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Research on Influence and Control of New Energy Access on Dynamic Stability of Power Grid

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Abstract. In order to solve the voltage instability problem under the influence of the increasing proportion of new energy in the receiving power grid and DC power outside the region, the research on the influence and control of new energy access on the dynamic stability of the power grid is put forward. Firstly, based on the improved small signal analysis method, the dynamic voltage stability model of the new energy receiving power grid is established. Then, considering the uncertainty of wind power, photovoltaic and load, aiming at the minimum total planning cost, a new energy receiving power network planning model considering dynamic voltage stability is established and solved. Finally, the simulation results show that the proposed new energy receiving power grid planning model can improve the receiving power grid's ability to accept future new energy and load uncertainty. The experimental results show that the configuration capacity of various types of equipment in the new energy receiving power grid has increased except for thermal power units, and the investment cost of scenario 2 has increased by 6.32% compared with scenario 1 in the planning period. Considering that the energy demand of wind power, photovoltaic output and load is uncertain, it will lead to the phenomenon of abandoning wind and light. In the second scenario, the energy storage system has a certain capacity margin, which can make full use of the efficient coordinated operation among energy storage, peak shaving units and controllable loads, reduce the energy purchase cost and improve the consumption of new energy. Therefore, the overall operating cost of the second scene is reduced by 51.42% compared with that of the first scene, and the overall wind rejection rate and light rejection rate are reduced by 62.76% and 64.01% respectively. Conclusion: This method can effectively reduce the risk of dynamic voltage instability of the receiving power grid.

Keywords. receiving power grid, Voltage stability, New energy, Energy storage, plan

1. Introduction

With the access of large-scale new energy stations, the emergence of various problems derived from itself has also brought great challenges to the power system [1]. Among them, the dynamic stability evaluation of power grid involves the phenomenon

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of low-frequency oscillation between generator sets, which has a negative impact on the operation of power system and restricts the power transmission between tie lines of power system. If it is not handled properly, it will have a strong impact on the stability of power system [2].

With the high proportion of new energy access, the dynamic stability of the power grid has been severely tested, so the power system has put forward higher standards for safety and reliability [3]. With the interconnection of various regions and the access of various dynamic components, the computational dimension of the dynamic model of power system has obviously increased, which also leads to the fact that the dynamic stability problem is a general differential algebraic problem in analysis, which also increases the difficulty of forecasting and analyzing the key parameters of large-scale power system [4]. In addition, in the case of high cost of new energy, how to analyze a large number of parameters of power grid efficiently and quickly is another problem faced by power system operation [5].

In recent years, due to the continuous rapid and substantial increase of new wind power projects and new photovoltaic installed capacity in China, the direct impact on the stability of the global power grid has been increasing [6]. The design of wind power system and some main power generation devices for dynamic power parameter transformation design of photovoltaic distributed generation need to be based on the fashionable power electronics technology, and the changes of small energy inertia characteristics of new energy units, the highly random changes and high fluctuations of system output changes will have a significant adverse impact on the stable and safe operation of the power grid [7].

2. Literature review

In order to speed up the realization of the "double carbon" goal, new energy power generation technologies, mainly wind power and photovoltaic, are developing rapidly. Considering the inverse distribution of new energy resources and loads, the country is building power grids with AC and DC transmission lines to improve the transmission capacity of new energy [8]. However, with the large-scale new energy grid connection, the large-scale development of load and the gradual increase of the proportion of DC power receiving outside the region, the voltage instability problem of heavy load nodes faced by the operation of the receiving power grid is becoming increasingly prominent, and it also has a certain impact on the power supply structure and energy supply mode of the receiving power grid, which brings more challenges to the further expansion planning of the receiving power grid [9]. Therefore, in order to solve the transient voltage stability problem of the receiving power grid, it is particularly important to fully consider the dynamic voltage stability state of load nodes and the uncertainty of wind power, photovoltaic and load in the receiving power grid, and realize the reasonable planning of the receiving power grid [10].

