Voltage Regulation Strategies for Photovoltaic Grid-Connected Systems Utilizing Electric Springs

Jun Liu, Quanhai Xu, Enzhong Wang, Tianchen Li and Guoliang Feng

Abstract—**The large-scale integration of distributed photovoltaic (PV) generation systems into distribution networks has increasingly highlighted the issue of voltage stability. Traditional voltage stability control strategies are limited in their ability to address the volatility and unpredictability inherent in renewable energy sources. Electric springs, as an innovative power compensation device, offer a novel approach to resolving voltage stability challenges through their unique energy buffering and regulation capabilities. This paper aims to propose an effective voltage stability control strategy by modeling and analyzing electric springs and their application in voltage stability control, thereby enhancing the reliability and quality of power supply in distribution networks. Furthermore, traditional radial-chord decoupling using PI controllers cannot dynamically adjust parameters. To overcome this limitation, adaptive fuzzy PID control technology is introduced to design an adaptive voltage stability control strategy, optimized using the whale algorithm. Simulation results and relevant metrics indicate that the proposed adaptive control strategy effectively maintains the stability of critical load voltages, demonstrating significant advantages.**

Index Terms—**Electric Spring; Voltage Stability Control; Fuzzy PID Control; Adaptive Control**

I. Introduction

To foster the global transition towards a green, low-carbon economy, optimizing energy consumption patterns and enhancing energy utilization efficiency can be adopted in constructing a clean, low-carbon energy system [1-3]. To adapt to the rapid development of economics, constructing a new type of power system has become an inevitable direction for development. This system, with clean energy as its core, possesses fundamental attributes such as cleanliness, low carbon emissions, safety, reliability, and high efficiency and flexibility. However, due to the inherent limitations of traditional power systems, they have not yet been able to fully address the many challenges brought about by the high proportion of new energy integration, widespread use of power electronic devices, and reduction of system moment of inertia [4-5]. In the widespread application of new energy generation methods such as wind and solar power, the inherent randomness, variability, and decentralization characteristics make the output on the power supply side more unstable [6-9]. The development of distributed photovoltaics also faces significant technical challenges. With a large number of distributed photovoltaic generation systems being connected to the end of the distribution grid, existing distribution grid planning and construction cannot meet the demands of large-scale photovoltaic grid connection. Traditional distribution grids, characterized by limited voltage regulation capabilities, poor economics, and low photovoltaic utilization rates, are no longer suitable for large-scale distributed photovoltaic grid connection [10-11]. On the other hand, the large-scale integration of photovoltaics will also have various impacts on the grid, such as the islanding effect, grid harmonic pollution, and increased grid energy losses. Changes in sunlight conditions can lead to significant fluctuations in output power, thereby affecting its stability [12-15]. Because of this, a deeper technical analysis of the integration of large-scale distributed photovoltaic systems into distribution networks plays a crucial role in promoting the rapid transformation of the energy structure [15-16].

The Electric Spring (ES) was proposed by Shu in 2012 and serves as a novel power compensation device [17]. It offers innovative solutions to address the challenges arising from the large-scale grid integration of distributed photovoltaic and other renewable energy sources. The Electric Spring technology subverts the traditional operation mode of power systems and proposes a new concept: to dynamically adjust the energy consumption of the load in the power grid with the change of new energy generation. This approach can effectively overcome the unpredictability of new energy generation, and improve the adaptability and overall stability of the power grid to new energy grid integration [18-21]. Electric Spring not only achieves local reactive power regulation but also provides the grid with more flexible adjustment mechanisms through dynamic load adjustments to accommodate the variability and uncertainty of renewable energy generation. Furthermore, Electric Spring technology, with its unique energy buffering and regulation capabilities, holds significant importance for optimizing grid operation modes. The potential value of Electric Spring technology in enhancing grid resilience, facilitating renewable energy integration, and optimizing power quality deserves further

Manuscript received November 3, 2024; revised February 23, 2025.

This work was supported by Research and Engineering Demonstration of Autonomous and Controllable Intelligent Control System for Ten Million Kilowatt Full Clean Energy Security (Grant no. CSIEKJ220700539).

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exploration. Further research is needed on its application prospects in promoting the development of smart grids, supporting the integration of distributed energy systems, and enhancing the sustainability of the power systems environment. In summary, with the continuous advancement of power electronics technology and the growing demands of power systems, research and application of reactive compensation technologies, especially novel power compensation devices such as Electric Spring, are gradually becoming a key research direction in the field of power systems. The development of these technologies not only meets current challenges in power systems but also provides new insights and solutions for the future development of the power grid.

