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Review Article

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Review of the economics of distributed PV and its impacts on the grid

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ABSTRACT

Based on the introduction of the distributed PV concepts and principles, this paper focuses on the impacts on the grid of distributed photovoltaic power generation performance, and combes the literatures of the economy. Performance The impacts on the grid performance include aspects of voltage, island effect, photovoltaic efficiency and harmonics. In economic terms, this paper describes the models of different perspectives and scholars. This study hopes it can be helpful to other scholars in the study of distributed photovoltaic grid.

Keywords: Distributed photovoltaic power generation, Power performance, Economy, Review

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INTRODUCTION

Distributed PV is the system that transforms solar energy into electrical energy through a series of PV modules. Grid-connected PV system mainly consists of three parts, they are PV arrays, inverters, and other aspects of the grid[1].

As one kind of Distributed generation systems, the working principle of Distributed PV is scientific. In the sunlight, solar phalanxes emit DC current, then the inverter converts DC current to alternating current which can be directly used by appliances.While the system is connected to the big power grid, leading that the system can deliver the excess electricity to the big power grid during the day and absorb the inadequate electricity from the big grid[2].Currently, there are lots of articles studying distributed PV both at home and aboard. This paper firstly introduces the concepts and principles of distributed PV,then sorts out and analyzes the following points ,the performance of distributed PV on the grid and the economy of the system.That is to say,the paper summarizes the status of research in the field.

EXPERIMENTAL SECTION

Voltage Impact

Some scholars established a Matlab simulation model of distributed photovoltaic power connected to the grid, using the model to study the impacts of distributed PV on system voltage and voltage adjustment strategies[5]. STEMBER L H and others studied the effects on the voltage of distributed PV accessing into10kV distribution network at different locations, and also studied the aximum capacity can be accepted by the big grid, and lastly studied the measures to increase the capacity of photovoltaic power generation[6]. Conti S and others, from the perspective of power system voltage drop,studied the mechanism of impacts of one single photovoltaic connected into the big grid, and finally defined a formula to calculate the PV capacity connected into the big grid[7]. The classical model to study the influences of distributed PV on the voltage is as following[5-7].

(1) Before the PV accessing to the big grid, two adjacent load point voltage drop size is：
(2)

$$\Delta U_m = U_m - U_{m-1} = -\frac{\sum_{n=m}^{N} P_n R_m + \sum_{n=m}^{N} Q_n X_m}{U_{m-1}} = -\frac{\sum_{n=m}^{N} P_n r l_m + \sum_{n=m}^{N} Q_n x l_m}{U_{m-1}} \qquad (1)$$

Where, P_n, Q_n respectively represent the active and reactive power of the load point.As $P_n > 0, Q_n > 0$,we can easily get $\Delta U_m < 0$.

(3) After the PV accessing to the big grid, there are two cases to calculate the two adjacent load point voltage drop.One case is that the load point is behind the access point,that is to say，

$$\Delta U_m = U_m - U_{m-1} = -\frac{\left(\sum_{n=m}^{N} P_n - P_v\right) r l_m}{U_{m-1}} \qquad (2)$$

When $\sum_{n=m}^{N} P_n > P_v$,then $\Delta U_m < 0$;when $\sum_{n=m}^{N} P_n < P_v$,then $\Delta U_m > 0$ .The other case is that the load point is before the access point,that is to say, the load voltage of the m^{th} point is always less than the nth point($n = m - 1$),namely

$$\Delta U_m = U_m - U_{m-1} = \sum_{k=p+1}^{m-1} \frac{\sum_{n=k}^{N} P_n r l_k}{U_{k-1}} - \sum_{k=p+1}^{m} \frac{\sum_{n=k}^{N} P_n r l_k}{U_{k-1}} = -\frac{\sum_{n=m}^{N} P_n r l_k}{U_{m-1}} < 0 \qquad (3)$$

Based on the above model, there are scholars studying the voltage changes of the PV connected to the grid from the perspective of the grid voltage drop. Separately analyzed the impacts on voltage of single and multiple photovoltaic accessed to the big grid,then reaching the conlusion that line voltage would rise after the PV connected to the big grid,and got the various factors affecting the voltage[8].

The model is described as following. Before the PV accessing to the big grid, two adjacent load point voltage drop size is as stated above. After all PV connected to the grid, we can get:

$$U_m - U_{m-1} = \sum_{k=1}^{m-1} \frac{\sum_{n=k}^{N} (P_n - P_{Vn}) r l_k}{U_{k-1}} - \sum_{k=1}^{m} \frac{\sum_{n=k}^{N} (P_n - P_{Vn}) r l_k}{U_{k-1}} = -\frac{\sum_{n=m}^{N} (P_n - P_{Vn}) r l_k}{U_{m-1}} \qquad (4)$$

Where P_{Vn} represents the photovoltaic power generation capacity of the n^{th} user.If $\sum_{n=m}^{N} P_n > \sum_{n=m}^{N} P_{Vn}$,when the sum of the power of the loads behind the m^{th} access point(including m) is bigger than the whole power of all the loads,the voltage would reduce.Vice versa.