At present, relevant researchers at home and abroad have carried out more research on the expansion planning and construction of power grid with large-scale new energy access and the optimal configuration of various types of equipment. Shen, X and others consider using the segmented utilization characteristics of cascade hydropower stations to coordinate with wind and solar power sources, and put forward a coordinated expansion planning model of power system considering the opportunity constraint and the efficient complementary characteristics of wind, solar and water [11].

Lin, J and others consider that large-scale out-of-area calls will cause great changes in the grid structure and power supply structure of the receiving power grid, and construct a two-stage stochastic planning method for transmission network to improve the system operation economy, and propose an improved Benders algorithm considering multi-parameter scene clustering [12]. Dai, C and others analyzed the coupling relationship between transmission network and communication network, studied the negative impact of transmission network and communication network failure on users' electricity consumption, and established an extended planning model for the coordination of transmission and communication networks, which can improve the coping ability of the dual-network coupling system in extreme scenarios [13]. Huang, J and others studied the static and transient voltage stability mechanism of the AC-DC hybrid system with large-scale new energy access, and established the reactive power expansion planning method of the system from different aspects [14]. The above research provides some theoretical guidance for solving the planning problem of new energy receiving power grid considering dynamic voltage stability and the influence of new energy and load uncertainty, but there are still some problems to be solved in the existing literature: after new energy sources such as wind power and photovoltaic are connected to the receiving power grid on a large scale, not only the real-time uncertainty of power supply and load should be considered, but also the influence of various types of power supply and load uncertainty on the stable operation and expansion planning of the receiving power grid should be further considered [15]. Therefore, it is urgent to study how to fully consider the dynamic voltage stability of the receiving power grid under the large-scale new energy access, and bring the uncertainty of wind power, photovoltaic and load into the planning of the receiving power grid, so as to leave a certain margin for the development and construction of the receiving power grid in the future, enhance the power grid's acceptance of future new energy and load changes, and further realize the economy and rationality of the receiving power grid planning [16].

This paper presents a new energy receiving power grid planning model considering dynamic voltage stability. Based on the improved small signal analysis method, the dynamic voltage stability of new energy receiving power grid is studied. By analyzing the uncertainty of wind power, photovoltaic and load in the receiving power grid, considering the constraints such as investment quota, voltage stability of load nodes and load energy demand, and taking the minimum total planning cost including investment cost, maintenance cost, operation cost and treatment cost as the objective function, a new energy receiving power grid planning model and solution model considering dynamic voltage stability are established, and the effectiveness of the proposed model is verified by simulation.

3. Methods

3.1 Dynamic Voltage Stability Model of New Energy Receiving Power Grid

Under the large-scale new energy supply and DC power access outside the area, the load bus voltage instability occurs in the receiving terminal, and the stability of the load bus voltage is closely related to the dynamic characteristics of the load [17]. Therefore, this paper studies the voltage stability of the load nodes of the new energy receiving network under the condition of small interference. The first-order electromechanical transient induction motor with constant impedance in parallel is used to describe the load of the new energy receiving power grid. At a certain moment, the Thevenin equivalent is performed for the part from the load bus side to the receiving power grid side, E_1 is the equivalent potential, R_1+jX_1 is the equivalent impedance, k_q is the capacity conversion ratio, and G and B are the conductance and electricity of the static part of the load respectively. X_r is excitation reactance, S is slip, and r_2 and x_2 are rotor resistance and reactance of load dynamic model. Then the voltage stability state index I_U of the load node of the new energy receiving network can be expressed as:

$$I_U = \frac{\frac{dP_e}{ds}\Big|_{s=s_0} - \frac{dP_L}{ds}\Big|_{s=s_0}}{T_r} \quad (1)$$

Among them:

$$\begin{cases} \frac{dP_e}{ds}\Big|_{s=s_0} = r_2 k_q^2 E_{el}^2 \cdot \frac{r_2^2 k_q^2 - s_0^2\left[R_{el}^2 + (X_{el}+k_q x_2)^2\right]}{\left[(s_0 R_{el} + r_2 k_q)^2 + s_0^2 (X_{el}+k_q x_2)^2\right]^2} \\ \frac{dP_L}{ds}\Big|_{s=s_0} = - i_L k_L (1-n_L)(1-s_0)^{i_L-1} \end{cases} \quad (2)$$

Where: e_{el} -potential, v; P_L -load power, MW; K_L, I_L -load rate and load index; N_L —— the proportion of quantity independent of rotational speed; T_r -rotor inertia time constant; S_0 -initial value of state variable.

