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Article

Research on Voltage Stabilizing Control Strategy of Critical Load in Unplanned Island Based on Electric Spring

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Abstract: Aiming to solve the problem of voltage fluctuation of critical load caused by lack of control when an unplanned island occurs in a microgrid, a voltage stabilizing control strategy of critical load based on electric spring is proposed in this paper. When unplanned islanding occurs in a microgrid system, the system bus voltage fluctuates dramatically due to instantaneous power imbalance, compromising the power supply safety of important loads on the bus. In this paper, the electric spring control mode is integrated into the voltage stabilizing control strategy of critical loads in an unplanned island for the first time to realize the protection of critical loads. First of all, a model of an optical storage AC/DC hybrid microgrid is built, the overall system architecture is determined, and the microgrid is divided into four working states. Second, the working principle of electric spring is introduced, and a decoupling control strategy based on double closed loop is proposed. Finally, the experimental simulation of the proposed control strategy is experimentally simulated in Matlab/Simulink environment. The simulation findings show that when the bus voltage and current of microgrid change due to an unplanned island, the proposed control strategy based on electric spring may achieve the stability of voltage and current on critical loads.

Keywords: microgrid; unplanned island; electric spring; critical load; voltage stability

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1. Introduction

The essential components of a microgrid are DG (distributed generation), power exchange devices, load, and protective equipment. It is a small system integrating power generation, delivery, and consumption and allows for independent control [1]. The island phenomenon of microgrid is a new problem that has arisen in distribution network operation as a result of dispersed generation's large-scale access to the load side [2,3]. When the distribution network in the power supply area loses system power due to maintenance, system failure, lightning strike, natural disaster, or human operation, the distribution network is disconnected and no longer provides energy to the microgrid, whereas the power required for load operation in the microgrid system is continuously provided by its internal distributed power supply. Thus, it becomes a self-contained small power grid system [4].

In order to improve the adaptability of a microgrid to the distribution network and the power supply security of the system, the concept of "seamless switching" was proposed [5]. The concept emphasizes that the microgrid can perform reliably in both grid connected and island states, as well as transition between them effortlessly [6]. When the control approach is changed, the system is unable to produce substantial fluctuations [7]. However, when unplanned islanding occurs in the microgrid, seamless switching is difficult to execute, and the system experiences significant fluctuations [8]. For the control problem of unplanned islanding, different scholars have come up with their unique solutions [9–13]. Zhong Cheng et al. proposed adopting P-σ, Q-V decoupling nonlinear control to realize direct voltage limiting during out of control phases and solved the problem of local load voltage and frequency out of limit caused by unplanned events [10]; Tongwen Wang et al. analyzed the mechanism of micro grid islanding based on the case of unplanned islanding in a primary distribution network, and evaluated and analyzed the applicability of passive anti islanding protection based on voltage and frequency detection [11].

The most common control approach is centralized voltage regulation, and the controller is in charge of the entire microgrid system under this control technique [14]. However, as the microgrid evolves toward downsizing, regionalization, and intelligence, the centralized voltage regulation mode will be unable to meet people's requirements in a gradual manner since it will be unable to differentially control each load under varying operating conditions [15]. The proposal of ES (electric spring) is a novel method to make a microgrid intelligent [16]. With the continuous deepening of the theoretical research on electric spring, different research results based on electric spring have been published [17–31]. Yin Fagen, Wang Chun et al. studied several typical topologies of electric spring and proposed three new electric spring topologies from the perspective of improving the voltage performance of non-critical loads [17]. In order to stabilize the load voltage and its power factor, Liu Xunyu et al. proposed a load voltage control method based on ES to suppress the voltage and power fluctuation of photovoltaic parallel nodes [18]; N. R. Chaudhuri, C.K. Lee et al. studied the performance of the electric spring under different load power factors and the proportion of critical load and non-critical load after the electric spring is connected to the distribution network. The simulation findings reveal when the proportion of noncritical load increases, the electric spring's regulating impact improves [19]. According to passive control theory, Bao Keqin analyzed the passivity and stability of the mathematical model of electric spring system and proposed the passive control strategy [20]; experiments by X Luo, Z. Akhtar et al. showed that multiple power springs have superior voltage regulation ability than a traditional synchronous compensator [21]. Fang Le et al. proposed an improved droop control strategy based on real-time parameter correction to solve the problem that the traditional droop control of single-phase multi electric spring cannot obtain stable voltage and frequency during control coupling [22]. The electric spring has also been proven to improve the power quality and help with voltage regulation [23–26], frequency regulation [27,28], power factor regulation [29], and reducing harmonic distortion [30]. At the same time, it can lower microgrid operation costs, achieve power supply and demand balance [31], and reduce the energy storage demand of power grid [32].

In this paper, a voltage stabilizing control strategy based on electric spring is proposed, which is based on the basic function of electric spring [16,23–26] to ensure the stable operation of critical loads. It is aimed at the fluctuation of critical loads caused by an out-of-control state in an unplanned island of a microgrid. For the first time, the control mode of electric spring is introduced into the system control in an unplanned island, ensuring the voltage stability of critical load in the out-of-control state.

The main contents of this paper are as follows:

1. We built an AC/DC hybrid microgrid, established a grid connected inverter model, realized the connection between microgrid and distribution network, and enabled the microgrid to switch seamlessly between grid connected and off grid states.
2. We briefly introduce the basic principle and working state of electric spring.
3. A three-phase electric spring was constructed using the basic idea of an electric spring, and a decoupling control method based on a double closed loop is provided.
4. The electric spring simulation model and microgrid parallel/off grid switching simulation model were built with MATLAB/Simulink simulation software, and they were integrated to verify that the proposed control strategy based on electric spring can ensure the voltage stability of critical loads when an unplanned island occurs in the microgrid. The simulation findings show that when an unplanned island occurs in the microgrid, the microgrid power is insufficient or overflows owing to the offline distribution network, the bus voltage changes, and the voltage at the main load changes as a result of the bus voltage. The electric spring balances the voltage and current at the critical load, ensuring the critical load's stable operation.

