Power grid investment strategy and risk analysis under the reform of transmission and distribution price

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Abstract—Power grid investment is the prerequisite of power grid development, which is influenced by various uncertainties. Power system reform introduced the new transmission and distribution pricing mechanism, and changed grid companies' operation and profit model. The system dynamic model of grid investment is established, and grid investment variation tendency under the interaction with transmission and distribution price, demand, regulation and so on is analyzed. The investment risk with the uncertainty of demand, construction cost and regulation is analyzed using annual cash flow method. The sensitivity analysis of uncertain factors is made through simulation, and the model rationality is verified. Scenes are generated by combining different values of uncertain factors, the variance of annual cash flow at different scenes is calculated to access the risk.

Keywords—power grid investment, transmission and distribution price, system dynamics, risk analysis， annual cash flow

I. INTRODUCTION

Power grid investment is the basis and premise of the development of power grid. Reasonable grid investment strategy is the necessary guarantee for the safe and stable operation and healthy development of power grid[1]. The unreasonable planning and the uncertainty of electricity generation and consumption may lead to the inability to recover the investment cost and inhibit the investment company's willingness to invest. Therefore, at the same time of developing investment strategies for grid company, the government departments need to develop a reasonable regulatory system and effective incentive policies to ensure the orderly conduct of power grid. In 2015, a new round of power system reform began to implement[2]. The core of the reform is 'Open two heads and control intermediate' which implements the new transmission and distribution pricing mechanism and changes the grid operating mode and profitability. The internal mechanism of the impact of the new model on the investment planning of the grid needs to be analyzed in depth.

Power grid investment planning is a complex system involving load demand, grid capacity, transmission and distribution price and investment, and each link interacts with each other[3]. Based on the theory of system dynamics, this paper established the simulation model of transmission and distribution investment planning. System dynamics has been applied in the field of power system, including load forecast[4], planning evaluation[5], demand side response[6] and investment analysis[7]. Reference [8] studies on the macro-level grid planning, but the influencing factors of power grid investment is considered relatively simple. Reference [9] conducts multi-scenario simulation which takes into account the demand-side resources, government incentives and other factors, but there is no combination of different factors and investment risk problem.

According to the impact of transmission and distribution price on the power grid investment mechanism, this paper develops investment strategies and analyzes the power grid investment risk. The factors affecting the power grid investment are load demand, project cost and government regulation. Risk analysis methods are analytic hierarchy process[10], net present value method[11], sensitivity analysis method[12], real option method[13], risk value analysis [14] and other methods.

In this paper, system dynamics is used to analyze the trend of power grid investment in the new transmission and distribution price regulation mode. Then this paper analyzes the uncertain factors of the dynamic model of the power grid investment system and uses the annual cash flow method to analyze the power grid investment risk. And the method adopted in this paper is illustrated by an example. Finally, the suggestions of power grid investment are given. The innovation of this paper lies in the uncertainty of the factors such as load, government regulation and project cost in the system dynamics model, so as to establish a detailed system structure. The previous research only analyzes the power grid investment under the mode of buying and selling difference. This paper analyzes the investment risk under the new grid operation mode.

II. SYSTEM DYNAMICS MODEL OF POWER GRID INVESTMENT SYSTEM

System dynamics is a combination of system science theory and computer technology, which studies the feedback structure and behavior of the system[15]. It can reflect the dynamic trend of complex nonlinear time-varying systems under the interaction of internal factors.

The power grid investment planning system is a complex dynamic system. The growth of the load results in the increase of the grid capacity. The increase of the grid capacity leads to the increase of the effective assets of the power grid and the change of the operation, maintenance and loss cost of the network. The permitted cost and the transmission and distribution price will change. Changes in transmission and distribution price will affect the power grid companies' willing to invest. The selected system elements include load, transmission capacity, permitted income, transmission and distribution price. These factors constitute a number of feedback loops in the system dynamics model, and then form a dynamic system with self-organization, adaptability and feedback characteristics. The system mainly includes load growth link, investment planning link, transmission and distribution price link. Figure 1 shows the grid investment planning system stack flow chart, the specific mathematical model analysis is as follows.