For the new energy receiving power grid planning problem, if the traditional small interference method is used for online calculation, there will be problems such as low calculation accuracy after linearizing the dynamic voltage of the system [18]. Therefore, in this paper, based on the improved small signal analysis method, E_{el} in equation (2) is replaced by the load node voltage U_i, which can keep some nonlinearity in the voltage stability state index of the load node, make the voltage follow the load change, and improve the calculation accuracy.

The improved voltage stability state index I_U' of the load node of the new energy receiving network can be expressed as:

$$I_U' = \frac{\frac{dP_{ei}}{ds}\Big|_{s=s_0} - \frac{dP_L}{ds}\Big|_{s=s_0}}{T_r} \quad (3)$$

Among them:

$$\frac{dP_{ei}}{ds}\Big|_{s=s_o} = r_2 k_q^2 U_i^2 \cdot \frac{r_2^2 k_q^2 - s_0^2\left[R_{el}^2 + (X_{el}+k_q x_2)^2\right]}{\left[(s_0 R_{el} + r_2 k_q)^2 + s_0^2 (X_{el}+k_q x_2)^2\right]^2} \quad (4)$$

3.2 Uncertainty model of wind, light and load in new energy receiving power grid

The construction period and commissioning date of newly-added wind power and photovoltaic power sources planned in the receiving power grid will be advanced or postponed due to various factors, and the available wind power and photovoltaic output and load energy demand in the power grid are uncertain due to the constraints of wind and solar energy resources in the planned area and the influence of load characteristics [19]. Therefore, in order to reduce the influence of uncertainty of wind power and photovoltaic output and load demand on the power grid planning of new energy receiving end, this paper constructs probability density functions g(h^{W}), g(h^{PV}) and g(E^{L}) of annual power generation hours and annual load demand of wind power and photovoltaic in the power grid of new energy receiving end respectively:

$$g(h^{W}) = \frac{a}{b}\left(\frac{h^{W}}{b}\right)^{b-1} \exp\left(-\frac{h^{W}}{b}\right)^{b} \tag{5}$$

$$\begin{cases} g(h^{PV}) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{h^{PV}}{8760}\right)^{\alpha-1}\left(1-\frac{h^{PV}}{8760}\right)^{\beta-1} \\ \alpha = \delta^{PV}\left[\frac{(1-\delta^{PV})\cdot\delta^{PV}}{(\varepsilon^{PV})^{2}} - 1\right] \\ \beta = \frac{(1-\delta^{PV})\cdot\alpha}{\delta^{PV}} \end{cases} \tag{6}$$

$$g(E^{L}) = \frac{1}{\sqrt{2\pi}\sigma^{L}} \exp\left(-\frac{(E^{L}-\bar{E}^{L})}{2(\sigma^{L})^{2}}\right) \tag{7}$$

Where: h^{W} and h^{PV} -annual utilization hours of wind power and photovoltaic, h; A, b—— shape parameters of Weibull distribution; Shape parameters of α, β-B distribution; δ^{PV}, ε^{PV} -the predicted mean and variance of solar irradiance, lx, lx^{2}; EL、$\bar{E}^{L}$—— Annual demand of load and its average value, MWh; σ^{L} -forecast variance of load, MWh.

Therefore, the annual total power generation P^{W} and P^{PV} of wind power and photovoltaic power in the new energy receiving power grid are respectively:

$$P^{W} = h^{W}\gamma^{W}E^{W} \tag{8}$$

$$P^{PV} = h^{PV}\gamma^{PV}E^{PV} \tag{9}$$

Where: γ^{W} and γ^{PV} -the minimum expansion planning unit capacity of wind power and photovoltaic, MW; E^{W} and E^{PV} —— Minimum expansion planning units for wind power and photovoltaic.