Aimed at the defect that the traditional decoupling control is sensitive to network parameters, Chen SY proposed an improved photovoltaic grid power control strategy,that is to control directly. This method takes into account the damping of RLC filter.The model in the paper is as following:

$$\begin{cases} P_2 = \frac{-U_2^2}{|Z_{12}|}\cos\phi_{12} - \frac{U_2^2}{Z_{20}}\cos\phi_{20} + \frac{m_\alpha U_{PV} U_2}{Z_{12}}\cos(\alpha-\phi_{12}) \\ Q_2 = \frac{-U_2^2}{|Z_{12}|}\sin\phi_{12} - \frac{U_2^2}{Z_{20}}\sin\phi_{20} + \frac{m_\alpha U_{PV} U_2}{Z_{12}}\sin(\alpha-\phi_{12}) \end{cases} \quad (5)$$

Where, U_{PV}, m_α, α respectively represent the output voltage of PV arraies, amplitude modulation ratio of PWM inverter and the phase shift angle. $P_2 + jQ_2$ represents the power injected. Ignore the power loss of the grid AC circuit and the power loss of the inverter. According to the instantaneous power balance and PWM principles,we can easily get the following: $P_2 \approx P_1 \approx P_{PV} = U_{PV} I_{PV}$.

Island Impact and Harmonics

BI Lei analysed the background and trends of distributed PV power system applications, discussed the various parts of its research status.And made the analysis and comparison about 'Solar Maximum Power Point Tracking'and 'Islanding Issues Prevent'[11].Li YQ studied the output characteristics of photovoltaic power generation system, providing an analytical model of photovoltaic power networks,getting the factors affecting the quality of the distribution network.The factors are as following:power injection changes, solar power factor and the short circuit capacity incorporated into the system.

Model is described as: When system power injected into the photovoltaic power changes,the current in line will produce a ΔI change.The voltage change value at the access point on the photovoltaic is:

$$\Delta U = (Rs + jXs)\cdot(\Delta Ip + j\Delta Iq) = |Zs|(\cos\phi + j\sin\phi)\cdot|\Delta I|(\cos\theta + j\sin\theta)$$
$$= \frac{U^2}{S_k}\cdot\frac{\Delta S}{U}\left[(\cos\phi\cos\theta - \sin\phi\sin\theta)\cdot j(\sin\phi\cos\theta + \cos\varphi\sin\theta)\right] \quad (6)$$

Where, ΔS represents the power changes. S_k represents the short-circuit capacity at the access point. $Zs = (Rs + jXs)$ represents equivalent impedance. ΔI represents the current change. θ represents the power factor angle. ϕ represents the grid impedance angle.

In this case the relative voltage change rate at the PCC is calculated as:

$$d = \frac{\Delta U}{U} = \frac{\Delta S\cos(\phi+\theta)}{S_k}\times 100\% \quad (7)$$

Zhou NC studied the micro-grid photovoltaic power access against the volatility of photovoltaic power.They used the AC-coupled configuration storage device to control the power fluctuations. Using the average power output of photovoltaic cells to determine the capacity of the energy storage device can effectively stabilize the power fluctuations and realize the power plug and play. Capacity energy storage device is described as:

$$\int_0^T P_s dt = \int_0^T P_c dt - \int_0^T P_{PV} dt = \max\left(\int_0^T P_{s-c}, \int_0^T P_{s-f}\right) = \max\left(\sum_{i=0}^{M}(P(m) - P_{opt})\frac{T}{N}, \sum_{i=0}^{M}(P_{opt} - P(k))\frac{T}{N}\right) \quad (8)$$

Where, P_{PV}, P_c respectively represent photovoltaic power generation and the total power output of the energy storage device. P_{opt} represents the average power exported. $\int_0^T P_{s-c}, \int_0^T P_{s-f}$ respectively represent the total charging energy and discharging energy of the energy storage device. After analys the formula,we can learn the acpacity of the energy storage device reach the minimum only if $P_c = P_{opt}$,then the output power of the energy storage device is a smoothing value.

WANG Baoshi and others used practical mathematical model to calculate the efficiency of the PV . In this model, we only need enter the four technical parameters,then we can get the I-U characteristic curve of the photovoltaic cell.The four parameters are short-circuit current, open circuit voltage, maximum power point current, maximum power point voltage[14].The model described in this paper is:

$$I = I_{sc}[1 - A(e^{U/(B\times U_{OC})}) - 1] \quad (9)$$

Where, A, B respectively represent intermediate parameters.

$$A = \left(1 - \frac{I_m}{I_s C}\right) e^{-U_m/(B\times U_{OC})}, B = \left(\frac{U_m}{U_{OC}} - 1\right)\left[\ln\left(1 - \frac{I_m}{I_{sc}}\right)\right] \quad (10)$$

Where, $I_{sc}, U_{OC}, I_m, U_m, P_m$ respectively represent short-circuit current, open circuit voltage, maximum power point current, maximum power point voltage.

