediate | Fridge       | 0.1                   | 0-1          | 1/120-∞           |
| 2        | 1 min  | Heater        | 0.3                   | 1-3          | 1/720-1/120       |
| 3        | 3 min  | Air conditioner | 0.2                 | 3-10         | 1/2400-1/720      |
| 4        | 10 min | Other         | 0.05                  | 10-30        | 1/7200-1/2400     |
| 5        | Backup | Backup       | -                     | 30-∞         | 0-1/7200          |

The classification of residents’ IL can make clear the scheduling objects, integrate the scattered resources, and provide the basis for future IL contract pricing. According to different response time, electrical characteristics and other factors, this paper classifies the residents' IL in Table 1. Among them, washing machine, dishwasher and disinfection cabinet are all other IL due to the dispersion of working time. Different IL has different scheduling mechanisms: the refrigerator is controlled by heating up or suspending refrigeration; the electric water heater is mainly controlled by slowing down heating; the air conditioner is controlled by constant temperature of 26 degree, and 24-28 degree is set as the temperature regulating range.
In the integrated energy service system, the electricity selling company can purchase electricity in many ways. In the new era, the market hopes that the electricity selling company will provide innovative services, that is, in addition to the traditional electricity selling business, the electricity selling company is encouraged to provide users with value-added services including contract energy management, comprehensive energy conservation and energy use consulting. From another point of view, both the seller and the user are participants in the market. The user is no longer simply a "buyer" or "consumer", but can form a sales and consumption alliance, jointly complete the day ahead market quotation, and provide auxiliary services in the power sales jurisdiction.

Due to the influence of weather change and fault burst, the actual power of feeder load often deviates from the planned value, and the excessive deviation will lead to the reduction of power quality and harm to the operation of distribution network. In the real-time market, in order to make up for the deviation of the day ahead market plan, the control center collects the signed IL status according to the two-way information channel and determines the corresponding adjustable equipment. Different types of IL backup resources provide corresponding backup auxiliary services according to the needs of each time period. The above behaviors can not be separated from the market environment incentives. In the power market, encouraged and guided by policies, IL users need to sign relevant contracts with power selling companies, establish mutual trust and mechanism, and on this basis, apply effective control strategies to increase or decrease the controllable load or shift the power consumption period, which helps to improve the comprehensive energy efficiency of reserve resource allocation on the generation side and demand side.

3. Discrete Fourier transform control strategy

It is a typical non-stationary strong stochastic process that the power flow of distribution network feeders changes rapidly and its amplitude changes greatly. The short-term power prediction accuracy of feeders is not high, the power flow fluctuation is large, and the power deviation from the original planned value occurs. At this time, we should use a certain method to call IL with different response time to accurately stabilize the power within the planned value fluctuation deviation range. DFT is one of the fast and effective methods to solve these problems.

DFT transforms the fluctuating signal from time domain to frequency domain, and then studies the frequency response and change rule of the signal. The unique information represented by frequency sequence is obtained by finite calculation, and then the power deviation in frequency domain is obtained. The above behaviors can not be separated from the market environment incentives. In the power market, encouraged and guided by policies, IL users need to sign relevant contracts with power selling companies, establish mutual trust and mechanism, and on this basis, apply effective control strategies to increase or decrease the controllable load or shift the power consumption period, which helps to improve the comprehensive energy efficiency of reserve resource allocation on the generation side and demand side.

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\[
Y(k) = \sum_{n=1}^{N-1} P_{\text{DEV}-T}(n)e^{-j2\pi nk/N}, 1 \leq n \leq N - 1
\]  

(1)

The Parsevals' theorem shows that the energy obtained in time domain is equal to that obtained in frequency domain. In Table 1, 6 kinds of IL have been characterized by different frequency bands. By using DFT to obtain the total deviation frequency domain signal in the period of \( T \) and mapping it to each kind of IL specific frequency band, the energy of these frequency bands can be obtained by Parseval's theorem. Therefore, the demand value of signal energy in different IL frequency band in can be obtained from (2):

\[
P_{\text{IL}_x} = \left( \sum_{k \in f_x} |Y(k)|^2 \right)^{1/2}, x = 1, 2, ..., 5
\]  

(2)
4. Interruptible load control strategy

4.1. Interruptible load control target
The deviation between measure value and planned value for the compensated power on the distribution feeder in one planning period (one day) can be expressed as:

\[ P_{\text{DEV}} = P_i - P_{0i} \]  

(3)

4.2. Evaluation standard
Appropriate performance evaluation standards can objectively and fairly evaluate the role of each control capacity on the control object, which is an important link to establish a standard order and promote the application of standby auxiliary service technology. In the power market, it is necessary to check the degree of load power change of distribution network with supporting evaluation standards as the basis for IL fine scheduling. Meanwhile, it is necessary to prevent IL over compensation. On the basis of meeting the control accuracy requirements, scheduling shall be minimized to avoid affecting the demand satisfaction of users.