The overall structure of the paper is shown in Figure 1.

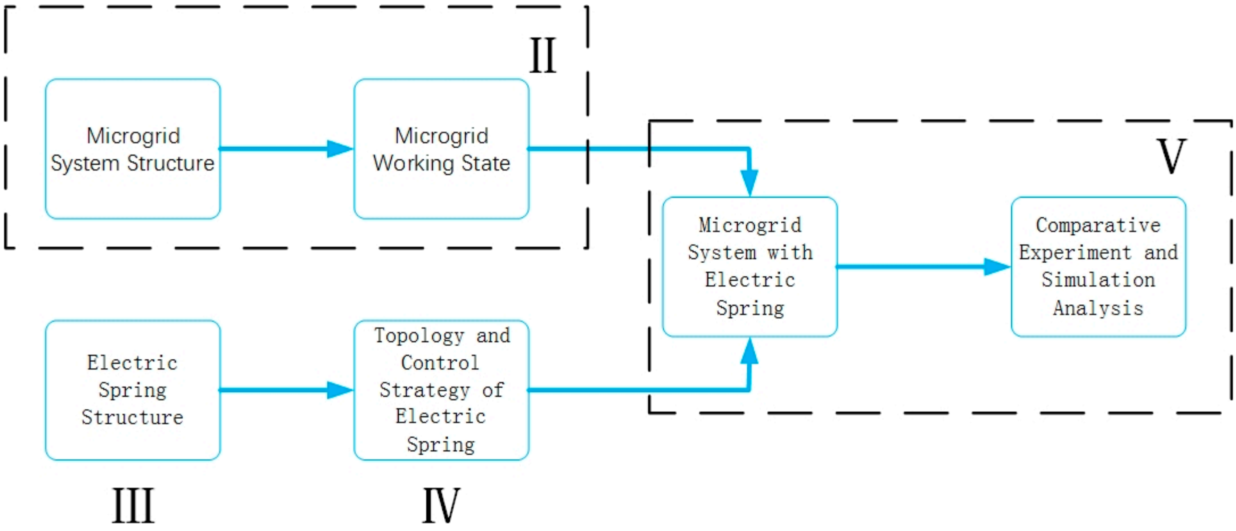


Figure 1. Paper structure chart.

2. Microgrid Structure and Working State

2.1. Microgrid System Structure

The microgrid system structure used in this paper is shown in Figure 2.

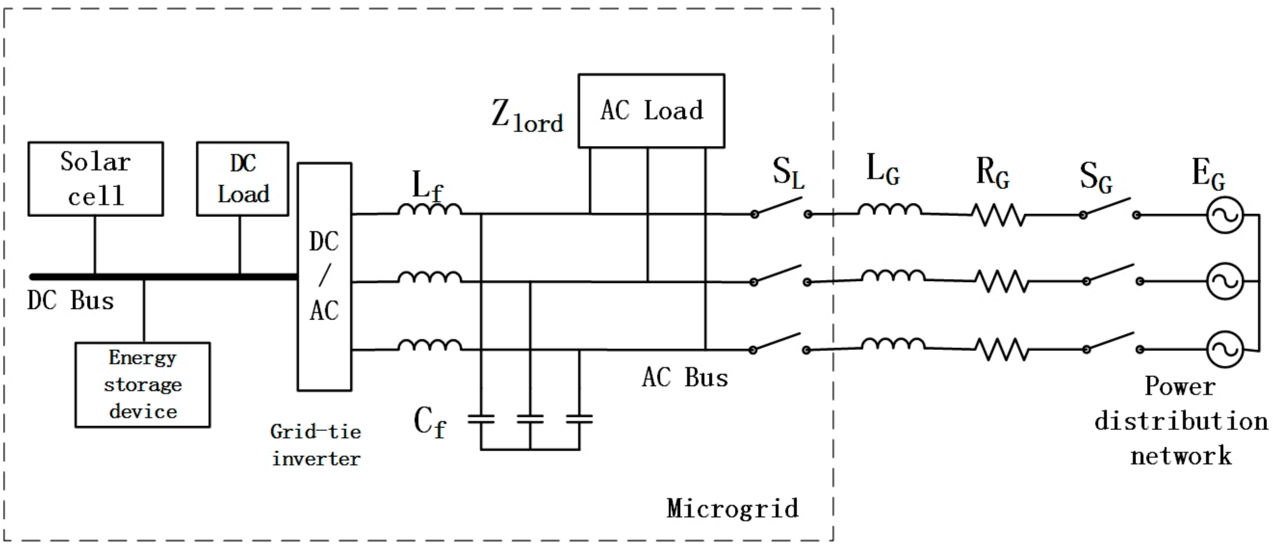


Figure 2. AC/DC hybrid microgrid system structure.

As shown in Figure 2, on the DC side of an AC/DC hybrid microgrid, the photovoltaic power supply, energy storage device, and DC load are connected through a DC bus; the DC bus is connected to the AC side through a DC/AC grid connected converter. To complete the microgrid system, the DC bus is converted into an AC bus, coupled to the local AC load, and finally connected to the distribution network through the local switch S_L. Among them, the DC side is composed of photovoltaic cells, energy storage devices, and DC loads, which are connected through DC bus, and the voltage of DC bus is V_{DC}. The DC bus is connected with the AC bus through the DC/AC grid connected inverter to realize the mutual conversion between AC and DC. The grid connected inverter features a three-phase three leg structure, and then the inverter is coupled to an LC low-pass filter to ensure the stability of the output current. Zload is a local load that is connected to the AC bus and is simultaneously supplied by the microgrid and distribution network local switch S_L, controlled by the controller of microgrid system. Grid connection impedance Z_G is composed of L_G and R_G, $Z_G = R_G + j\omega\ L_G$. S_G is the main network protection switch, which is automatically triggered in case of power grid failure to disconnect the distribution network and microgrid, resulting in an unplanned island. The AC bus voltage is V_{PCC} and the distribution network voltage is E_G.