A. Load grwoth link

The variables involved in the load growth link include load demand, load demand increment and load growth rate. The load demand increment is the product of the load growth rate and the previous year's load demand. Considering the actual situation of economic society and power grid development, the load demand increment gradually changes from high speed to low speed, and finally stabilizes, so this paper uses table function to express the trend of the load growth rate.

$$D(t) = D(t-1) + \Delta D(t) \quad (1)$$

$$\Delta D(t) = D(t-1) \bullet a \quad (2)$$

$$a = LOOKUP(Time) \quad (3)$$

Where, D(t)—the load demand of the t year; ΔD(t)—the load demand increment of the t year; a—the load growth rate; LOOKUP—the table function in the system dynamics, whose input and output is non-explicit function, but rather a curve; Time—the year.

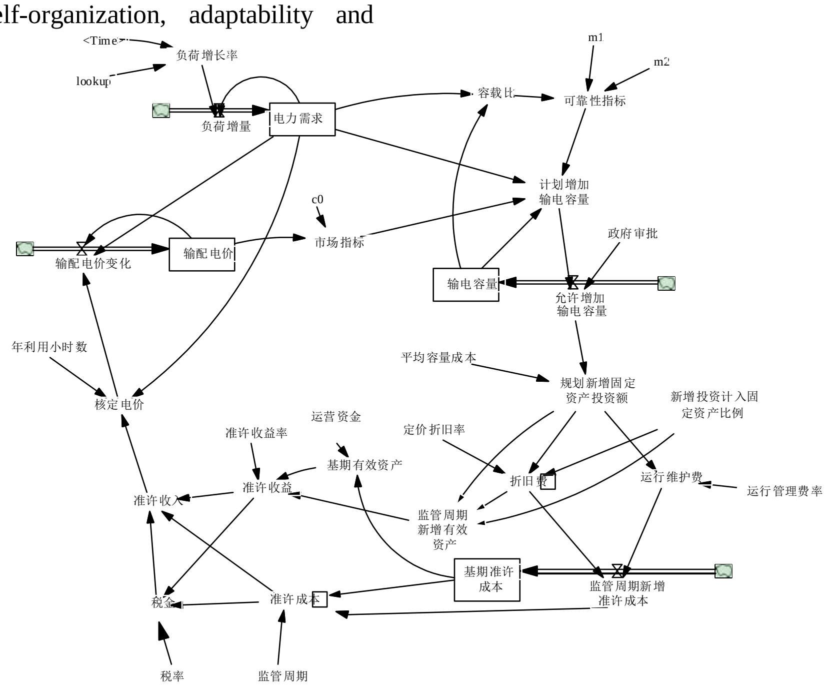

Figure 1 Power grid investment planning system stock and flow diagram

B. Load grwoth link

Developing power grid investment strategies should consider the two main factors: safety and stability requirements, market interest. First, with the load growth, in order to satisfy safety and stability requirements, the grid needs to maintain a certain capacity-load ratio, so the transmission capacity will increase correspondingly with the load growth. Second,, when the transmission and distribution price is low, the grid company will increase investment to increase the allowable income so that the transmission and distribution price is improved driven by market interest. This link represents the process of planning, government review and actual construction into use based on the reliability and market.

$$S(t) = S(t-1) + \Delta S_s(t) \quad (4)$$

$$\Delta S_s(t) = DELAY(\Delta S_y(t), T_c) \quad (5)$$

$$\Delta S_y(t) = \Delta S_j(t) \bullet b \quad (6)$$

$$\Delta S_j(t) = D(t) \bullet x + S(t) \bullet y \quad (7)$$

$$x = \begin{cases} (m_2 - m_s) / m_2, m_s \le m_1 \\ 0 \qquad\qquad , m_s > m_1 \end{cases} \quad (8)$$

$$m_s = S(t) / D(t) \quad (9)$$

$$y = \begin{cases} (c_0 - c) / c_0, c \le c_0 \\ 0 \qquad\qquad , c > c_0 \end{cases} \quad (10)$$