3.3 New Energy Receiving Power Grid Planning Model Considering Dynamic Voltage Stability

Wind power, photovoltaic and load are increasing under the background of new energy receiving power grid construction. In order to solve the transient voltage stability problem brought by large-scale new energy access to the receiving power grid, improve the receiving power grid's acceptance of future new energy and load development, realize the rational planning of the receiving power grid, and ensure the stable operation of the power grid, this paper comprehensively considers the constraints such as investment amount, voltage stability of load nodes, operation of various types of equipment, and load energy demand, and puts forward a new energy receiving power grid planning model with the goal of minimizing the total planning cost of the new energy receiving power grid.

In order to improve the economy of the new energy receiving power grid in the planning period, the objective function of this paper is to minimize the total planning cost f of the new energy receiving power grid in the planning period T, which consists of investment cost F_1, maintenance cost F_2, operation cost F_3 and treatment cost F_4:

$$\min F = \min(F_1 + F_2 + F_3 + F_4) \tag{10}$$

(1) investment cost F_1

$$\begin{cases} F_1 = \sum_{t=1}^{T} \varepsilon_t\left(C_{1,t}^{W} + C_{1,t}^{pv} + C_{1,t}^{Th} + C_{1,t}^{Es} + C_{1,t}^{Su}\right) \\ \varepsilon_t = (1+\varphi)^{-t} \end{cases} \tag{11}$$

Where: $C_{1,tW}$, $C_{1,tPV}$, $C_{1,tTh}$, $C_{1,tEs}$ and $c_{1,tSu}$ -investment cost of wind power, photovoltaic, thermal power unit, energy storage and transformer, ten thousand yuan; ε_t and φ-present value coefficient and discount rate.

$$\begin{cases} C_{1,t}^{W} = \frac{\varphi(1+\varphi)^{y^W}}{(1+\varphi)^{y^W}-1} \cdot c_1^{W}\gamma_t^{W}E^{W} \\ C_{1,t}^{PV} = \frac{\varphi(1+\varphi)}{(1+\varphi)^{y^{y^{2V}}}-1} c_1^{pV}\gamma_t^{PV}E^{pV} \\ C_{1,t}^{Th} = \frac{\varphi(1+\varphi)^{y^{yh}}}{(1+\varphi)^{y^h}-1} c_1^{Th}\gamma_t^{Th}E^{Th} \\ C_{1,t}^{Es^{Es}} = \frac{\varphi(1+\varphi)^{y^{Es}}}{(1+\varphi)^{y^{Es}}-1} c_1^{Es}\gamma_t^{E_s}E^{Ess} \\ C_{1,t}^{Su} = \frac{\varphi(1+\varphi)^{y^{su}}}{(1+\varphi)^{y^u}-1} c_1^{Su}\gamma_t^{Su}E^{Su} \end{cases} \tag{12}$$

Where: c_{1W}, c_{1PV}, c_{1Th}, c_{1Es} and c_{1Su} -unit investment cost of wind power, photovoltaic, thermal power unit, energy storage and transformer, ten thousand yuan /MW; E^W, E^{PV}, E^{Th}, E^{Es}, e^{Su} -the minimum expansion planning investment unit of various types of equipment, MW; γ_{tW}, γ_{tPV}, γ_{tTh}, γ_{tEs}, γ_{tSu} -the minimum number of investment units for expansion planning of various types of equipment; Y^W, y^{PV}, y^{Th}, y^{Es}, y^{Su} -the service life of various types of equipment, a.

(2) Maintenance cost F_2

$$\begin{aligned} F_2 &= \sum_{t=1}^{T} \varepsilon_t\left(C_{2,t}^{W} + C_{2,t}^{PV} + C_{2,t}^{Th} + C_{2,t}^{Es} + C_{2,t}^{Su}\right) \\ &= \sum_{t=1}^{T} \varepsilon_t\left(c_2^{W}\gamma_t^{W}\lambda_t^{W}E^{W}h_t^{W} + c_2^{PV}\gamma_t^{PV}\lambda_t^{PV}E^{PV}h_t^{PV} + \right. \\ &\quad c_2^{Th}\gamma_t^{Th}\lambda_t^{Th}E^{Th}h_t^{Th} + c_2^{Es}\gamma_t^{Es}\lambda_t^{Es}E^{Es}h_t^{Es} + \\ &\quad \left. c_2^{Su}\gamma_t^{Su}\lambda_t^{Su}E^{Su}h_t^{Su}\right) \end{aligned} \tag{13}$$