The most widely used traditional control scheme for the first-generation Electric Spring is the dual loop PI control. This method employs two sets of PI controllers, an AC common point voltage controller and a DC voltage controller. This system is simple, easy to implement, and responds rapidly, but it can only achieve a single voltage stabilization target control [22]. Shuo et al. proposed a decoupling control method based on the second generation of Electric Spring, which achieves decoupling control of system current and can simultaneously control the stability of CL voltage and the power factor angle of intelligent load SL [23]. However, in practice, this decoupling control does not fully achieve the decoupling of power factor angle and CL voltage. MOK proposed a radial chord decoupling control method, namely the RCD method [24]. This decoupling method can achieve the decoupling of two components, but the ES regulation process depends on the implementation of energy storage components, and it is impossible to predict the working status of energy storage components, making the control process complex.

The overall classification of electric springs includes AC electric springs and DC electric springs [25-29]. AC electric springs are further divided into single-phase electric springs and three-phase electric springs. This article focuses on single-phase AC electric springs. In response to the inadequacy of the traditional radial-tangential decoupling method using PI controllers in dynamic parameter adjustment, adaptive fuzzy PID control technology is introduced to improve the adaptability and robustness of the system in the face of voltage fluctuations. The research findings will contribute to the advancement of Electric Spring technology in smart grids, and address a series of new challenges brought by the integration of large-scale photovoltaic power generation systems, particularly in terms of voltage stability.

The rest of this paper is organized as follows. Section 2 gives preliminaries of the Electric Spring model and Fuzzy PID controller. Section 3 presents the details of the proposed method. Section 4 shows the experiments of the proposed method. Finally, conclusions are given in Section 5.

II. Electric Spring Model

The circuit structure of the Electric Spring is shown in Figure 1. The symbols marked R_f, L_f, C_f, U_a in the figure respectively represent the resistance, inductance, capacitance of the output filter, and the non-critical load voltage. By applying the voltage law of Kirchhoff, the following results can be obtained:

$$u_a - u_{es} = L_f \frac{di_f}{dt} + R_f i_f \tag{1}$$

$$u_s = R_{nc} i_1 + u_{es} \tag{2}$$

where U_a represents the output voltage of the half-bridge inverter, U_{es} denotes the output voltage of the electric spring, i_f indicates the current on the filtering inductor, U_s represents the bus voltage of the AC system, R_{nc} represents the impedance value of non-critical loads, and finally i_1 denotes the current flowing through non-critical loads. By applying the Kirchhoff current law on the AC side, the following results can be obtained:

$$i_1 + i_f = C_f \frac{du_{es}}{dt} \tag{3}$$

$$u_a(t) = (\frac{V_{dc}}{2})PWM - \left(\frac{V_{dc}}{2}\right)\overline{PWM} \tag{4}$$

where V_{dc} is the DC side voltage of the inverter.

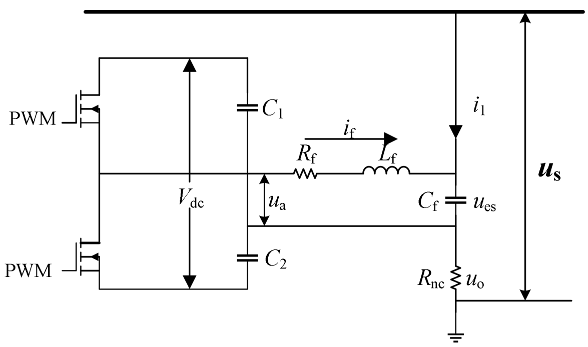

Fig. 1. The circuit structure of the electric spring.

By performing the Fourier transform on equation (4), the fundamental and harmonic components can be separated:

$$u_a(t) = u_{1a}(t) + \sum_{h=1}^{\infty} a_h \cos(\frac{2\pi h}{T_s}t) + b_h \sin(\frac{2\pi h}{T_s}t) \tag{5}$$

In equation (5), T_s represents the periodic on-off cycle of the switching device in the Electric Spring, h denotes the order of harmonics. The average output voltage of the inverter during a single switching cycle is calculated as follows:

$$\overline{u_a(t)} = \frac{1}{T_s}\int_0^{T_s} u_{1a}(t)dt + \sum_{h=1}^{\infty} a_h \cos(\frac{2\pi h}{T_s}t) + b_h \sin(\frac{2\pi h}{T_s}t) \tag{6}$$

In equation (6), the first part represents the average value of the fundamental frequency (50 Hz) within a single switching cycle. When the switching frequency significantly exceeds the fundamental frequency, this part can be regarded as the DC component. By substituting the expression of equation (6) into equation (1), equation (7) can be obtained.