Where, S(t)—the transmission capacity of power grid at t year; ΔSs(t)—the actual increased transmission capacity; ΔSy(t)—the increased transmission capacity allowed by government; Tc—average programming construction cycle; DELAY()—the delay function of system dynamics; ΔSj(t) —the planning increased transmission capacity; x—the reliability signal which reflects the request of transmission reliability from load growth; ms—capacity ratio; [m1,m2] —the range of capacity ratio; y—market signal which reflects the impact of transmission and distribution price on investment willing; c—the transmission and distribution price; c0—the reference price;

C. Load grwoth link

According to the latest 'Provincial Power Transmission and Distribution Pricing Method' , transmission and distribution price is equal to the permitted income divided by the total electricity sales.

$$c(t) = c(t-1) + \Delta c(t) \quad (10)$$

$$\Delta c(t) = c_1(t) - c(t-1) \quad (11)$$

$$\text{s}\, c_1(t) = \frac{F_{all}(t)}{D(t) \cdot h} \quad (12)$$

$$F_{all}(t) = F_{\cos}(t) + F_{inc}(t) + F_{tax}(t) \quad (13)$$

$$F_{\cos}(t) = C_{allowj}(t) + C_{allowx}(t) \quad (14)$$

$$C_{allowj}(t) = C_{allowj}(t-1) + C_{allowx}(t) \quad (15)$$

$$C_{allowx}(t) = C_{dep}(t) + C_{opr}(t) \quad (16)$$

$$C_{dep}(t) = Inv_x(t) \cdot r(t) \cdot k_{dep} \quad (17)$$

$$C_{opr}(t) = Inv_x(t) \cdot k_{opr} \quad (18)$$

$$F_{inc}(t) = (A_j(t) + A_x(t)) \cdot k_p \quad (19)$$

$$A_j(t) = C_{allowj}(t) + C_{working}(t) \quad (20)$$

$$A_x(t) = Inv_x(t) \cdot r(t) - C_{dep}(t) \quad (21)$$

$$Inv_x(t) = \Delta S_s(t) \cdot Z_{cap}(t) \quad (21)$$

$$F_{tax}(t) = (F_{\cos}(t) + F_{inc}(t)) \cdot k_{tax} \quad (22)$$

C(t)—the transmission and distribution price; Δc(t) —the change of transmission and distribution price; c1(t)—calculated price; Fall(t)—the all allowed revenue; Fcos(t)—the allowed cost from project; Finc(t)—the allowed revenue from project; Ftax(t)—the tax cost; Callowj(t)—the base cost; Callowx(t)—Increased allowed cost in regulation cycle; Cdep(t—Depreciation Cost; Copr(t)—the operation and maintenance cost; Invx(t)—the planned increased investment on the fixed asset; r(t)—ratio of the new investment included in the fixed asset; kdep—pricing depreciation rate; kopr—operation and maintenance cost rate; Zcap(t)—unit capacity investment of grid; Aj(t) —effective base asset; Ax—increased effective asset; kp—allowed revenue rate; Cworking(t)—Operation capital; ktax—Comprehensive tax rate;

III. INVESTMENT RISK

A. Investment risk factors analysis

The power industry is a capital-intensive industry. The power grid construction has the characteristics of large investment scale, long construction period and long investment return period[16]. Because there are many uncertainties in the long payback period, grid investment is at risk of irrecoverable investment costs. Because there are many uncertainties in the long payback period, grid investment is at risk of irrecoverable investment costs. In the traditional purchase and selling price profit model, due to the uncertainty of Internet price and sales price, the grid companies can sometimes get higher profits, and sometimes there may exist the risk that investment costs can not be recovered. In the new operating mode, the cost-revenue control approach tries to make the grid company recover the cost, but it may also lead to excessive investment for power grid companies to increase the transmission and distribution price, thereby increasing the burden on users, so the government will conduct strict supervision on the investment.

