Realize stable supply in the supply chain of distribution using power storage equipment when electricity demand is fluctuant

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Abstract

In some areas, personal demand for electricity power is small and rigid, and the load demand at different times is fluctuant. Thus， it is difficult to adjust demand fluctuations through pricing regulation at a local scale. The cost of power production would be significantly reduced if the demand becomes stable. In the view of system engineering, our research intends to make the supply chain for power distribution stable and optimized via using storage equipments in active distribution network. In this paper, we want to find a stable supply power load and appropriate capacity of the equipment. Power storage device serves as a warehouse, and the cost under three cases is discussed.

Keywords: load fluctuation, stable, system engineering, storage device, cost;

1. Introduction

Currently, smart grid has different meanings in different countries. Most countries and regions are making their own plans for electricity power development in accordance with the smart grid. China has proposed a three-stage plan to promote the construction of "strong and smart grid ". The first stage is the pilot phase (2009-2010), which focuses on "strong and smart grid” development and planning, the set of technical and management standards, and the development of critical technology and equipment. The second stage is the comprehensive construction phase (2011-2015), which focuses on speeding up the construction of the UHV power grid and the distribution network, initializing the smart grid system’s operation, and achieving major breakthroughs and applications of key technology and equipment. The last stage is for the full completion of the unified "strong and smart grid" technology and equipment, with the objective to achieve the international advanced level.

In the process of the smart grid construction, power grid building in rural areas is an important component of the China National Grid intelligence. Related data show that, the consumption of county level is over 52% of the social consumption, and the number is growing rapidly. In 2008, the number of rural electricity users came to 207 million. Power consumption in households was 90%, but the total electricity consumption for living accounted for only 18%[1]. It can be seen from the data that, the demand for electricity in rural areas is mainly in household consumption and the demand load for a single user is low. The demand of power in rural areas is mainly rigid (such as lighting) with very low price elasticity of demand. Therefore, it is difficult to adjust demand by means of pricing regulation.

As a monopoly company of power distribution, the state grid corporation rarely considers users’ satisfaction in rural areas. The phenomenon that electricity supply is interrupted at the peak of the power demand in some areas is still very often. It is hard for the management of power distribution. In the view of system engineering, we may find

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a way to solve the problem. Merrill M. Flood have said that the System Engineer has been using increasingly during the past decade—powerful techniques from science, mathematics, and economics in 1960[2].

As we all know, it can greatly reduce the cost of power production and the consumption of fossil energy, and make a great contribution to the environmental protecting when they supply a stable electricity load. However, the electricity demand is usually fluctuant. In other words, demand is fluctuant while supply is stable. We find the distribution networks are the key to solve the problem above in the view of system engineering. It may be able to solve this problem establishing a special active distribution network.

Active distribution network (ADN), is a network that has internal control for distributed or decentralized energy, and has a capacity of operation and control. One of the planning for Chinese smart grid is about smart distribution network, which is to improve the quality and reliability of supply, and to solve the problem of decentralized and small-capacity multi-access for energy[3].

It would become easier to adjust the local electricity demand fluctuation if access to a number of energy storage (such as rechargeable batteries) devices whiles the construction of distribution network. Traditional power system generator output follows the load changes, while the load of future power system can change to match generator generation to a large extent. A lot of research projects on smart grid discuss the active distribution network and related methods for optimization[4].

This study focuses on the simplified active distribution network with storage devices. We want to apply energy storage device in some areas (such as rural areas of economic backwardness in China and regions with rigid demand) to balance the fluctuations and the cost of device is discussed under three circumstances. .

The paper is organized as follows. The following section is about Literature Review describing the power load fluctuations and storage devices associated power distribution network. Section 3 describes a method to balance load and the cost is discussed. In section 4, we present main conclusions.