2.2. Microgrid Working State

According to the switches S_L and S_G in Figure 1, the system can be divided into four working states. The transformation relationship between different states is shown in Figure 3:

1. When both S_G and S_L are all closed, the microgrid system operates in the grid connected state, the inverter adopts PQ control, and the distributed generation and distribution network jointly supply energy for the local load.
2. When S_G and S_L are all disconnected, the microgrid system operates in an off-grid state, with the inverter set to v/F control and the distributed power supply in the microgrid supplying electricity to the local load independently.
3. When the S_G is closed and the S_L is disconnected, the system is in a transitional state. Before the S_L takes effects, the grid-connected inverter will perform preprocessing to ensure the stability during switching. When switching from off grid to grid connection, the inverter receives the action signal, performs pre-synchronization processing, adjusts the inverter's output voltage to synchronize with the distribution network's voltage, makes grid connection preparations, and then closes the S_L to complete grid connection; grid connection is switched to off grid. When receiving the action signal, the inverter performs power preprocessing, redistributes the power on the AC bus, reduces the power proportion of the distribution grid in the system, and ensures the stability of the whole system when the distribution grid is disconnected.
4. When S_L is closed but S_G is disconnected due to protection action, the island state at this time is generated by the action of protection switch, which is not part of the typical microgrid's operation plan, making it an unplanned island. When an unplanned island occurs, the inverter is unable to redistribute power since it does not receive the off-grid switching preparatory action signal, and the distribution network goes off-line, causing the entire microgrid system to fail. The power balance of the system is disrupted within a short period of time, resulting in large fluctuations in the voltage and current of the microgrid bus, which are out of control. Although the grid connected inverter receives the islanding detection signal, so that the control strategy of the inverter is switched from PQ control to v/F control during grid connection, due to the large power imbalance of the microgrid system, if only v/F is used to control the bus voltage, large fluctuations will occur, making power supply reliability impossible to maintain. The power supply of AC load cannot be assured at this time. Therefore, this paper introduces the electric spring as the protection measure in case of unplanned islanding to ensure the voltage stability of critical loads in case of fluctuations caused by unplanned islanding.

3. Electric Spring Structure

3.1. Working Condition of Electric Spring

An electric spring is an electrical device that can control voltage oscillation, provide voltage support, and store electric electricity. The load in a microgrid can be divided into two categories: CL (critical load) and NCL (non-critical load). An electric spring and a non-critical load make an intelligent load. When the bus voltage of microgrid fluctuates, the fluctuation is transferred to the non-critical load through ES, ensuring that the voltage of the critical load does not change significantly. Figure 4 depicts the operational state of the electric spring under various voltage situations.

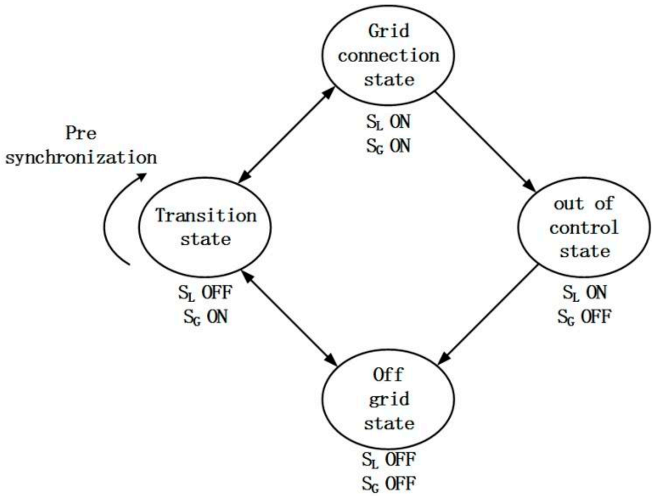


Figure 3. Four working states of microgrid.

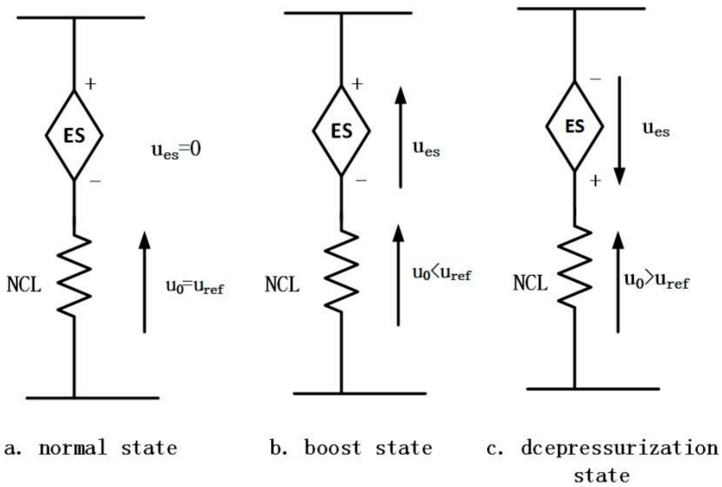


Figure 4. Working state of electric spring.

Figure 4 shows the three working states of the electric spring, where uerf is the system reference voltage, U_0 is the voltage at both ends of NCL, and u_{es} is the voltage at both ends of the electric spring. When the system is stable, the electric spring does not work, and the NCL terminal voltage is the system voltage, as shown in Figure 4a. When the voltage of the system fluctuates, the electric spring participates in the system and maintains the total voltage of the system by regulating the voltage between itself and NCL, ensuring the stability of the system.

The physical relationship expression for the electric spring is as follows:

$$q = \begin{cases} Cu_c, \text{Capacitance mode} \\ -Cu_c, \text{Inductance mode} \end{cases} \tag{1}$$

$$q = \int i_c dt \tag{2}$$

where C is the capacity of condenser, u_c is the potential difference between the two ends of the electric spring capacitor during normal operation, and i_c is the current on the capacitor, q is the amount of charge stored in the capacitor of the electric spring.