The following uncertainties exist in the dynamic model of grid investment system:

(1) Uncertainty of load forecast

The investment plan of the power grid is based on the forecast of future load growth. The load growth is affected by factors such as the national economic development situation, demand side management and distributed power generation. There is a fluctuation in the overall development trend. If the forecast is high, it will cause over-investment and low equipment utilization. If the forecast is low, it will cause power supply requirements unsatisfied, power transmission equipment overload and even endanger system security.

(2) Uncertainty of engineering cost

The grid investment is determined according to the planning of the power grid expansion and transformation. The planning scheme should meet the technical standards such as safety, adequacy and line loss of power supply. Different standards will lead to the different selection of corresponding power transmission equipment, communication facilities, intelligence construction and other investment, thereby increasing the investment uncertainty.

(3) Uncertainty of government regulation policy

The supervision of the government is mainly reflected in the regulation of the level of transmission and distribution price and the supervision and approval of power grid construction projects. There exists uncertainty when the regulatory authority determines the effective assets of the grid company and the permitted rate of return. The valid assets identified may be deviated from the actual effective assets, resulting in the inability to recover the investment costs. In addition, the regulatory manages project approval to control the grid improper or excessive construction.

B. *Risk Evaluation*

This paper uses the annual cash flow as an indicator to measure the power grid investment and income. The annual cash flow is equal to the transmission service income minus the investment costs.

$$C.F. = c_y \cdot D_s \cdot h - \Delta S_s \cdot Z_{cap,s} \tag{23}$$

Where, C.F.—Annual cash flow; cy—Forecast transmission and distribution price; Ds—Actual load demand; hs—Actual load utilization hours; ΔSs—actual increased transmission capacity; Zcap,s—Actual unit capacity project cost;

Transmission and distribution price is calculated by the cost-revenue approach based on the forecast load demand and grid planning in the regulatory cycle. And due to the existence of the above uncertain factors, the estimated approved income are deviated from the actual construction investment requirements of the grid, so the actual income and allowable income is also biased.

The different uncertainties are set to different values, and the different scenarios are combined to simulate each scene by using the system dynamics model. Select the basic scene, use the transmission and distribution price of the basic scene as the transmission and distribution price as other scenes and get the annual cash flow time series. Calculate the standard deviation of all scenes as the indicator of the assessment of investment risk. The standard deviation is the ratio of the standard deviation to the mean, and the larger the standard deviation, the greater the risk.

IV. Case Study

A. *Analysis on Development Trend of Power Grid Investment*

A regional power grid consists of 220 / 110kV substation and 110kV lines. This paper ignores the cost of sharing from the higher power grid and calculates the price according to “Provincial Power Transmission and Distribution Pricing Method”. The initial transmission capacity of the grid is 200MW. The maximum power demand is 150MW. The capacity ratio ranges from 1.8 to 2.1. The equipment life is 25 years. The depreciation rate is 4% and this paper uses the straight-line depreciation method to calculate the depreciation rate. The operation and maintenance rate is 5%. Permitted allowance rate is 6% and the comprehensive tax rate is 17%. Vensim Software is used to simulate the power grid investment system.