$$L_f \frac{di_f}{dt} + R_f i_f = \frac{1}{T_s}\int_0^{T_s} u_{1a}(\tau)dt + \sum_{h=1}^{\infty} a_h \cos(\frac{2\pi h}{T_s}t) - u_{es} \tag{7}$$

Since the low-pass filter will remove the high-frequency components in the current, equation (7) can be simplified as follows:

$$L_f \frac{d\overline{i_f}}{dt} + R_f \overline{i_f} = \frac{1}{T_s}\int_0^{T_s} u_{1a}(\tau)d\tau - u_{es} \tag{8}$$

Therefore, the fundamental frequency voltage generated by the half-bridge inverter can be expressed as:

$$u_{1a}(t) = \frac{V_{dc}}{2} m(t) \tag{9}$$

where $\mathrm{m}(t) = M \sin(100\pi t + \theta)$

Assuming that the switching devices are lossless, the active power balance between the DC side and the AC side of the converter can be expressed as follows:

$$P_{dc} = \frac{1}{2}(\mathrm{C}_1 + C_2)\frac{d(V_{dc}^2)}{dt} = i_f^2 R_f \tag{10}$$

By combining equations (1) to (3), as well as equations (9) and (10), the state-space model of the constructed electric spring is formulated as follows:

$$\begin{aligned} \frac{di_f}{dt} &= -(\frac{R_f}{L_f})i_f + \frac{1}{2}(\frac{m}{L_f})V_{dc} - (\frac{1}{L_f})u_{es} \\ \frac{du_{es}}{dt} &= (\frac{1}{C_f})i_f + (\frac{1}{R_{nc}C_f})u_s - (\frac{1}{R_{nc}C_f})u_{es} \\ \frac{dV_{dc}}{dt} &= (\frac{R_f}{C_1 + C_2})(\frac{i_f^2}{V_{dc}}) \end{aligned} \tag{11}$$

By linearizing and ignoring the variation of DC voltage, a series of linear time-invariant equations can be obtained:

$$\begin{aligned} \frac{di_f}{dt} &= -(\frac{R_f}{L_f})i_f + \frac{1}{2}(\frac{m}{L_f})V_{dc} - (\frac{1}{L_f})u_{es} \\ \frac{du_{es}}{dt} &= (\frac{1}{C_f})i_f + (\frac{1}{R_{nc}C_f})u_s - (\frac{1}{R_{nc}C_f})u_{es} \end{aligned} \tag{12}$$

In the aforementioned derivation process, it is assumed that the DC side voltage remains stable and consistent with the reference voltage, and the directionality of the converters during the exchange of active power is disregarded, assuming that they have the same direction.

III. The Proposed Method

To realistically simulate the impact of grid-connected photovoltaic power generation systems on voltage, a mi-crogrid model is constructed in this paper. This model in-cludes a photovoltaic grid connection system, load, dis-tribution network, and Electric Spring. In this model, a battery pack is connected to the photovoltaic side to achieve the stable control of voltage. By setting up three different scenarios that closely approximate real grid-connected conditions, the simulation verified the feasibility and effectiveness of the voltage regulation strategy.

A. Construction of a photovoltaic grid-connected system with Electric Springs

Figure 2 illustrates the structure of a distributed photo-voltaic grid-connected system with electric springs. This structure includes the power source, line impedance, photovoltaic grid-connected system, and the Electric Spring.

The microgrid model includes the connection methods of photovoltaic arrays, grid-connected inverters, electric springs, and other necessary grid components. In the model, each photovoltaic generation unit is configured to simulate the output characteristics of actual photovoltaic panels, including the Maximum Power Point Tracking (MPPT) algorithm, to ensure that the photovoltaic array can work efficiently under varying light and temperature conditions.

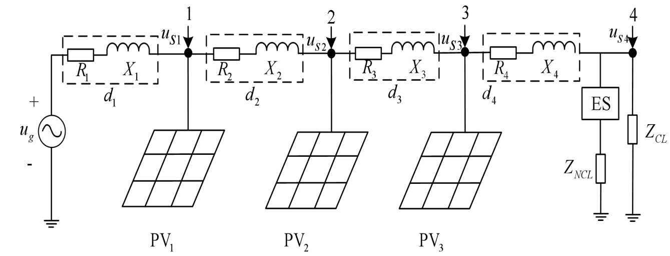

Fig. 2. Distributed photovoltaic grid-connected structure with electric spring.

B. Adaptive Fuzzy PID Stable Voltage Control Strategy

1) Fuzzy PID control strategy

When designing a fuzzy controller, the first step is to determine the fuzzy language variables and their corresponding domain range. In this paper, the deviation e, deviation change e_c, and PID parameters K_p, K_i, and K_d are chosen as the fuzzy linguistic variables, representing error, error change, and proportional integral derivative control parameters, respectively.