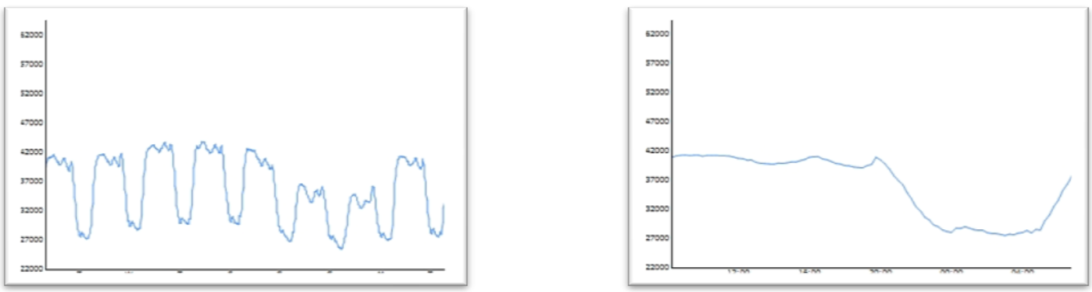

Fig.1 (a) Electricity demand – Last 7 Days; （b） Electricity demand - Last 24 Hours 2011.4.19

2. Literature reviews

2.1. Demand fluctuation

Many literatures have described the fluctuations of electricity demand. And demand fluctuations have two classes. One is the volatility of demand for power, and the other is the volatility for load. It is very easy to calculate the power demand while knowing the load requirements and the time. This paper referred to fluctuations is the load fluctuations in a given period.

In[5], they assume the duration of the planning horizon *T* periods; since the electricity demand at any point in a period may be uncertain. And power system load sequence is both volatile and has a special periodic[6]. So, average daily load was divided into four times: low time, morning peak time, flat time and evening peak time. For example four times were: 0:00~7:00, 8:00~12:00, 13:00~18:00, 18:00~23:00[7]. And the time of 24h in 1 day is divided into three times: peak, average, and low. An example is: 00:00~08:00 for the low load, 09:00~19: 00 for average load, and 20:00~24: 00 for the peak load[8]. The figure (Fig. 1) shows the total instantaneous MW demand being supplied across England, Wales and Scotland[9].

In[10], they approximate these demand functions by means of piecewise-linear functions (see Fig.2.a), and the accuracy of these approximations increases with the number of pieces. In this paper, we also simplified power demand curve (see Fig.1.b) in the same way, and an adequate accuracy of the approximation is between 2 and 4 pieces of a day.

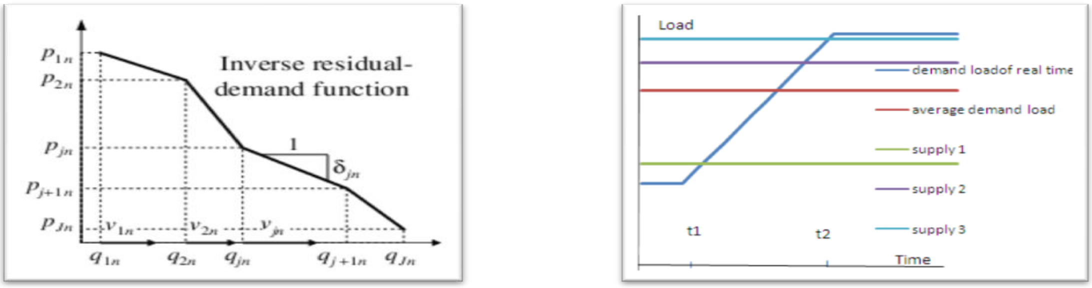

Fig.2 (a) Inverse residual-demand function; （b） Simplified demand fluctuations curve