3.2. Operation Mode of Electric Spring

The controller, a PWM (pulse width modulation) converter, and a low-pass filter are the essential components of the electric spring. Figure 5 depicts the access mode. To establish an intelligent load, the critical load is directly connected to the power source, and the electric spring is attached to the non-critical load branch. The intelligent load is then connected to the critical load in parallel. When the line voltage fluctuates, closed-loop control adjusts the voltage and current of ES to transmit the fluctuation to the non-critical load, ensuring the voltage stability of the critical load end.

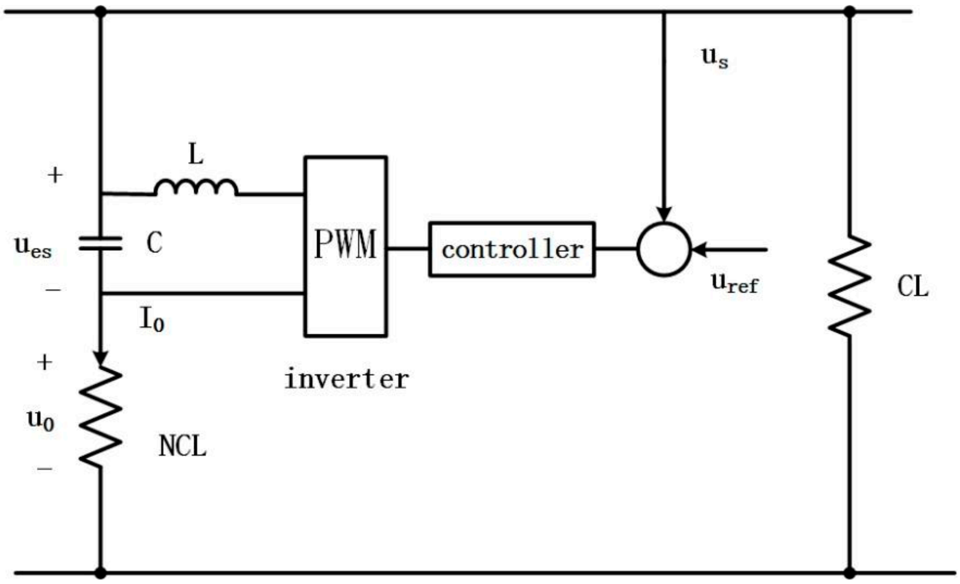


Figure 5. Basic structure of electric spring.

Suppose P_{in} is the input power of the system, P_{NC} is the active power on the non-critical load, and P_C is the active power on the critical load. The power balance equation of the system is as follows:

$$P_{in} = P_{NC} + P_C \tag{3}$$

The voltage vector equation is:

$$\vec{u}_s = \vec{u}_{ES} + \vec{u}_0 \tag{4}$$

where u_s is the critical load voltage, u_{ES} is the electric spring voltage, u_0 is the no-critical load voltage.

According to Equation (3), the system input power is made up of critical load and non-critical load, and ES consumes reactive power. When the system input power varies, it is necessary to adjust the power of non-critical load in order to ensure the power stability on critical load. From Equation (4), the critical load voltage u_s is the vector sum of u_{ES} and u_0. When there is a fluctuation, ES will construct a voltage vector to keep u_s stable. As a result of ES control, the voltage and power of important loads can be ensured, while the fluctuation is transferred to noncritical loads.

4. Topology and Control Strategy of Electric Spring

As shown in Figure 5, the electric spring is composed of PWM inverter, controller, and LC low-pass filter. This paper improves the three-phase electric spring by removing the neutral line and integrating the line on the basis of the traditional three-phase four-wire system to build a three-phase three-wire electric spring, making the entire system structure more succinct and effective.

As shown in Figure 6, a battery or DC power supply is used on the DC side of the main circuit structure of the three-phase electric spring. The advantage of using this kind of device is that it may provide not only reactive power compensation for the load, but also active power compensation. It has better regulation ability than a standard reactive power compensation electric spring with a capacitor as the DC side device. The ABC three-phase is connected to the low-pass filter, but the low-pass filter of the electric spring used in this paper is connected to the primary side of the isolation transformer instead of the non-critical load branch, and the secondary side of the isolation transformer is connected in series with the non-critical load The voltage vector that the low-pass filter produces can be expressed as:

$$\vec{U}_{ES1} = \left\{ \vec{U}_{ESA1}, \vec{U}_{ESB1}, \vec{U}_{ESC1} \right\} \tag{5}$$

where U_{ES1} is the voltage output by the low-pass filter, and U_{ESA1}, U_{ESB1}, and U_{ESC1} are respectively the electric spring A, B, and C phase voltage.

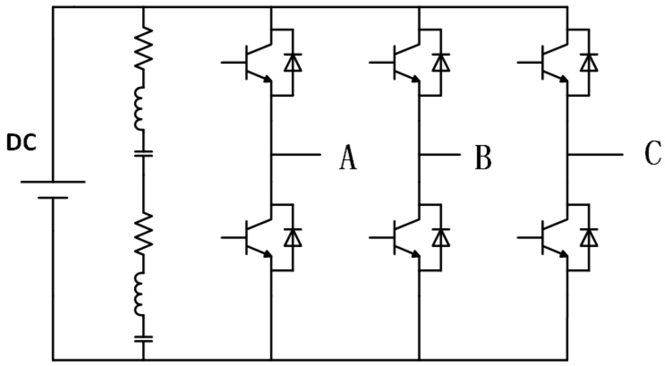


Figure 6. Three phase electric spring topology.

The secondary voltage vector of the isolation transformer is:

$$\vec{U}_{ES2} = \left\{ \vec{U}_{ESA2}, \vec{U}_{ESB2}, \vec{U}_{ESC2} \right\} \tag{6}$$

where U_{ES2} is the secondary voltage of the isolation transformer and U_{ESA2}, U_{ESB2}, and U_{ESC2} are respectively the A, B, C phase voltage that the electric spring actually connected to circuit.