Figure 3 shows the structural diagram of the RCD control strategy based on fuzzy PID. The values K_p, K_i, and K_d calculated through fuzzy inference are put into the PID controller and combined with the classical PID control algorithm to generate a more accurate and adaptable control signal.

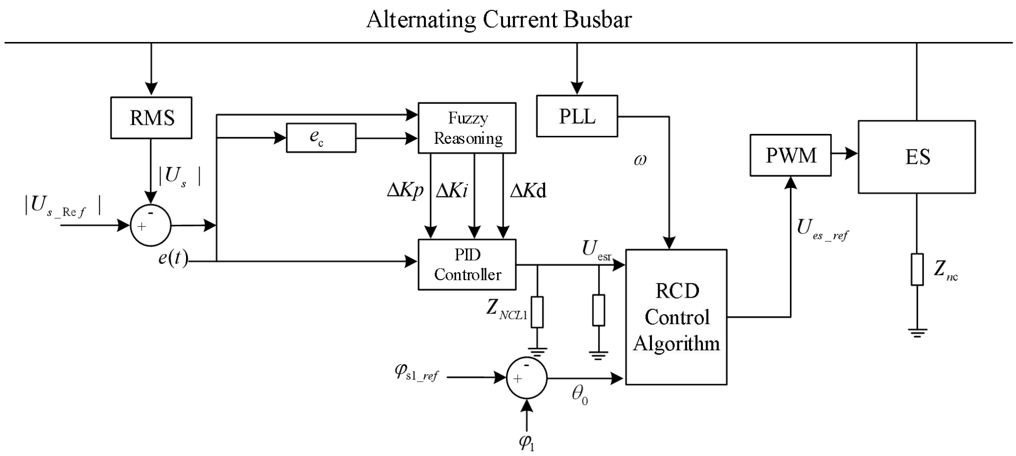

Fig. 3. RCD control strategy structure based on fuzzy PID..

The PID controller dynamically adjusts its proportional (P), integral (I), and derivative (D) gains based on the input fuzzy value to optimize the control of radial voltage.

Through this method, the PID controller can more accurately respond to voltage fluctuations and quickly adjust the voltage back to the set target value.

Finally, the output of the PID controller is utilized to drive the PWM signal, which controls the compensating voltage required for the output of the electric spring. By precisely controlling the charging and discharging processes of the electric spring, the radial voltage in the power grid can be effectively adjusted, thus the voltage can be maintained stability.

2) Adaptive fuzzy PID

Although fuzzy PID controllers can handle system un-certainties and nonlinear issues, their design process relies on expert knowledge and usually involves a large amount of parameter for adjustment and optimization. Addi-tionally, to maintain optimal performance in dynamically changing environments, fuzzy PID controllers need to integrate additional adaptive mechanisms. This article introduces an adaptive strategy to improve the perfor-mance of the algorithm. The whale optimization algorithm is used to adjust and optimize real-time PID parameters, especially when dealing with voltage fluctuations caused by renewable energy, an adaptive mechanism is intro-duced to make the RCD algorithm adapt to a wider range of environmental changes, to provide a more stable and reliable control strategy for power system.

By improving parameters through adaptive strategies and balancing the global search ability and local optimization ability of the algorithm, the convergence speed and optimization accuracy of the algorithm can be improved, which helps to overcome local optima and increase the control accuracy of PID control parameters.

During the simulation of whale hunting behavior, whales strategically move around potential prey. In this hypothetical model, if the position of a whale represents an optimal solution of the objective function, other whales will adjust their position to increase the likelihood of finding a better solution. The adjustment of positions is achieved through a specific calculation formula, which provides a detailed description of the rules for updating whale positions.

$$D = \left| C \bullet X^*(t) - X(t) \right| \tag{13}$$

$$X(t+1) = X^*(t) - A * D \tag{14}$$

where A and C represent vectors composed of coefficients, t denotes the current iterations. $X^*(t)$ represents the vector of the position of the whale with the highest fitness at a specific iteration time, $X(t)$ denotes the position vector of the specific whale in that iterations.

Furthermore, the specific values of A and C are determined by the following calculation formula:

$$A = 2a \bullet r - a \tag{15}$$

$$C = 2r \tag{16}$$

parameter a decreases linearly from an initial value of 2 to 0, r is a random variable vector between 0 and 1.

The process of improving adaptive parameters is as follows:

(1) Improvement of parameter a

In Equation (15), a is represented as:

$$a = 2 - t * (2 / Max\_iter) \tag{17}$$

Throughout the entire iteration process, a linearly decreases from 2 to 0. At the beginning of the algorithm, larger values are beneficial for exploration, but as a decreases, the algorithm may quickly shift towards exploiting local regions, ignoring the potential optimal solutions in wider areas. Simultaneously, there are shortcomings such as insufficient adaptability and lack of dynamic adjustment.

