Planning Method of Diffusion Capability for the Multiple Resources of User-side Including Distributed Photovoltaic Access

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Abstract. High penetration of distributed renewable energy is the trend of future power and energy systems. Under the background of retail electricity market reform, retail price mechanism is of great significance to facilitate large-scale integration and consumption of user-side renewable energies. Considering the adoption of renewable energy is essentially the diffusion process of technological innovation, we presented an evaluation method for measuring the diffusion capability of distributed photovoltaic with the retail price mechanism. Firstly, based on the residential double-step tariff structure, the decision models were proposed for energy transactions between retailers and customers using Ramsey pricing theory. Secondly, by introducing the methodology of system dynamics, the market feedback mechanism between the electricity price design and the integration capacity of distributed photovoltaic was analyzed, thus the evolutionary model of distributed photovoltaic dynamic diffusion under the price policy was established. Finally, the criterion of stable diffusion of distributed photovoltaic based on Lyapunov function was developed in this paper.

1. Introduction
The widely used net metering devices in smart grid environment provide technical support for evaluating the incentive effect of different tariff policies on users' access to distributed renewable energy. However, with the rapid growth of distributed renewable energy with net metering function and the users' access to renewable energy, the purchase of electricity from power suppliers could be reduced, and the income of power suppliers could also be reduced. In order to maintain the balance of revenue and expenditure, the electricity price increases, which forces more users to access renewable energy. The possibility of "death spiral" has been mentioned many times in [1]. With the application of new technologies such as photovoltaic and energy storage, the deteriorating business environment of electricity sellers will become more prominent. The short-term revenue impact of residential photovoltaic systems is evaluated on power users, retailers and network service providers [2]. The commercial photovoltaic devices are studied and analyzed with the impact of retail price on distributed photovoltaic access [3]. A recent empirical study abroad also shows that the dynamic price has a significant impact on the distributed photovoltaic access, and reveals that there is a feedback relationship between the distributed photovoltaic capacity and the retail price mechanism [4].
photovoltaic diffusion of New York city residents is analyzed with the interaction between retail price and photovoltaic access [5-6]. It can be seen that there is coupling effect and feedback effect between consumer demand with price elasticity and retail price mechanism. Considering that the diffusion of distributed renewable energy on the user side is a dynamic process that changes with time, it is necessary to evaluate the impact of price and key factors on the diffusion process of distributed renewable energy from the perspective of system evolution. Assuming that photovoltaic access does not have a negative impact on the safe and stable operation of the power grid, the Ramsey pricing principle is applied to build a decision-making model of electricity purchase and sale for consumers and power suppliers under the structure of double step tariff. Based on the market feedback mechanism of electricity price design and distributed photovoltaic access, considering the diffusion model which can describe the characteristics of photovoltaic investment return, the system evolution model of distributed photovoltaic dynamic diffusion guided by electricity price is established. On this basis, a stable diffusion criterion based on Lyapunov function is proposed to evaluate the impact of different market environment and price policies on users' decision to access distributed photovoltaic.

2. Retail price mechanism and photovoltaic diffusion model

2.1. Retail rate model

The electricity price rate model adopted in this paper is a two-part structure of electricity consumption cost and access cost, in which the electricity price is determined by double step pricing method, and the form of access cost is referred to [6].

\[ T_k = D_i + A \]  
\[ D_i = \left\{ \begin{array}{ll}
\pi_i d_i, d_i \in (0, d_s) \\
\pi_i d_s + \pi_2 (d_s - d_i), d_i \in (d_s, +\infty)
\end{array} \right. \]  

2.2. User decision model

It is assumed that the distributed photovoltaic system adopts the "self use" mode, and the average utilization hours are constant in cycle \( K \), and the subsidy form only considers the kilowatt hour subsidy of distributed photovoltaic power generation, and has a linear relationship with the power generation. In period \( K \), the surplus of user \( I \) is:

\[ D_i = \left\{ \begin{array}{l}
c_u(T_k, r_i) = U_i - T_k(d_i) + B_k \cdot x_{PV_i} - \xi_k r_i \\
d_i = q_i - x_{PV_i} \\
x_{PV_i} = r_i \cdot \eta \\
\eta = H \cdot P_{PV}^{sc} G_{PV} \left[ 1 + Z_{r_i} (W_{PV_i} - W_r) \right] / G_{sc}
\end{array} \right. \]  