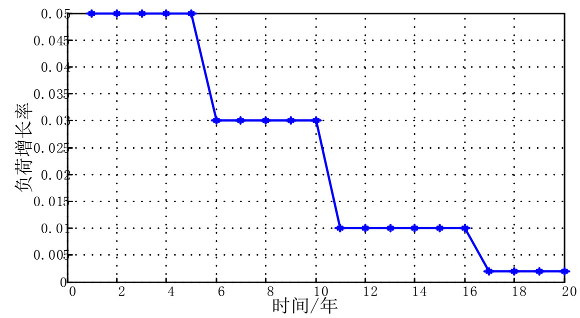

Figure 1 Load growth trend

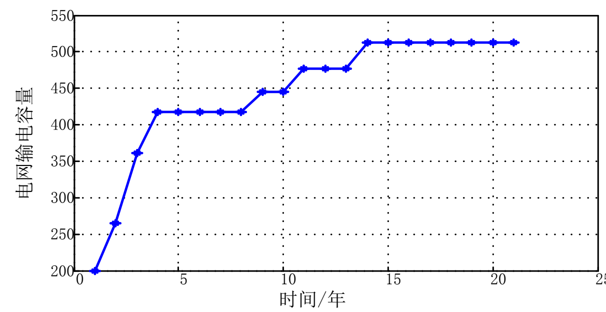

Figure 2 Power grid capacity change trend

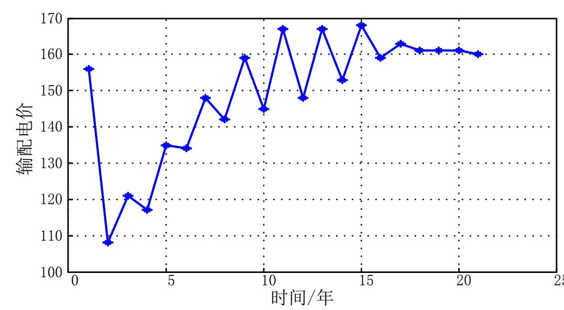

Figure 3 Transmission and distribution price change trend

From the above simulation results, in Figure 3 with the load growth, power transmission capacity has rapid growth at first and then stabilizes, which reflects the grid capacity’s characteristics of the ladder increase. The grid has a certain safe operation range and a complete power grid construction can make the system security margin greatly improved. When the security margin is close to the upper limit, then the next round of power grid construction will start. For Figure 4, the initial transmission and distribution price is determined before the reform. The transmission and distribution price falls a lot when the price is determined by the new approach. Then the power grid will raise the transmission and distribution price to increase revenue and investment. The result shows that the cost plus revenue policy can promote the power grid companies' investment to increase the power grid asset which can enhance their own income and play an effective incentive.

B. Sensitivity Analysis

The sensitivity analysis is an effective method to analyze the influence of the change of the parameters on the other variables in a certain range. Sensitivity analysis is an effective method to study the variation range and influence degree of the uncertainty factors. According to the above analysis, this paper conduct sensitivity analysis of load, project cost and government regulation to analyze the influence of these uncertain factors on power grid investment and transmission and distribution price. The unit cost of the project cost is set at 1.4 million yuan/MW, 1.7 million yuan/MW and 2 million yuan/MW. The load growth rate is adjusted to the load growth rate in Figure 2 multiplied by a coefficient with coefficients of 0.9, 1 and 1.1 respectively. Government allowance investment return is used to reflect the government regulation which is set as 4%, 7% and 10%.

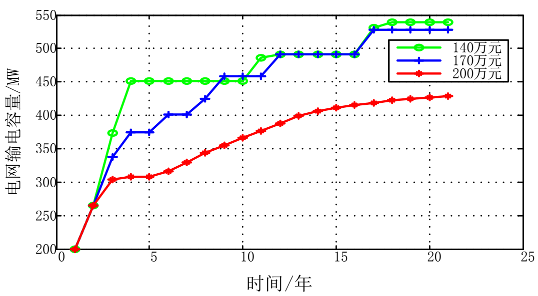

Figure 5(a) Grid capacity change trend with different construction cost

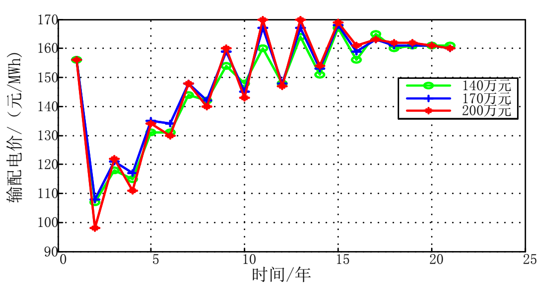

Figure 5(b) Transmission and distribution price change trend with different construction cost