To improve a, a hyperbolic tangent function is introduced, employing a nonlinear decrease method based on the hyperbolic tangent function:

$$a = 2 - \tanh(sqrt(2 / pi) * (1 - (t / Max\_iter)^2) \tag{18}$$

By introducing the hyperbolic tangent function, the improved whale optimization algorithm adjusts the value of a in each iteration according to the current iteration count t and the maximum iterations Max_iter, making search agents more flexible and adaptive.

This nonlinear variation mode helps to avoid the premature convergence problems that may occur in standard WOA, as it can finely control the contraction and diffusion behaviors of search agents. Especially when dealing with optimization problems with complex search spaces and multiple local optima, the improved method can balance exploration and utilization more effectively, thereby increasing the probability of finding the global optimal solution.

(2) Setting the parameter $a2$

The auxiliary parameter $a2$ is introduced as follows:

$$a2 = -1 + t * ((-1) / Max\_iter) \tag{19}$$

where t represents the current number of iterations, Max_iter denotes the maximum number of iterations. This kind of linear reduction ensures that $a2$ gradually changes throughout the entire execution period of the algorithm. $a2$ linearly decreases from -1 to -2, participates in the calculation of the new position of the search agent along with parameter a. The change in $a2$ affects the movement strategy of search agents during the contraction process, especially in the later iterations of the algorithm. In adaptive optimization algorithms, the introduction of parameter $a2$ enhances the algorithm's search capability and provides a more dynamic mechanism for updating search agents. This design not only improves the convergence speed of the algorithm but also enhances its performance in solving complex optimization problems.

IV. Experiment

A. Setting experimental conditions

In the study of voltage stability in power systems, the voltage stability of critical loads is crucial. To deeply explore the influence of grid voltage U_g and electric spring U_es on the stability of critical load voltage, this paper sets three actual operating conditions for analysis. Condition 1: distributed photovoltaic grid connection condition. Condition 2: photovoltaic side fluctuation condition. Condition 3: simultaneous fluctuations on both photovoltaic and grid sides.

These conditions are shown in Table I:

TABLE I
UNITS FOR MAGNETIC PROPERTIES

	Photovoltaic connection time	Photovoltaic side fluctuation time	Grid side fluctuation time
Condition 1	access at 0.2s	no fluctuation	no fluctuation
Condition 2	access at initial moment	0.2s	no fluctuation
Condition 3	access at initial moment	0.2s	continuous fluctuation

B. Construction of simulation model

In order to deeply explore the performance of photovol-taic grid connected systems with electric springs in actual power systems. The model simulates a scenario in which multiple photovoltaic power generation units are con-nected to the grid in an actual power system. The con-struction fully considers the characteristics of photovol-taic power generation units and various situations that may be encountered during grid connection, aiming to provide a reliable test platform for the research on volt-age stability control of electric spring. The photovoltaic grid-connected unit continuously adjusts the DC side voltage of the grid-connected inverter through MPPT, so that the photovoltaic array always operates near its maximum power point. This ultimately achieves maxi-mum power grid connection.

1) Distributed photovoltaic grid connection condition

In this paper, to deeply analyze the impact of distributed photovoltaic system grid connection on the voltage sta-bility of microgrids, as well as the regulatory role of elec-tronic spring in this process, a model containing three photovoltaic grid-connected components was construct-ed. In the model, three photovoltaic grid-connected components were set up, each consisting of a photovol-taic array and a grid-connected inverter. To simulate real operating conditions, the input temperature was set to 25℃ and the light intensity was set to 1000 lux. During the model operation, the distributed photovoltaic system is connected to the microgrid system at the 0.2-second time point. During the grid connection process, the photovol-taic system injects power through nodes, thereby affect-ing the voltage of critical loads in the microgrid. In this condition, an electric spring was introduced, and two strategies, fuzzy PID control and adaptive control were adopted to observe their impact on the stability of critical load voltage.

Figure 4 shows the waveform of the critical load voltage with the adoption of fuzzy PID control and adaptive control strategies. It can be seen from the figure, that during 0-0.2 seconds, voltage fluctuates slightly around 220V. After the distributed photovoltaic integration at 0.2 seconds, the overshoot of adaptive control is smaller than that of fuzzy PID control. After the system stabilizes, both control strategies can stabilize the critical load voltage at about 220V, meeting the stable operation requirements of the microgrid. However, compared with the fuzzy PID control strategy, the adaptive control strategy shows better performance in maintaining voltage stability.

