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Application of Electric Spring in Traction Train Auxiliary Power Supply System

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Abstract Auxiliary power supply system is an important component of traction trains. Voltage fluctuation of auxiliary power supply system is a nonnegligible factor threatening the safe operation of traction trains. This paper based on electric spring theory aims to stabilize the voltage of the critical load in traction train auxiliary power supply system. And a method of stabilizing the voltage of the critical load with the electric spring is proposed. In this paper, a simulation model is established by Matlab/Simulink to verify the validity of the electric spring. The simulation results show that the electric spring can effectively mitigate the voltage fluctuation of the critical load, ensuring the critical load to work with a steady voltage.

Keywords: *electric spring, voltage fluctuation, traction train, auxiliary power supply system*

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1. Introduction

A traction train is powered by pantograph contacted with traction power network. The traction motor and auxiliary power supply system in the train are powered by traction transformer. The auxiliary power supply system provides power for all electrical equipment except the traction motor. Its normal and steady work is related to the safety and comfort of the passengers. So, it plays an important role in a traction train. However, frequent passing neutral section of trains, switching of large loads and other factors will cause voltage fluctuation of the auxiliary power supply system. These will threaten the safe operation of the train.

At present, there are many researches on the normal and stable operations of auxiliary power supply system. [1] and [2] applied the inverter parallel technology to the train auxiliary power supply system to improve its reliability and redundancy. [3] analyzed the overvoltage of auxiliary power supply system caused by the passing neutral section of the train. In [4], a method is put forward to mitigate the overvoltage. [5] analyzed the voltage fluctuation caused by the start of the air conditioning loads in the auxiliary power supply system. And then put forward that changing the start sequence can mitigate the voltage fluctuation.

These researches mentioned above were aimed at the stability of the whole auxiliary power supply system, and had some certain effect. However, the traction train is a kind of special power load travelling at a high speed. Its voltage fluctuation range is relatively large. Moreover, there are multiple voltage levels in the train, and the operation modes of the loads in it are changeable. It is difficult to ensure the stability of auxiliary power supply system. So, the voltage of auxiliary power supply system will inevitably fluctuate.

This paper firstly introduces the voltage regulation principle of the electric spring. Then from the point of the critical load in traction train auxiliary power supply system, proposing that the electric spring can be used to stabilize the voltage of the critical load when system voltage fluctuates. Finally, the voltage stabilizing simulation model is established by Matlab/Simulink. By analyzing the simulation results. this paper verifies that in the case of parallel operation of the critical load and the noncritical load, electric spring has a function of stabilizing the critical load voltage.

2. Operation Principle of Electric Spring

Electric spring (ES) [6] was put forward in recent years. It is a novel technology which can suppress the voltage fluctuation of power grid caused by the integration of distributed generation. The electrical loads are separated into critical loads and noncritical loads by ES. In specific application scenarios, those requiring constant voltage can be classified as critical loads. Critical loads have a high demand for their voltage stabilization. Noncritical loads allow their voltage to fluctuate in a certain condition. ES is connected with the noncritical load in series to form the smart load. Then the smart load connects with the critical load in parallel. The connection of ES in the circuit is shown in Figure 1. ES can transfer the voltage fluctuation of the system to the noncritical load, ensuring that the critical load voltage can remain constant. It is the most important function of ES.

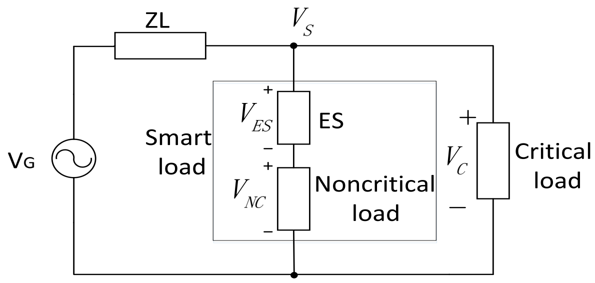

Figure 1. Connecting diagram of ES in the circuit

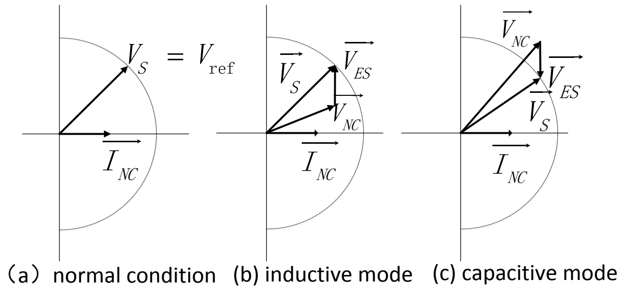

Figure 2. Typical operating modes of ES

Three typical operating modes [7] of ES are shown in Figure 2. The circles in the vector diagrams represent the rated value of the point of common coupling(PCC) voltage V_{ref}. V_{ES} represents the ES voltage, V_{NC} represents the noncritical load voltage, V_C represents the critical load voltage, I_{NC} represents the current flowing through the noncritical load.