In the power market, the assessment of 10kV feeder power in the distribution network is generally that the root mean square error of all day prediction results of the daily prediction curve of feeder power is not more than 10%, and the maximum prediction error is not more than 30%. The expression is

\[ R_{\text{MSE}} = \sqrt{\frac{\sum_{i=1}^{N_n} (P_i - P_{0i})^2}{C_T \sqrt{n_{\text{day}}}}} \]  

(4)

\[ \delta_{\text{max}} = \max \left( \frac{|P_i - P_{0i}|}{P_i} \right), i = 1, 2, \ldots, n_{\text{day}} \]  

(5)

Based on the \( R_{\text{MSE}} \) standard, this paper constructs the evaluation standard of 10kV feeder power in the distribution network, and guides the deviation to approach the zero axis, but does not require the deviation of actual power value and planned value to be zero in real time, so as to reduce the frequency of IL regulation. Therefore, \( R_{\text{MSE}} \) is divided into: 1) short-term index \( S_{\text{RMSE}} \), which responds to real-time power deviation; 2) long-term index \( L_{\text{RMSE}} \), which suppresses large fluctuation of feeder power. \( S_{\text{RMSE}} \) and \( L_{\text{RMSE}} \) are assessed every 15 minutes.

\( S_{\text{RMSE}} \) aims to evaluate the short time power correction effect, and can be given by:

\[ S_{\text{RMSE}} = \sqrt{\frac{\sum_{i=1}^{N_n} P_{\text{DEV-AVE}}^{\text{AVE}-\min}}{C_T \sqrt{n_{\text{min}}}}} \leq \varepsilon_1 \]  

(6)

and can be transformed as:

\[ S_{\text{RMSE}} = 2 - \frac{1}{C_T^2 n_{\text{min}}^2} \sum_{i=1}^{n_m} P_{\text{DEV-AVE}}^{\text{AVE}-\min} \]  

(7)

\( L_{\text{RMSE}} \) aims to evaluate the short time power correction effect, and can be given by:

\[ L_{\text{RMSE}} = \left| \frac{\sum_{i=1}^{N_n} P_{\text{DEV}}}{C_T \cdot N_{15}} \right| \leq R_{15} \]  

(8)

4.3. Control threshold
This strategy focuses on the long-term control effect and does not require the feeder power deviation to cross zero frequently in the assessment time. In line with the above \( R_{\text{MSE}} \) standard, three thresholds are set in the regulation area.
4.3.1. **Dead time.** There is no need to compensate for the small power fluctuation, and it does not affect the customer satisfaction as much as possible. The dead time start condition is:

\[ D_x = C_T \cdot L_R \cdot \delta_{i5} \cdot R_{ILx} \]  

(9)

4.3.2. **Emergency time.** At some time of the day, the actual power value will greatly exceed the planned value, which requires a lot of IL emergency compensation deviation. The starting conditions of emergency regulation area are:

\[ E = P_{DEV,\text{max~yday}} \cdot R_f \cdot X \]  

(10)

4.3.3. **Normal time.** The demand value of IL scheduling is modified to make the usage capacity and scheduling times of controlled IL meet the actual requirements. The starting conditions of the normal time is:

\[ D_x < N < E \]  

(11)

4.4. **Deviation compensation**

According to the DFT control requirements, it is necessary to input the power deviation in t period to calculate the IL capacity. The length of T is determined by the frequency band classification of IL and \( R_{MSE} \) standard. After a lot of experiments and simulations, it is most appropriate to take 15 minutes before the calculation point as the sampling interval. The sampling frequency is determined by the distribution network automation. The distribution network automation construction in China is relatively weak, and the level is uneven. This paper collects data every 1s.

Assuming the control system takes \( i \) time as the starting point, takes the unadjusted \( P_{DEV,i-15min} \) as the original data, uses DFT to convert it into frequency domain, and establishes the corresponding relationship with each frequency band in Table 1, then obtains the scheduling needs evaluation of all kinds of IL from Parsevals’ theorem, through the correction of three control thresholds:

\[ P_{R,i} = \sum P_{ILx} + C \]  

(12)

As a result, the compensation value \( P_{R,i} \) of the power \( P_{DEV,i} \) at time \( i \) can be obtained from the flow chart in Figure 1.

![Flow chart](image)

**Figure 1. Process to obtain the compensation value of the deviation**

4.5. **Control process**

With the standard of \( R_{MSE} \), the control process of interruptible load is illustrated in Figure 1.
The power deviation $P_{DEV}$ is calculated in real time according to the sampling time. The sampling time is 15 minutes before the control point. $S_{RMSE}$ and $L_{RMSE}$ are assessed every 15 minutes, and the contracted IL users are numbered.

Determine 3 control thresholds. Using DFT to calculate $P_{ILx}$ By missing roll.

- If $P_{ILx} > D$, the IL is not scheduled to suppress the power fluctuation.
- If $P_{DEV} > E$, the following rules are ignored: whether the evaluation standard is met; whether the correction conditions are met; scheduling IL compensation deviation.
- If $D < N < E$, the goal is: $P_{DEV}$ is as small as possible; meets the evaluation criteria; schedules IL according to the modified conditions.

According to 3 control thresholds, correct $P_{ILx}$ to $P_{R}$, compensate $P_{DEV}$, and make $P_{DEV}$ close to zero.

Scroll and mark the amount and times of IL used.

In addition to emergency regulation, each IL dispatch value recovers the economic operation value in batches every hour.

Verify the control effect of the whole day and set the control threshold of tomorrow’s control.

Figure 2. Control process of DFT based on $R_{MSE}$

5. Conclusions
With the deepening of power reform, the distribution network needs to develop auxiliary services to regulate load power with the integrated energy service system of multiple participation. Based on the method of statistical analysis, aiming at the demand of power market and combining with the characteristics of interruptible load, this paper puts forward the strategy of using DFT to control the distribution network interruptible load, integrating the interruptible load resources, dispatching different interruptible load to compensate the power shortage or absorb the excess power in a specific period of time, so as to reduce the power prediction deviation of the distribution network feeder and improve the service ability of the power selling enterprises.

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