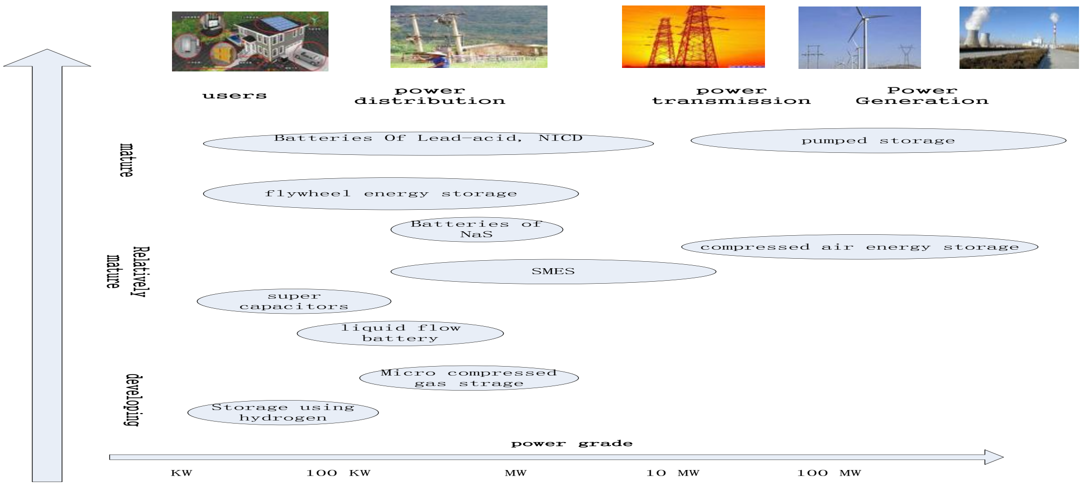

Fig.3 technical capability and commercial availability of energy storage types

2.2. Electricity power storage devices

With the improvement of interconnecting standards, it becomes easy for the various systems of power generation or energy storage to access to the grid. It can be also easily interconnected on between distributed generation (wind power, photovoltaic power) systems and energy storage systems (such as fuel cells, energy storage in hybrid vehicles) at all different levels, even these systems are different kinds or various capacities[11]. China has carried out a large number of basic researches on large-scale distributed energy storage device.

Electric energy storage technology will bring great changes for the scheduling and control of power system. With the application of energy storage system, we can effectively implement demand side management, and eliminate gap between the peak and valley of demand. And it is effective way to reduce power production cost, to increase the stability of power system, and to compensate load fluctuations.

Energy storage technology can be classified into four types (physical, electromagnetic, electrochemical, and phase change) according to its specific way of running. Physical storage technology includes pumped method, compressed air and flywheel energy storage; electromagnetic storage technology includes superconducting magnetic energy storage, super capacitors and high energy density capacitors; electrochemical energy storage includes lead-acid, nickel hydride, nickel cadmium, battery energy storage, etc.; phase change storage technology includes ice storage and so on. The fig (see Fig.3) shows the current levels of various energy storage technologies and their technical maturity in China[12].

3. A model to balance load of demand

3.1. Assumptions and model

This paper considers the electricity fluctuation in some regions. We assume that electricity power demand of a single user is small, one day is a period, the power demand of electricity consumption fluctuates with time in each period, and there are many users using active distribution network. So we simplify the fluctuations in active distribution networks as follows: fluctuations in demand consist of three parts: peak time, sustained changing time, and off-peak time; and the gaps between peak and trough are smaller than the average load (meaningful using storage equipment). Following [9], we assume that the demand function of the real-time load is linear. We study the situation of a period (i.e. one day), and get the demand curve for real-time load based on Figure 1. We set T as a period, real-time electricity demand load function ($r(t)$) is a function of time (t), then the power load function (r) can be formulated as (see Fig.2.b):

$$r(t)=\begin{cases} a & ; \quad t\in(0,t_1] \\ a+\dfrac{b-a}{t_2-t_1}(t-t_1) & ; \quad t\in(t_1,t_2) \\ b & ; \quad t\in[t_2,T] \\ a<b;t_1<t_2 & \end{cases} \tag{1}$$

We set a , b , t_1, t_2 and T constant. In this paper, we treat power storage equipment as a warehouse. Related parameters are defined as follows:

- *I* :maximum capacity of storage devices;
- C_1: unit cost of device operation per time when storing electricity power (We assume that there is no running cost of the discharge);
- C_2: unit cost of not meeting the demand at a certain time;
- C_3: fixed cost of the equipment;
- C_4: unit cost of untapped excess power;
- *C*: total cost of the storage device.