When the isolation transformer ratio is n, the relationship between the two voltage vectors can be obtained as follows:

$$\frac{n}{1} = \frac{\vec{U}_{ES1}}{\vec{U}_{ES2}} \tag{7}$$

Due to the limitations of the technology, the PWM inverter circuit will produce certain harmonic signals, which cannot be avoided. Isolation transformers, on the other hand, can mitigate the detrimental effects of harmonics and other disturbances in the output voltage of electric springs. Moreover, by altering the isolation transformer ratio, the working range of the electric spring can be expanded and the adjusting power of the electric spring can be enhanced.

The controller generates control signals to control the six IGBTs in the inverting circuit, achieving the control of the electric spring. Based on the classical PI control of electric spring, a decoupling control strategy based on double closed-loop control is proposed in this paper. The specific control structure is shown in Figure 7.

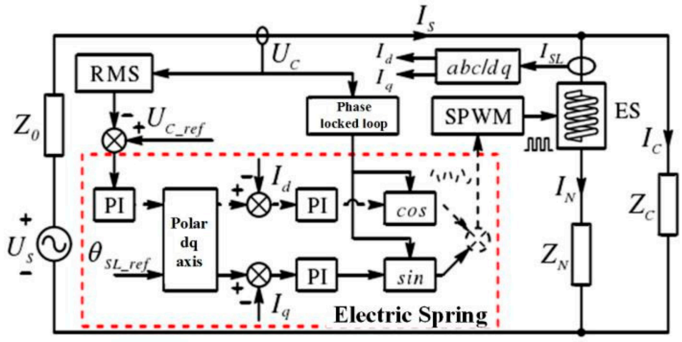


Figure 7. Decoupling control strategy of electric spring.

Double closed-loop control of electric spring is an improved control strategy for PI closed-loop control of DC side voltage U_{dc} of critical load voltage U_c and electric spring inverting circuit, which controls the reactive power compensation of electric spring output by adjusting the output voltage amplitude U_{ES} of electric spring. One PI closed-loop is used to feedback the voltage U_C of the critical load, while the other PI closed-loop is used to control the DC side capacitive voltage U_{dc} to maintain a constant value. The DQ transformation decouples the current flow via the electric spring and non-critical loads, allowing the current component under the d-axis and q-axis to be regulated independently and freely, resulting in greater control freedom. Since the current component under d-axis and q-axis is separately determined by the power factor angle of the smart load θ, and the expected value of θ_{SL} and current is determined by I_{SL}, the electric spring control strategy based on DQ decoupling may correct the power factor of the smart load while also stabilizing the critical load voltage U_C.

5. Comparative Experiment and Simulation Analysis

According to the contents of the previous sections, an example simulation analysis was carried out in Matlab/Simulink environment. The parameters of each part of the simulation model are as follows.

The microgrid system parameters is shown in Table 1.

Table 1. Microgrid system parameters.

AC bus voltage	380 V
AC bus frequency	60 Hz
CL Rated power	1000 W
NCL Rated power	1000 W

The main parameters of three-phase electric spring are shown in Tables 2–4.

Table 2. Main parameters of the IGBT.

Internal resistance	R_{on}	0.001 Ω
Snubber resistance	Rs	10^5 Ω
Sunbber capacitance	Cs	∞

Table 3. Main parameters of the RLC.

Resistance	R	1 Ω
Inductance	L	0.001 H
Capacitance	C	10^{-6} F

Table 4. Main parameters of the PI controller.

Proportional	K_p	0.1
Integral gain	K_i	1
Output limits	-	$[10^6, -10^6]$
Sample time	t	50×10^{-6}

The system structure of AC/DC hybrid microgrid with electric spring is shown in Figure 8.

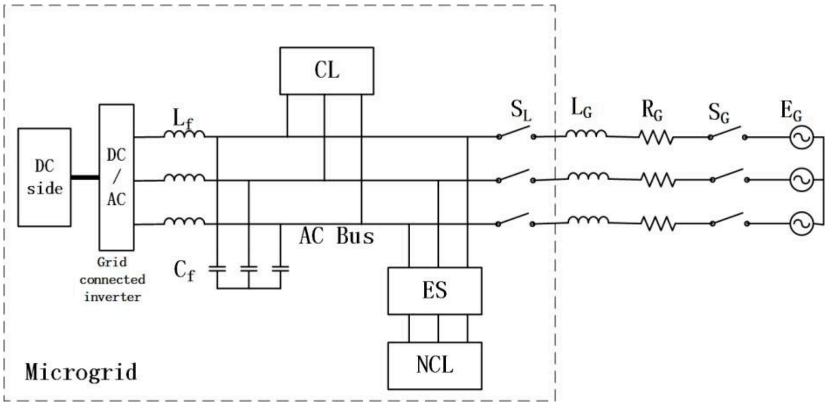


Figure 8. Microgrid system with electric spring.

In this paper, unplanned islands are divided into two categories:

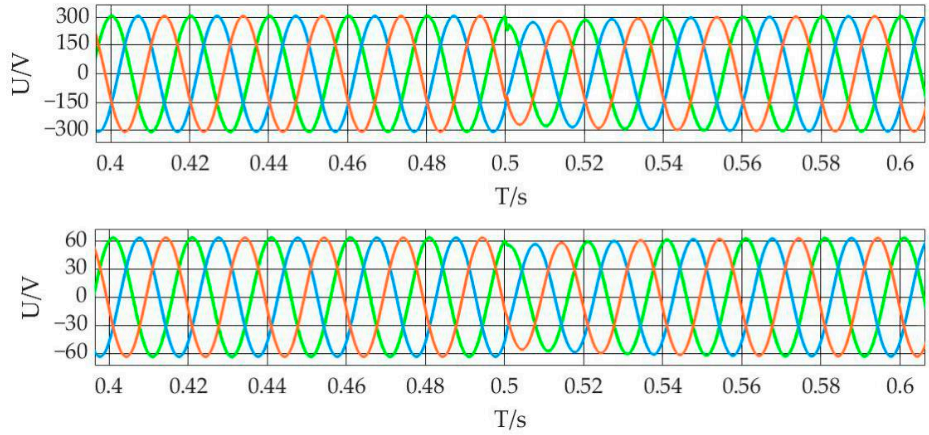
Class I: when connected to the grid, the microgrid and distribution network simultaneously supply power to AC loads, and the power of the critical load is lost in the event of an island;

Class II: when connected to the grid, the microgrid not only supplies power to the AC load, but also transmits power to the distribution network. The power of the critical load overflows when an island occurs.