Economic Impact

Ma SH integrated multiple indicators to establish a calculation model about grid-connected photovoltaic cost. The indicators are initial investment,annual operation and maintenance costs,wages welfare,equipment upgrades overhaul cost and so on.

Zeng Ming established two-factor model of learning curve on the basis of the Wright model of the learning curve.And studied the effects cumulative production of solar PV modules and the cumulative amount of R&D on PV costs.He forecast the ten years PV costs of our country based on the curve in the paper, getting a conclusion that the PV cost varies with the two factors changing. The model in the paper is as following.

$$C_t = C_0 Q^{-\alpha} R^{-\beta} \quad (11)$$

Where, C_t represents the PV cost,the unit is RMB/W . C_0 represents the initial cost. Q represents the cumulative production of the PV. R represents the cumulative amount of research and development. α represents the vector index of Q $(0 < \alpha < 1)$. β α represents the vector index of R $(0 < \beta < 1)$ .To calculate the historical data of the parameters in the model, we can get the following formula.

$$C_t = 399804.11754 Q^{-0.18458} R^{-0.334561} \quad (12)$$

Wang YL and others set t he calculation model of the cost of photovoltaic power generation set, and discussed the relationship between the factors of battery efficiency and cost of power generation. At last he got two conclusions. The first is that the photoelectric conversion efficiency is between 14% to 18%,and the second is that the photovoltaic power generation cost deduces by about 5% if the photoelectric conversion efficiency rises by 1%[26].The model in the paper is as following.

$$C = \frac{C_{kw} \times W_p + C_m \times n}{nhfw} \tag{13}$$

Where, C represents the cost of photovoltaic power generation, the unit is $RMB/kW \cdot h$. C_{kw} represents the cost of the operation and maintenance, the unit is RMB/a. n represents the running time of power plant. h represents the standard peak irradiation time, h/a. f represents the output power coefficient, $\%$. W represents the average power, kWp. W can be gotten by power attenuation coefficient $(\%/a)$.

Huo Molin developed the bottom-up model based on the whole life cycle cost structure. And analysed the fall potential of the cost of photovoltaic power generation of China in 2020 under the main driving factors,getting the conclusion that if the photovoltaic power generation cost reduces more, the scale of application and sustainable development will realize. Technological innovation can greatly contribute to PV cost. The model in the paper is as following.

$$LCOE = \frac{\sum_{t=1}^{t=N} \frac{O_t}{(1+d)^t} + I}{\sum_{t=1}^{t=N} \frac{O_t}{(1+d)^t}} \tag{14}$$

Where, $LCOE$ represents the discounted cost of power generation. N represents the life cycle of photovoltaic power generation system. I represents the initial investment cost. O_t represents the running and repairing cost. d represents the discount rate.

ZHONG Yu studied the cost compensation strategy of the grid connected photovoltaic government. He used the Bi level programming model to study the best ratio of cost compensation and the optimal number of grid connected power generat. The model in the paper is as following.

$$\begin{cases} C_i = c(w_i) \\ w_i = \left(c\left(\frac{Tp_0}{1-\rho} \right) \right)^{-1} \end{cases} \tag{15}$$

The following conclusion can be obtained by the marginal cost, namely $\rho \geq 1 - \frac{Tp_0}{c(w_0)}$.The model showed that the optimal scale of installed capacity is a function of ρ,which represents the proportion of compensation provided by the government. Where, w_i represents the installed capacity. p_0 represents the future average power price. T represents the average life expectancy of the project. ρ represents the proportion of compensation, and the value is $(0 < \rho < 1)$.

Shi Jun constructed the cost of photovoltaic power generation mathematical analysis model, and discussed the factors affecting the cost of PV electricity price. They are the installed cost, sunshine time, loan conditions, the expected recovery period of investment and operation cost etc. At last in the paper, he conducted the investment analysis on the investment of photovoltaic power generation at the present stage. The model in the paper is as following.

$$T_{\cos t} = (C_{ivs} / P_{er} + C_{ivs} \times R_{op} + C_{ivs} \times R_{loan} \times R_{\text{int} r} - I_{sub}) / (P \times H_{fp}) \quad (16)$$

Where, C_{ivs} represents the installed cost. P_{er} represents the payback period of investment. R_{op} represents the operating expense ratio. R_{loan} represents the ratio of loans to total amount of investment. $R_{\text{int} r}$ represents the loan interest rate. I_{sub} is the other income of power station. P is installed power. H_{fp} is power generation hours at full load.

RESULTS AND DISCUSSION

Summary

This paper summarizes the effect of distributed photovoltaic power generation on power system performance as well as its economic literature. The influence of photovoltaic power on the grid includes the influence on the performance of the voltage, islanding effect, photovoltaic efficiency, the harmonic influence and so on. There are many researches on the cost model. Some models are linear, while some are nonlinear. The former are easy, while the latter are complex. At last, this paper hopes the overview can do a favor for the other scholars.

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