Where: $C_{2,tW}$, $C_{2,tPV}$, $C_{2,tTh}$, $C_{2,tEs}$ and $c_{2,tSu}$ -maintenance cost of wind power, photovoltaic, thermal power unit, energy storage and transformer in the planned period of the receiving power grid, RMB 10,000; C_{2W}, c_{2PV}, c_{2Th}, c_{2Es}, c_{2Su} -unit maintenance cost of various types of equipment, ten thousand yuan /MW; λ_{tW}, λ_{tPV}, λ_{tTh}, λ_{tEs}, λ_{tSu} -the construction status of various types of equipment, with 1 indicating that it has been put into construction and 0 indicating that it has not been put into construction; H_{tW}, h_{tPV}, h_{tTh}, h_{tEs}, h_{tSu} -utilization hours of various types of equipment, h.

(3) Operating cost F_3

$$F_3 = \sum_{t=1}^{T} \varepsilon_t\left(C_{3,t}^{Li} + C_{3,t}^{Co} + C_{3,t}^{buy}\right)$$
$$= \sum_{t=1}^{T} \varepsilon_t \left\{ c_3^{Li} \cdot \sum_{(ij)\in\Omega_t} \frac{R_{ij}\left[\left(P_{i,t}^{Li,loss}\right)^2 + \left(Q_{i,t}^{Li,loss}\right)^2\right]}{U_l^2} + c_3^{Co}\phi^{Co}\gamma_t^{Th}\lambda_t^{Th}E^{Th}h_t^{Th} + c_3^{buy}E_t^{buy} \right\} \quad (14)$$

Where: $C_{3,tLi}$, $C_{3,tCo}$ and $C_{3,tbuy}$ —— line operation loss cost, coal consumption cost and energy purchase cost of thermal power unit operation in the planned period of the receiving power grid, RMB 10,000; C_{3Li} -unit loss cost of the line, ten thousand yuan /MW; C_{3Co} -unit loss cost of coal consumption, ten thousand yuan /t; R_{ij} -resistance of line ij, ω; $P_{ij,tLi,loss}$ -active loss of line ij, MW; $Q_{ij,tLi,loss}$ -reactive loss of line ij, Mvar; Ω_l -line set; U_l -rated voltage of the line, v; ^{Co} —— coal consumption coefficient of thermal power unit operation; C_{3buy} -unit energy purchase cost, ten thousand yuan /MW; E_{tbuy} -total purchased energy, MWh.

(4) Equipment residual cost F_4

$$F_4 = \sum_{t=1}^{T} \varepsilon_t\left(C_{4,t}^{W} + C_{4,t}^{PV} + C_{4,t}^{Th} + C_{4,t}^{Es} + C_{4,t}^{Su}\right)$$
$$= \sum_{t=1}^{T} \varepsilon_t\left(c_4^{W}\gamma_t^{W}E^{W} + c_4^{PV}\gamma_t^{PV}E^{PV} + c_4^{Th}\gamma_t^{Th}E^{Th} + c_4^{Es}\gamma_t^{Es}E^{Es} + c_4^{Su}\gamma_t^{Su}E^{Su}\right) \quad (15)$$

Where: $C_{4,tW}$, $C_{4,tPV}$, $C_{4,tTh}$, $C_{4,tEs}$ and $c_{4,tSu}$ -residual cost of various types of equipment in the planned period of the receiving power grid, ten thousand yuan; C_{4W}, c_{4PV}, c_{4Th}, c_{4Es} and c_{4Su} —— converted cost of unit residual value of various types of equipment, ten thousand yuan /MW.

3.4 Example Simulation

Based on the actual operation data of wind power, photovoltaic and load in a new energy receiving power grid in a certain area, the IEEE38-node power system is used to simulate and verify the new energy receiving power grid planning model proposed in this paper, which includes 3 thermal power units, 2 wind power collection sources, 3 photovoltaic collection sources and 3 energy storage systems, and the load and 3 incoming calls outside the area are distributed in each node. The total planning period of the new energy receiving power grid is 10 years, the initial year is 2023, the maximum power load is 500MW, and the annual demand is 2.9×10^{6} MWh. Relevant parameters of various types of equipment are shown in Table 1. Relevant parameters of wind, light and load uncertainty model are shown in Table 2.