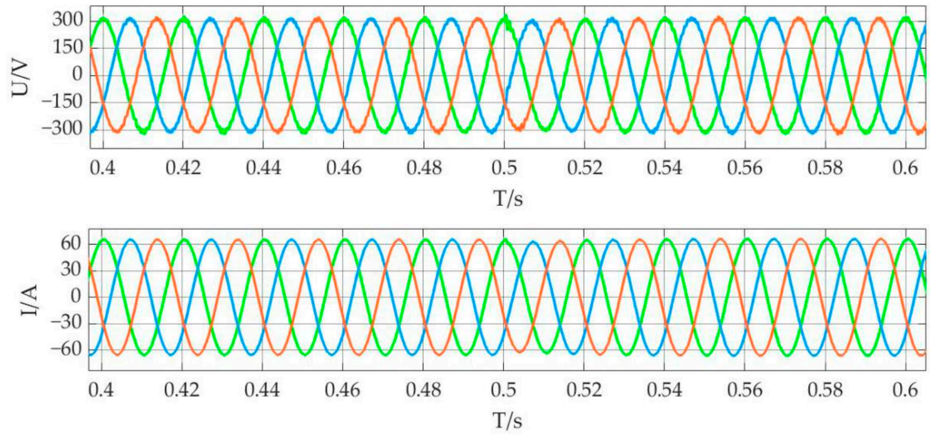
5.1. Simulation Analysis of the First Kind of Unplanned Island

When linked to the grid in these circumstances, the microgrid and the large grid both supply electricity to the load on the AC bus at the same time. When the large power grid suddenly goes offline, the microgrid alone supplies power to the load. At this time, the microgrid alone is unable to supply the load demand. A power gap will be generated on the AC bus, and the voltage drop of the critical load will be quick, returning to normal after a period of time. When the electric spring is connected, the sudden voltage drop on the critical load will cause the electric spring to act forward, raising the voltage in the forward direction to guarantee the critical load voltage remains stable. The voltage and current on the critical load are shown in Figure 9.

According to Figure 9a, when the first type of unplanned islanding occurs (0.5 s), due to the offline distribution network, there is an instantaneous power gap in the microgrid system and the voltage drop of the critical load. After a period of time, the V/F control module restores the initial rated voltage. When the electric spring is connected, on the other hand, according to Figure 9b, the unplanned islanding occurs (0.5 s), and the voltage drop on the critical load will be detected by the electric spring controller, prompting the action of the electric spring, as shown in Figure 10. When an unplanned island occurs in 0.5 s, the electric spring will take a positive action, raising the output voltage, maintaining the bus voltage stability, and ensuring that the voltage on both sides of the critical load does not fluctuate much. The final comparison results are shown in Figure 11. It can be clearly seen that without ES, the critical load voltage will drop to about 267.1 V in 0.5 s and then recover to the rated voltage after 0.125 s. However, if ES is connected, the voltage of the critical load will be raised near the rated voltage only when it drops to 299.7 V, and the voltage protection of the critical load will be realized in only 0.036 s, because ES can play the role of power compensation. Compared with v/F control, adding electric spring control, the maximum variation of voltage is reduced from 42.9 V to 10.3 V, a decrease of about 76%; and the recovery time is shortened from 0.125 s to 0.036 s, a decrease of about 71%. Therefore, electric spring control has faster response speed, better sensitivity, and less fluctuation, and has a better effect on voltage stabilizing control of critical loads.



(**a**)



(**b**)

Figure 9. Voltage and current diagram of the first type of islanding critical load. (**a**) With v/F control. (**b**) With electric spring control.

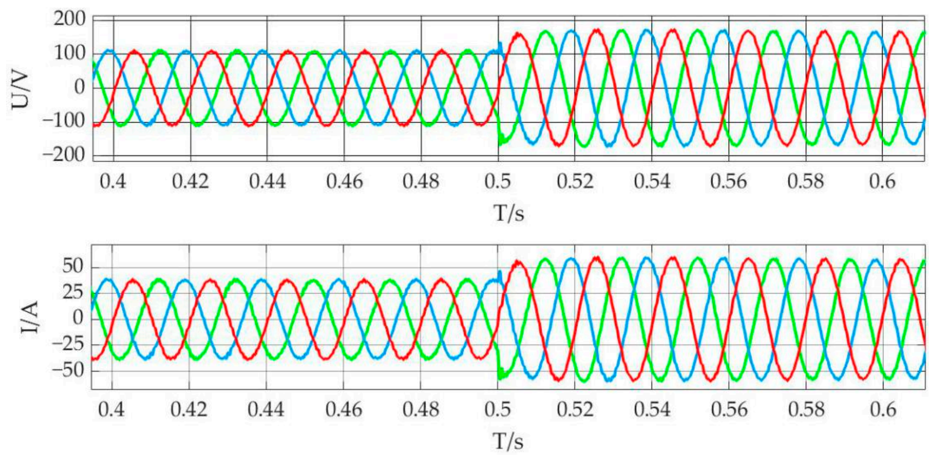


Figure 10. Voltage and current diagram of the first type isolated island of electric spring.