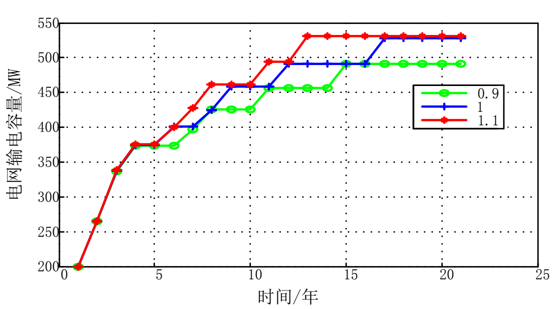

FIGURE 6(A) GRID CAPACITY CHANGE TREND WITH DIFFERENT LOAD GROWTH RATE

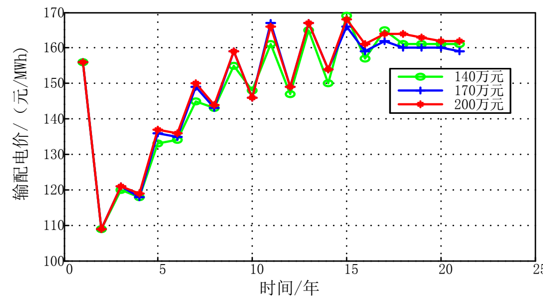

FIGURE 6(B) TRANSMISSION AND DISTRIBUTION PRICE CHANGE TREND WITH DIFFERENT LOAD GROWTH RATE

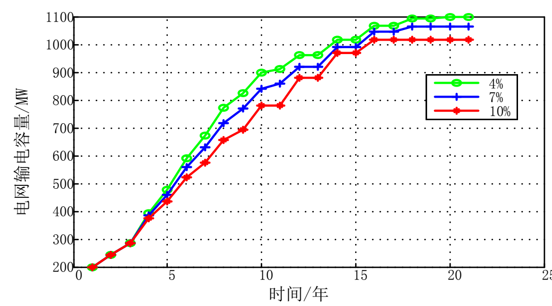

FIGURE 7(A) GRID CAPACITY CHANGE TREND WITH DIFFERENT ALLOWED YIELDS

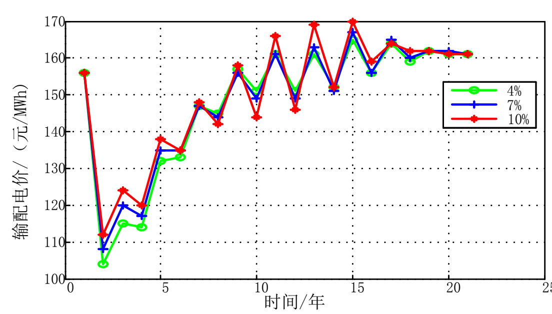

Figure 7(b) Transmission and distribution price change trend with different allowed yields

Figure 5 reflects the impact of different investment prices of unit capacity on transmission and distribution price and transmission capacity. Different investment prices of unit capacity reflect the difference between the line and transformer selection. The larger the capacity of the transformer and the better the quality of the line, the unit investment price, the value of the fixed assets and the transmission and distribution price is higher. High input brings the improvement of system reliability and reduces the capacity of investment correspondingly. Figure 6 reflects the impact of load growth rate on transmission and distribution price and transmission capacity. The greater the load growth rate, the need to increase the capacity of grid is more and corresponding transmission and distribution price is higher. Figure 7 reflects the impact of allowable revenue rate on transmission and distribution price and transmission capacity. The higher the revenue rate, the transmission and distribution price is higher. High revenue will result in the low willing of investment, so the transmission capacity will reduce. The above sensitivity analysis shows that three kinds of uncertain factors will affect the investment of power grid, and the change trend also proves that the system dynamics model established in this paper is reasonable.