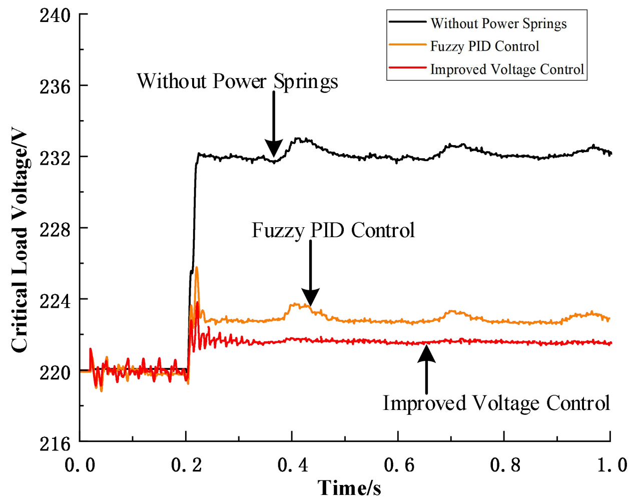

Fig. 4. Critical load voltages for different control strategies in Condition 1.

The Integral of Time multiplied by Absolute Error (ITAE) was introduced as an evaluation index. ITAE is a commonly used performance index for control systems, which can be used to evaluate the control quality and stability of the system. Figure 5 presents a comparison of ITAE metrics between fuzzy PID control and adaptive control strategies. According to the analysis of the ITAE index, it can be seen that compared with the fuzzy PID control strategy, the adaptive control strategy not only has faster convergence speed but also has better control precision. This means that the adaptive control strategy can adjust the critical load voltage to the target value in a shorter time and maintain small errors throughout the entire control process.

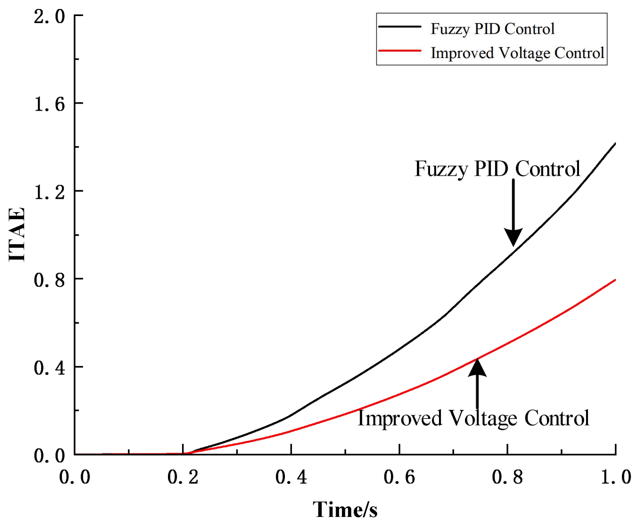

Fig. 5. ITAE of different control strategies in Condition 1.

Through simulation experiments and comparison of performance indexes, it can be concluded that under Condition 1, the adaptive control strategy possesses significant advantages over the fuzzy PID control strategy in maintaining the voltage stability of critical loads in the microgrid. The rapid response and high-precision control capability of the adaptive control strategy make it an effective tool for handling complex grid environments and voltage fluctuations.

2) Photovoltaic side fluctuations

In the study of this paper, the fluctuation on the photovoltaic side is a factor that can not be ignored. The output power of photovoltaic arrays is influenced by various environmental conditions, among which the changes in temperature and light intensity are the most important factors.

These environmental fluctuations may cause unstable fluctuations in the output voltage of photovoltaic arrays, thereby affecting the stability of critical load voltage in microgrid systems.

In the experiment, it is assumed that the distributed photovoltaic system is initially connected to the microgrid system, and the light intensity is reduced from 1000 lux to 500 lux at 0.2 seconds to simulate a decrease in light intensity, such as the appearance of cloud cover or other obstructions.

Figure 6 shows the waveform of critical load voltage with the adoption of fuzzy PID control and adaptive control strategies. It can be seen from the graph that from 0 to 0.2 seconds when the electric spring is not engaged, the critical load voltage deviates from the reference voltage by about 220V+12V. Due to the connection of the electric spring, both control strategies can reduce the voltage of critical load deviation to about +4V. At 0.2 seconds, the output power of distributed photovoltaic decreases， causing a decrease in the critical load voltage. Both control strategies compensate for the voltage by controlling the electric spring after the decrease in distributed photovoltaic output power. Therefore, after 0.2 seconds, the critical load stabilizes at around 220V, meeting the requirement for stable microgrid operation. It is worth noting that the adaptive control strategy performs better in maintaining voltage stability. it can more accurately respond to changes in the grid state and rapidly adjust the operation mode of the electric spring to maintain voltage stability.