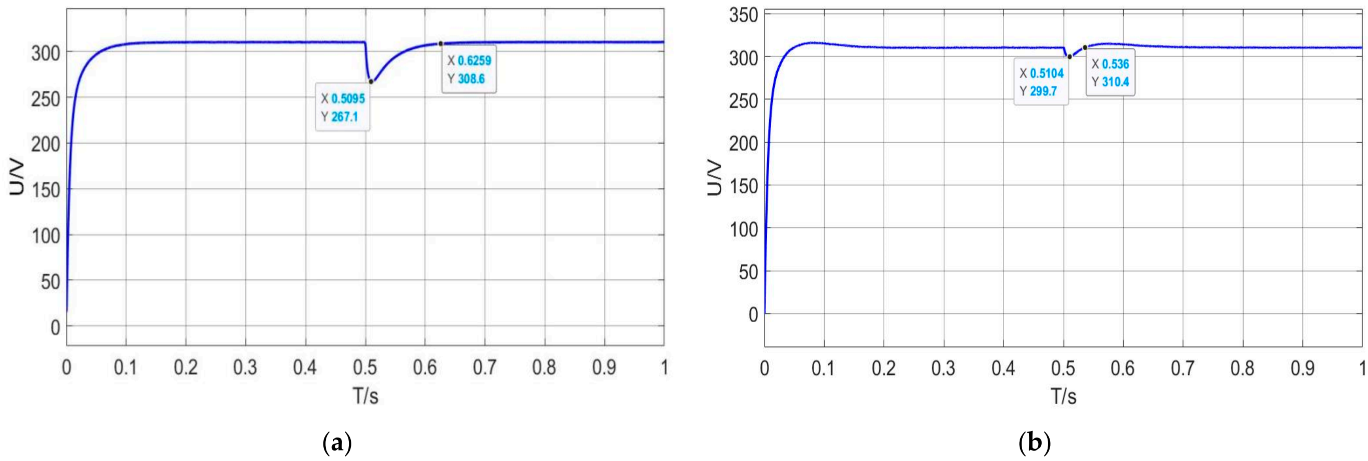
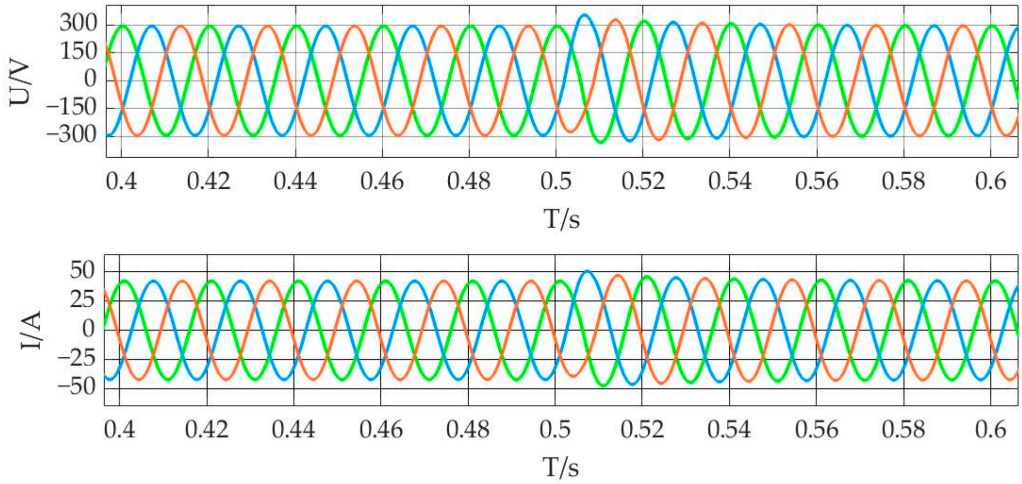


Figure 11. Critical load voltage curve. (**a**) With v/F control. (**b**) With electric spring control.

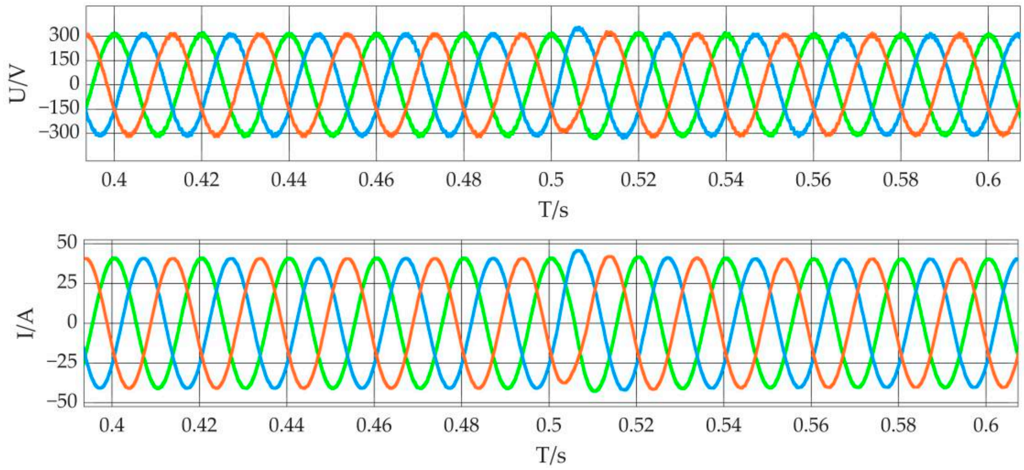
5.2. Simulation Analysis of the Second Kind of Unplanned Island

When connected to the grid in these circumstances, the microgrid not only meets the power supply demand of the load on the AC bus, but also supplies power to the large power grid. When the large power grid suddenly goes offline, the microgrid solely supplies power to the load and no longer transmits energy to the distribution network. At this point, all of the energy in the distribution network flows to the AC bus, resulting in AC bus power overflow and a rapid rise in the voltage drop of essential loads, which will eventually revert to normal. When the ES is connected, the abrupt rise of the voltage in critical load causes the electric spring to reverse action and reduce the voltage in reverse, ensuring the critical load voltage is stable. The voltage and current on the critical load are shown in Figure 12.