C. Investment risk Analysis

Different values of load growth, project cost and government regulation are combined to get different scenes, and then this paper calculates the annual cash flow value in each scene. Three values of load growth, two values of project cost and two values of allowable revenue rates are combined to get 12 scenes as a basic scene.

TABLE Ⅰ RISK FACTORS COMBINATION OF SCENES

Scene	**Load Growth Rate**	**Project Cost(Million yuan/MW)**	**Allowance Revenue Rate**
One	1.1	1.7	10%
Two	1.1	1.7	7%
Three	1.1	1.4	10%
Four	1.1	1.4	7%
Five	1	1.7	10%
Six	1	1.7	7%
Seven	1	1.4	10%
Eight	1	1.4	7%
Nine	0.9	1.7	10%
Ten	0.9	1.7	7%
Eleven	0.9	1.4	10%
Twelve	0.9	1.4	7%

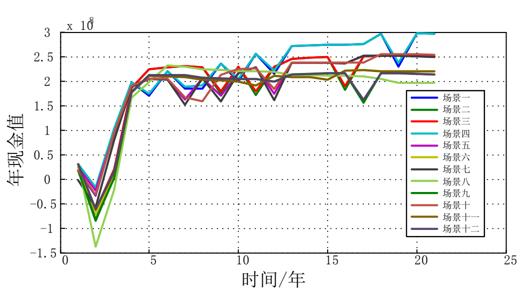

FIGURE 8 CHANGE TREND OF YEAR CASH FLOW UNDER DIFFERENT SCENES

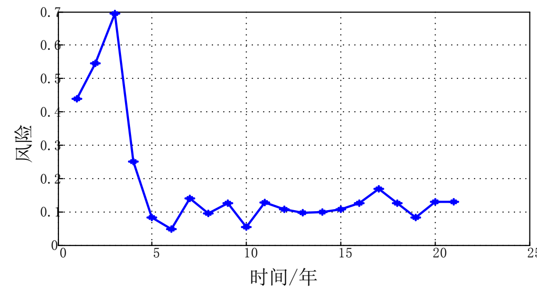

FIGURE 9 COEFFICIENT OF VARIANCE OF YEAR CASH FLOW

From the overall trend of annual cash flow, because of the low transmission and distribution price and high grid investment, the grid company's annual cash flow is negative. With the price adjusted, the grid investment tends to saturation and the annual cash flow becomes a positive value. The annual cash flow reflects the financial security status and the ability to invest continually of the grid company. This paper calculates the variance of the cash flow for 12 scenes each year to get the variance of the time series, as shown in Figure 9. It can be seen that in the period of rapid development of power grid, the variance of the cash flow is large. All kinds of uncertain factors will cause a great risk to investment, so the grid's company needs to develop a reasonable investment strategy. When the power grid matures, the cash flow variance is relatively small and the risk is small, so the grid company can recover the investment costs stably.

V. CONCLUSION

In this paper, the system dynamics model of power grid investment is established, through which the changing trend of grid investment and transmission and distribution price, load demand and government regulation is analyzed. This model comprehensively considers the relevant factors of power grid investment and can reflect the changing trend of power grid investment in the new operation mode. The sensitivity analysis of the uncertain factors such as load demand, project cost and government regulation is carried out through simulation which proves the effectiveness of the model and shows that the strategy of determining the investment capacity according to the security and price signal is reasonable. By calculating the standard rate of annual cash flow in each scene, it can be seen that the risks are different in different periods of power grid construction, especially in the period of rapid development of power grid, so it is necessary to strengthen the prevention and avoidance of investment risks.

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