2.3. Photovoltaic technology diffusion model

A universal bass diffusion model is able to describe the application and promotion process of a new technology through four coefficients: innovation coefficient, imitation coefficient, fitting coefficient and market potential. On this basis, the user side distributed photovoltaic technology diffusion model is established as:

\[ S(t) = MP \left( \frac{1 - e^{-(p+q)t}}{1 + \rho \cdot e^{-(p+q)t}} \right) \]  

in which the market potential (MP) can be given by:

\[ MP = R^{MS} e^{-a^{PR}} \]
3. Stable diffusion mechanism and dynamic evaluation

3.1. Market feedback mechanism and model

The market feedback mechanism of retail price design and distributed photovoltaic access capacity formation is shown in Figure 1. The mechanism takes the electricity price and distributed photovoltaic access capacity as state variables, comprehensively considers technological innovation, investment return, electricity seller's income and expenditure and current trading policies, and dynamically reflects the diffusion effect of consumer side distributed photovoltaic under the guidance of electricity price over time.

![Figure 1. Market feedback mechanism for distributed PV integration](image)

The system evolution model of distributed photovoltaic dynamic diffusion is established as follows:

\[
\begin{align*}
T_{k+1} &= \arg \max_{\{T_k, B_k, R_k\}} c(T_k, B_k, R_k) \\
R_{k+1} &= \left\{ \begin{array}{ll}
R_k, & S(t_{k+1}, R_{k+1}) < R_k \\
S(t_{k+1}, T_k, B_k), & \text{otherwise}
\end{array} \right.
\end{align*}
\]

(6)

The ratio of the annual maximum generation power of distributed photovoltaic to the annual maximum load of the city is used to represent the PV capacity penetration level in the grid:

\[
\epsilon_{CP} = \frac{P_{PV \max}}{\rho_{Load \max}} \times 100\%
\]

(7)

The maximum access capacity of distributed photovoltaic is:

\[
R_{\max} = \frac{P_{Load \max} \cdot \epsilon_{CP}}{P_{PV \max}}
\]

(8)

3.2. Stable diffusion and determination method

In order to analyze the stability of the user side distributed photovoltaic diffusion, its access process can be regarded as a dynamic evolution process of a nonlinear dynamic system. There are mainly indirect method and direct method to judge whether a dynamic system model is stable. The main idea of the indirect method is to find the analytical solution of the dynamic system by numerical iteration under the given initial value. Although this method is a common analysis method, it is too complex and time-consuming for complex dynamic system. The direct method does not need to solve the differential equation, but only needs to construct a special form of Lyapunov function. By judging the symbolic attribute of the function at the equilibrium point, the stability of the dynamic system can be determined. In this paper, the direct method is used to analyze the dynamic diffusion stability of distributed photovoltaic system:
The equilibrium point of distributed photovoltaic diffusion process is calculated by (7) which describes the dynamic system of distributed photovoltaic diffusion process.

(2) Lyapunov function is constructed. The Lyapunov function constructed in this paper is shown as:

$$V(\sigma) = \frac{MR^2}{2} - \frac{R^2}{k_o} \int S(T,R)dR$$

The first term on the right side of the equation is a constant term related to the market potential to ensure the positive definiteness of the constructor; the second term is the integral term, which indicates that the diffusion of distributed photovoltaic has path dependence on the S-shaped curve.

(3) Evaluate the limited access capacity of distributed photovoltaic. The limit access capacity is defined as:

$$R_p^m = MP \left[ \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} \cdot e^{-(p+q)t}} \right], t \to \infty$$

4. Conclusions
In this paper, the user side distributed photovoltaic technology diffusion capability is quantitatively evaluated, and the retail rate model, user decision model, power seller decision model and distributed photovoltaic technology diffusion model are constructed respectively. By constructing the market feedback mechanism of electricity price design and photovoltaic access, a distributed photovoltaic dynamic diffusion model guided by price strategy is established. The Lyapunov direct method is used to evaluate the stability of the dynamic diffusion of distributed photovoltaic system and obtain its maximum access capacity.

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