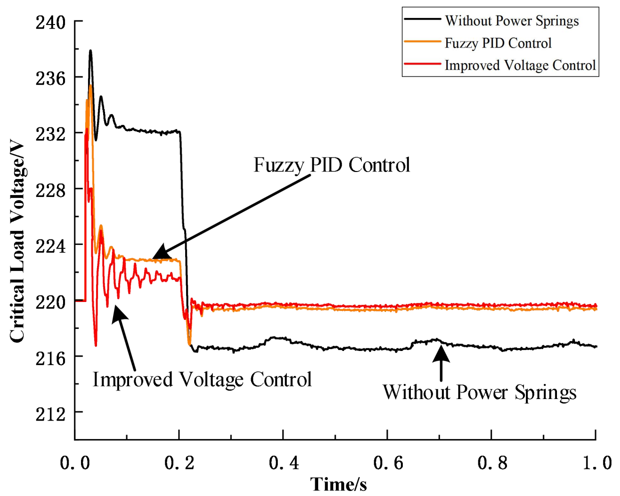

Fig. 6. Critical load voltages for different control strategies in Condition 2.

Figure 7 shows the comparison of ITAE index between fuzzy PID control and adaptive control strategies. According to the analysis of ITAE indicators, it can be observed that compared with the fuzzy PID control strategy, the adaptive control strategy not only has faster convergence speed, but also has better control precision. This means that the adaptive control strategy can adjust the critical load voltage to the target value in a shorter time and maintain small errors throughout the entire control process.

Through the above simulation experiments and comparison of performance metrics, it can be concluded that under Condition 2, the adaptive control strategy possesses significant advantages over the fuzzy PID control strategy in maintaining the stability of critical load voltage in microgrids.

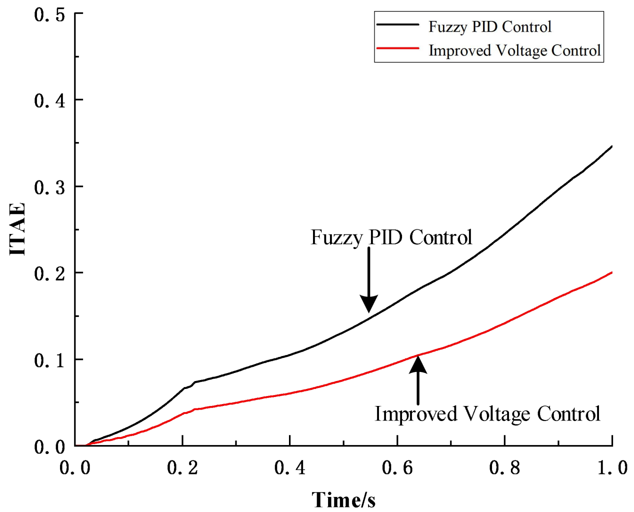

Fig. 7. ITAE of different control strategies in Condition 2.

3) Simultaneously fluctuating on both the photovoltaic and grid sides

Environmental factors such as temperature and light in-tensity can affect the output of photovoltaic arrays, while variations in grid loads, faults, or other external factors may cause fluctuations in grid voltage. In such cases, the role of electric spring becomes particularly cru-cial as they need to simultaneously address fluctuations on both the photovoltaic and grid sides to ensure the voltage stability of the microgrid.

This paper designed simulation experiments for Condition 3. Figure 8 illustrates the waveform of critical load voltage with the adoption of fuzzy PID control and adaptive control strategies.

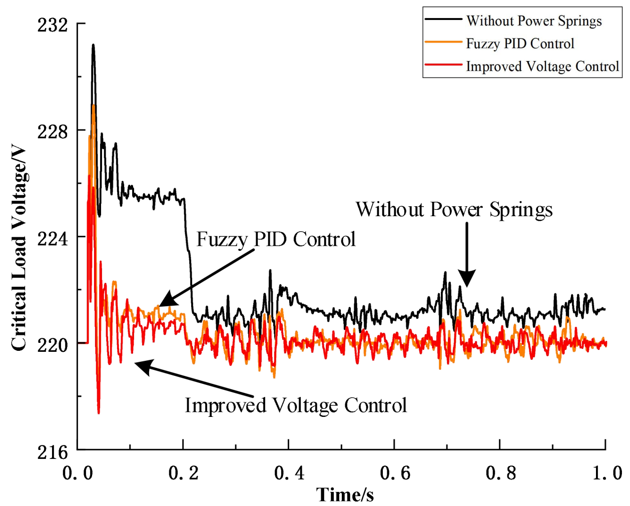

Fig. 8. Critical load voltages for different control strategies in Condition 3.