We divide the load of the real-time demand into two stages. It is in first stage when demand is less than supply; otherwise it is in the second stage. We set q^* as stable power supply load and define two stage power demand load function as follows:

$$q=\begin{cases} q_1(t) & (r<q^*) \quad t\in(0.t^*] \\ q_2(t) & (r\geq q^*) \quad t\in(t^*,T] \end{cases} \tag{2}$$

We get the relationship between q^* and t^* as follows by formulas *(1)* and *(2)*:

$$t^*=\frac{t_2-t_1}{b-a}(q^*-a)+t_1$$

(3)

Within the period T, we set $R(t)$ as electricity power demand function as follows:

$$R(t)=\int_0^t qdt=\int_0^t rdt \quad ;t\in(0,T] \qquad (4)$$

Due to our study fixed in a period T, The stored power must be depleted at the end of the second stage. Meanwhile, the electricity stored in the first stage cannot exceed the maximum capacity (I) of energy storage devices. Denote by S_1 and S_2 the power need to store in the first stage and the additional power in the second stage, respectively. Then we have:

$$S_1=\int_0^{t^*}(q^*-q_1)dt \quad ; \quad S_2=\int_{t^*}^{T}(q_2-q^*)dt \qquad (5)$$

3.2. Results and analysis

This study intends to find a stable load (q^*) and an appropriate capacity (I) of the storage device by analyzing the total cost with the application of the device.

Case one: meeting the needs of all users in the entire period while equipment capacity is large enough. It is obvious that we need:

$$R(T)\le q^*T \qquad (6)$$

Here, we set $I=S_1$ ($S_1\ge S_2$). Now we obtain the total cost as follows:

$C=C_1t^*+C_3+C_4(S_1-S_2)+pq^*T$

Substituting formula *(1), (3), (4)* and *(5)* to *(6)*, we discovered that C is an increasing function of q^*.So we take the minimum of q^* ($q^*T = R(T)$). The total cost contains the cost of operation when charging, fixed cost and purchasing cost in this circumstance. The results follow:

$$\begin{cases} q^*=b-\dfrac{t_1+t_2}{2T}(b-a) \\ t^*=t_2-\dfrac{t_2^2-t_1^2}{2T} \\ I=(b-a)(t_2+t_1)\dfrac{(2T-t_2)^2-t_1^2}{8T^2} \\ C=C_1t_2-C_1\dfrac{t_2^2-t_1^2}{2T}+C_3+pq^*T \end{cases}$$

Case two: meeting the demand in the second stage, while the capacity of device is fixed as I. Obviously, we have:

$$\cdot\begin{cases} I<(b-a)(t_2+t_1)\dfrac{(2T-t_2)^2-t_1^2}{8T^2} \\ q^*>b-\dfrac{t_1+t_2}{2T}(b-a) \end{cases}$$

Otherwise, it changes to case one. We set $I=S_2(S_1>S_2)$, and get the result as follows:

$$I=(b-q^*)\frac{2T-t_2-t^*}{2} \qquad (7)$$

So we get the stale load (q^*) by formula *(3)* and *(7)* if I was fixed:

$$\begin{cases} I = \frac{1}{2}[\frac{t_2 - t_1}{b-a}(q^* - a) + t_1 + t_2 - 2T](q^* - b) \\ q^* = \frac{at_2 - bt_1 + T(b-a) \pm \sqrt{2I(b-a)(t_2 - t_1) + (T - t_2)^2 (b-a)^2 + 2abt_1 t_2}}{t_2 - t_1} \end{cases}$$