According to Figure 12a, when the second type of unplanned island occurs (0.5 s), since the distribution network is offline, the microgrid system can no longer transmit electric energy to the distribution network. At this point, all of the energy flows into the AC bus, resulting in AC bus power overflow and a rapid rise in the voltage at the critical load. After a period of time, the v/F control module restores the initial rated voltage. However, according to Figure 12b, when the electric spring is connected, an unplanned island occurs (0.5 s), the voltage rise on the critical load will be detected by the electric spring controller, forcing the electric spring to operate, as shown in Figure 13. When an unplanned island occurs in 0.5 s, the electric spring will reverse, lowering the output voltage, maintaining the bus voltage's stability, and ensuring that the voltage on both sides of the critical load does not fluctuate much. The final comparison results are shown in Figure 14. It is obvious that without the ES, the critical load voltage will rise to about 341.5 V in 0.5 s and then recover to the rated voltage after 0.079 s. However, with ES attached, the critical load voltage will only climb to about 321.4 v and then be suppressed near the rated value in 0.039 s. Compared with v/F control, adding electric spring control, the maximum variation of voltage is reduced from 31.5 v to 11.4 v, a decrease of about 64%; and the recovery time is shortened from 0.079 s to 0.039 s, a decrease of about 51%. Therefore, with electric spring control, the reaction speed is faster and the change in amplitude is smaller, which has a better effect on voltage stabilizing control of important loads.



(**a**)



(**b**)

Figure 12. Voltage and current diagram of the second type of islanding critical load. (**a**) With v/F control. (**b**) With electric spring control.

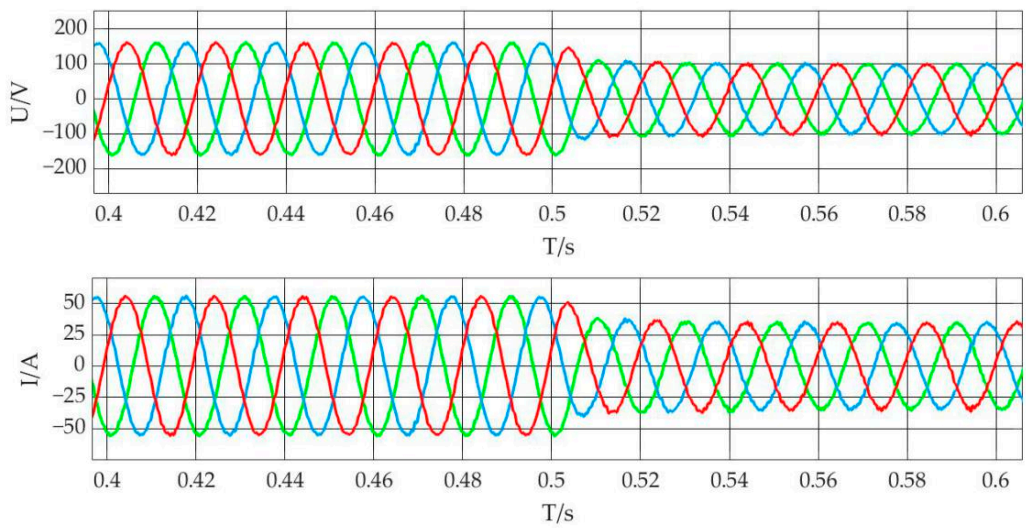
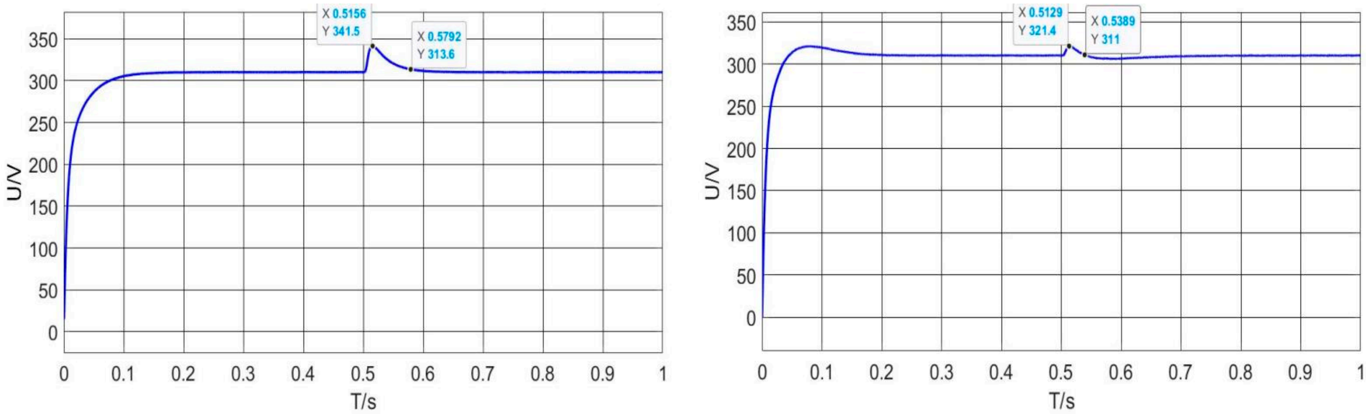


Figure 13. Voltage and current diagram of the second type isolated island of electric spring.



(**a**) (**b**)

Figure 14. Critical load voltage curve. (**a**) With v/F control. (**b**) With electric spring control.

According to Figure 9, Figure 11, Figure 12, and Figure 14, when the voltage of critical load rises or falls abruptly due to an unplanned island of a microgrid, the electric spring can realize the voltage stabilizing control of key simulation and protect the critical load.

6. Conclusions

In this paper, the electric spring was introduced into the voltage stabilizing control of critical load when an unplanned island occurs for the first time. The following findings are drawn from the analysis and design of power springs, as well as simulated analysis of several scenarios when an unplanned island develops in a microgrid:

1. When unplanned islanding occurs, the control technique based on three-phase electric spring described in this research is effective and can meet the goal of voltage stabilizing control of important loads.
2. In different island states, the electric spring behaves differently, but it can protect the critical load in both boost and step-down states.
3. Compared with v/F control, electric spring control can reduce the amplitude change about 60% and cut the recovery stability time about 50%. As a result, as compared to traditional control, the voltage stabilizing control technique for critical loads employing electric spring is faster and more effective.

Electric spring, as a novel power system theory, suggests a new approach to optimizing system structure and simplifying system control. At present, the research of electric spring is still in the primary stage, and the exploration of its technology needs to be bolstered. Follow-up research will concentrate on expanding its topology and ensuring its reliability.

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