Due to grid side disturbances persisting throughout the entire period from 0 to 1 second, the waveform of the critical load voltage exhibits a fluctuating state. At 0.2 seconds, the decrease in output power of distributed photovoltaic resulted in varying degrees of decrease in critical load voltage. However, because of the timely connection of the electric spring, both voltage stabilization strategies achieve good voltage stabilization effects, and the voltage can be effectively maintained at a stable level.

As shown in Figure 9, the ITAE index of the adaptive control strategy is smaller than that of the fuzzy PID control strategy, which indicates that the adaptive control strategy has better effect in voltage stability control.

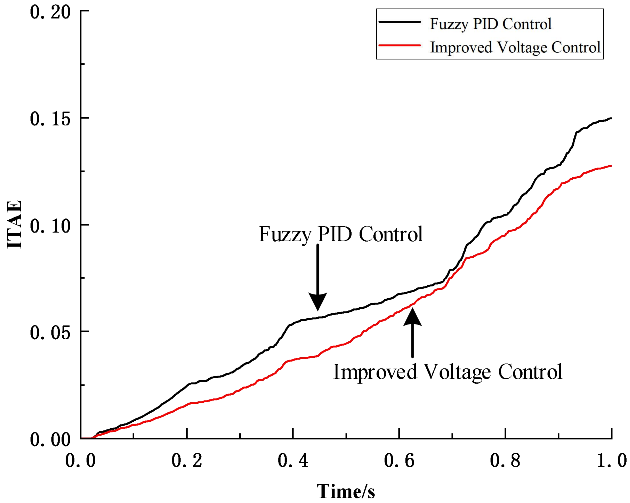

Fig. 9. ITAE of different control strategies in Condition 3.

C. Data summary

In this study, a series of simulation experiments were conducted to comprehensively evaluate the performance of different voltage stability control strategies, and the key performance indicators of these strategies were compared in Table II and Table III. This table provides a detailed list of the performance of the adaptive control strategy, fuzzy PID control strategy, and unconnected electric spring in terms of voltage deviation and standard deviation. Through comparative analysis, the adaptive control strategy demonstrates superiority in both key performance indicators.

TABLE II
COMPARISON OF CONTROL STRATEGY (DEVIATION VALUE)

	without Electric spring	fuzzy PID control	adaptive control
Condition 1	9.59	2.33	**1.31**
Condition 2	0.174	0.263	**0.111**
Condition 3	0.542	0.340	**0.197**

TABLE III
COMPARISON OF CONTROL STRATEGY (STANDARD DEVIATION)

	without Electric spring	fuzzy PID control	adaptive control
Condition 1	4.91	1.27	**0.71**
Condition 2	6.17	2.19	**1.37**
Condition 3	1.97	0.986	**0.711**

Taking into account the voltage deviation value, standard deviation, and ITAE index, it can be seen that the adaptive voltage stabilization strategy performs well in terms of control accuracy and steady-state error. This strategy not only responds quickly to changes in the power grid status but also maintains a small error over long-term operation, ensuring the stable operation of the power grid. It has important practical significance for designers and operators of power systems, providing an effective control strategy for improving the voltage stability of distribution networks. Future research can further optimize adaptive control strategies on this basis to adapt to a wider range of power grid operating conditions and more complex voltage fluctuations.

V. CONCLUSION

This paper deeply studied the voltage stabilization strategy based on Electric Spring in photovoltaic grid-connected systems, aiming to solve the voltage stability problem caused by distributed photovoltaics connected to the distribution network. A microgrid model was constructed to simulate the operation of PV grid-connected systems, loads, distribution networks, and electric springs to evaluate the performance of different control strategies under actual grid-connected conditions. In the model construction part, a microgrid model containing three photovoltaic grid-connected units was designed, and the output power variation of the photovoltaic grid-connected units was simulated by changing the light intensity. Each photovoltaic grid-connected unit is equipped with a maximum power point tracking algorithm to ensure that the photovoltaic array always operates near its maximum power point so that the maximum power grid connection can be achieved. Simulation results indicate that under distributed photovoltaic integration and photovoltaic side fluctuation conditions, compared with the fuzzy PID control strategy, the adaptive control strategy can more effectively maintain the stability of critical load voltages. Especially in the complex condition of simultaneous fluctuation on both the photovoltaic side and the grid side, the adaptive control strategy exhibits faster convergence speed and better control accuracy, thereby achieving more stable voltage output.

Future research can focus on the synergistic effect between Electric Spring and energy storage systems. By cooperating with energy storage systems, electric springs can participate more flexibly in demand-side management, such as storing energy when electricity prices are low and releasing energy when prices are high, thereby reducing overall energy costs.

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