Table 1. Relevant parameters of various types of equipment

device type	Wind power	photovoltaics	Thermal power unit	accumulation energy	transformer
Unit investment cost/(ten thousand yuan /MW)	600	550	800	450	200
Unit maintenance cost/(ten thousand yuan /MW)	0.45	0.4	1.6	4.3	0.1
Minimum expansion planning unit /MW	10	10	10	10	5
Conversion coefficient of unit residual value	0.05	0.06	0.07	0.07	0.08
Life /a	20	20	20	10	20

Table 2. Relevant parameters of wind, light and load uncertainty model

parameter	value
a	5.5
b	1800
α	9
β	50
$\sigma^L/(10^6$ MWh)	2.465

4. Results and discussion

In order to verify the validity of the new energy receiving power grid planning model proposed in this paper considering dynamic voltage stability, the following two scenarios are set for comparative analysis.

Scenario 1: The traditional deterministic planning model of new energy receiving power grid is not considered, which is influenced by wind power, photovoltaic and load uncertainties and dynamic voltage stability constraints in the receiving power grid.

Scenario 2: Considering the influence of wind power, photovoltaic, load uncertainty and dynamic voltage stability constraints, that is, the new energy receiving-end power grid planning model considering dynamic voltage stability in this paper. The capacity planning results and planning cost comparison results of various types of equipment in the new energy receiving power grid under two scenarios are shown in Table 3 and Table 4 respectively. Considering that the energy demand of the load in the power grid of the new energy receiving end is fluctuating, and the output of wind power and photovoltaic is also obviously uncertain, when the energy demand of the load is low and the power generation output of wind power and photovoltaic is high, in order to avoid the damage caused by excessive electric energy to the power grid of the receiving end, the wind or light will be abandoned.

Table 3. Planning Results of Scenario 1 and Scenario 2

plan	Wind power	photovoltaics	Thermal power unit	accumulation energy	transformer
Scene 1	400	250	300	220	85
Scene 2	480	300	200	400	100

Table 4. Comparison Results of Planning Costs between Scenario 1 and Scenario 2

project	Scene 1	Scene 2
cost of investment	6.7235	7.1482
maintenance expense	0.5168	0.3826
running cost	0.6293	0.3057
Processing cost	-0.0026	-0.0053
Total planning cost	7.867	7.8312

Combined with the simulation results in Table 3 and Table 4, it can be seen that compared with Scenario 1, the configuration capacity of all types of equipment in the new energy receiving power grid in Scenario 2 has increased except thermal power units, and the investment cost in Scenario 2 has increased by 6.32% in the planning period. Considering that the energy demand of wind power, photovoltaic output and load is uncertain, it will lead to the phenomenon of abandoning wind and light. In the second scenario, the energy storage system has a certain capacity margin, which can make full use of the efficient coordinated operation among energy storage, peak shaving units and controllable loads, reduce the energy purchase cost and improve the consumption of new energy. Therefore, the overall operating cost of the second scene is reduced by 51.42% compared with that of the first scene, and the overall wind rejection rate and light rejection rate are reduced by 62.76% and 64.01% respectively.

5. Conclusion

In this paper, the influence and control of new energy access on the dynamic stability of power grid are studied. Considering the large-scale out-of-area calls and the increasingly prominent dynamic voltage instability of the receiving power grid after new energy access, a new energy receiving power grid planning model considering dynamic voltage stability is proposed and verified by an example simulation. Through the simulation and comparative analysis, it can be concluded that the new energy receiving power grid planning model, which fully considers the uncertainties of wind power, photovoltaic power generation and load demand, can bring the uncertainties of wind power, photovoltaic power and load into the receiving power grid planning, enhance the acceptance of new energy and load expansion in the future, improve the utilization rate of new energy, effectively reduce the risk of dynamic voltage instability of the receiving power grid, and further realize the economy and rationality of the receiving power grid planning.

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