In this case, we have to waste electricity in the second stage if meeting all the power demand. To simplify the study, we set storing time $t_0 \in (0, t_1]$ (there exists another circumstance ($t_{0\in}(t_{1,}t_2])$).And we get the formula:

$$I = (q^* - a)\, t_0 \qquad (8)$$

We want to find the best q^* via finding the minimum total cost, and the total cost is described as follows:

$$C = C_1 t_0 + C_3 + C_4 (S_1 - I) + pq0T \qquad (9)$$

Substituting formula *(3)*, *(5)* and *(8)* to *(9)*, and we get the derivative of q^*:

$$\frac{2dC}{dq^*} = C_1 \frac{t_2 - t_1}{b-a} + 2T(C_4 + p) - C_1(2T - t_1 - t_2)\frac{b-a}{(q^* - a)^2} \qquad (10)$$

We set the equation *(10)* zero and obtain the best C regardless whether it gets or not the minimum value at this point ,since there are many parameters. The results are described as follows:

$$\begin{cases} q^* = (b-a)\sqrt{\frac{C_1(2T - t_1 - t_2)}{C_1(t_2 - t_1) + 2T(C_4 + p)(b-a)}} + a \\ t^* = (t_2 - t_1)\sqrt{\frac{C_1(2T - t_1 - t_2)}{C_1(t_2 - t_1) + 2T(C_4 + p)(b-a)}} + t_1 \\ I = \frac{1}{2}[(t_2 - t_1)\sqrt{\frac{C_1(2T - t_1 - t_2)}{C_1(t_2 - t_1) + 2T(C_4 + p)(b-a)}} + (t_1 + t_2 - 2T)](\sqrt{\frac{C_1(2T - t_1 - t_2)}{C_1(t_2 - t_1) + 2T(C_4 + p)(b-a)}} - 1)(b-a) \end{cases}$$

Case three: partly meeting of the demand in the second stage with a certain fixed capacity *(I)* of storage device. In this circumstance we get the following constrain:

$$S2 - I > 0 \ ; \ S1 - I > 0 \qquad (11)$$

Otherwise, it changes to case two. In this circumstance the total cost describes as follows:

$$C = C_1 t_0 + C_2 (S_2 - I) + C_3 + C_4 (S_1 - I) + pq^* T \qquad (12)$$

In order to find the extreme value of the cost($C\ (q^*, I)$), we denote formula *(1)*, *(3)*, *(4)*, *(5)* and *(8)* to equation *(12)*, and make the partial derivatives for q^*, I zero:

$$\begin{cases} \frac{\partial C}{\partial q^*} = 0 \\ \frac{\partial C}{\partial I} = 0 \end{cases}$$

Then we obtain the best results for q^* and I described as follows:

$$\begin{cases} q^* = \frac{C_1}{(C_2 + C_4)} + a \\ I = \frac{C_1}{(C_2 + C_4)^2}(pT + t_1 C_2 + t_1 C_4 - TC_2 + C_1 \frac{t_2 - t_1}{b-a}) \end{cases}$$

We do not discuss the problems whether there exists the extreme value of the cost($C(q^*, I)$) in this case, because the results for q^* and I contain too many parameters. For other cases, they can be decomposed into the above three cases.

4. Main conclusion

This paper explores three cases using energy storage devices, and analyzes their cost structure and strategies of capacity and load in each case. From the perspective of cost, our study tries to find appropriate capacity (I) of the equipment and the supply load (q^*) in three different circumstances. It can significantly improve the capacity of control and initiative for active distribution networks, by the means of choosing different capacity and load. It may improve performance of the entire supply chain system for distribution when we use storage device on the local scale. If we can easily assume these parameters related to the cost of device, our study can greatly optimize power production and transmission, and bring resource conservation and great social and environmental benefits. The use of energy storage device in the future can also be combined with the micro-network technology to balance the load fluctuations. In this paper, demand function is got by simulated method which is not based on real-time electricity demand in rural areas of China, and the model does not use examples to illustrate whether the use of energy storage devices can achieve economic benefits. There will be the topic of future research.

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