As shown in Figure 2, the system vector equation is:

$$\overrightarrow{V_{ES}} + \overrightarrow{V_{NC}} = \overrightarrow{V_S}. \quad (1)$$

If the system voltage has no fluctuation, the PCC voltage V_S equals to V_{ref}, the ES voltage V_{ES} is zero. The operating mode is shown in Figure 2(a). When the system voltage is raised, V_S is higher than V_{ref}. Taking the noncritical current $\overrightarrow{I_{NC}}$ as a reference vector, the ES injects the voltage $\overrightarrow{V_{ES}}$ leading the current vector $\overrightarrow{I_{NC}}$ by 90°. Here the ES absorbs the reactive power of the system, so that the PCC voltage V_S will return to V_{ref}. The operating mode of the ES is shown in Figure 2(b). When the system voltage decreases, V_S is lower than V_{ref}, the ES injects the voltage $\overrightarrow{V_{ES}}$ lagging vector $\overrightarrow{I_{NC}}$ by 90°. Here the ES emits reactive power to the system, so that V_S will be lifted to V_{ref}. The ES works in capacitive mode as shown in Figure 2(c). With the operations of the ES controlling the reactive power of the system dynamically, the PCC voltage V_S remains relatively stable:

$$\left|\overrightarrow{V_S}\right| = \left|\overrightarrow{V_{ES}} + \overrightarrow{V_{NC}}\right| = V_{\text{ref}}. \quad (2)$$

The physical model of the ES used in this paper is composed of a PWM inverter and a LC low pass filter. The circuit diagram of the ES is shown in Figure 3. The control block diagram [8] used in this paper is shown in Figure 4. When the measured value of V_S is different from the reference voltage V_{ref}, the error between them will be input to the PI controller, the Saturation module and the Abs module, and multiplied by half of the DC bus voltage, then the amplitude of ES control signal is obtained. The P and I values are set according to [9] The phase of the control signal is adjusted according to $\overrightarrow{I_{NC}}$. The PLL module outputs the phase of $\overrightarrow{I_{NC}}$. If V_S exceeds the conference voltage V_{ref} , the phase of $\overrightarrow{V_{ES}}$ injected by the ES should lead $\overrightarrow{I_{NC}}$ by 90°, the ES works in inductive mode. Similarly, if V_S is lower than the conference voltage V_{ref}, the phase of $\overrightarrow{V_{ES}}$ should lag $\overrightarrow{I_{NC}}$ by 90°, the ES works in capacitive mode. The model for the ES can be written as:

$$\begin{cases} V_S - V_{ES} - Z_0 I_0 = 0 \\ I_0 + I_f = I_c \\ I_c = C_f \dfrac{dV_{ES}}{dt} \end{cases} \quad (3)$$

$$\begin{cases} L_f \dfrac{dI_f}{dt} = V_a - V_{ES} \\ V_a = \dfrac{V_{dc}}{2} m \end{cases} \quad (4)$$

V_a is the output of the inverter. L_f and C_f represent the inductance and capacitance of the filter respectively.

The control signal can be written as:

$$m = \frac{(V_S - V_{ref})}{V_t} G(t) \quad (5)$$

G(t) is the compensating function; V_t is the amplitude of the PWM triangular carrier.

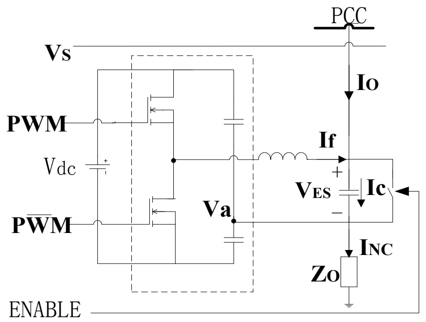

Figure 3. Circuit diagram of the ES

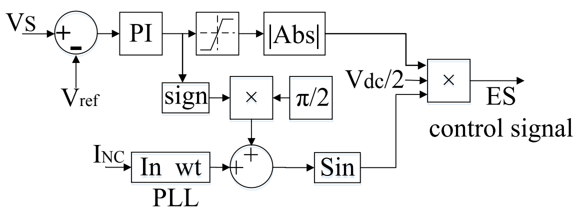

Figure 4. Control block diagram of the ES used in this paper

Train auxiliary power supply system failure is a small probability event, but train outage accidents still happen occasionally. There are still some potential factors threating the safe operation of auxiliary power supply system. The voltage fluctuation of auxiliary power supply system has a lot of adverse effects on auxiliary power supply equipment, for examples: causing the lights and train TV flicker, affecting the accuracy of detection devices, reducing the load life and so on. Those will threaten the safety of the train in extreme cases. According to the voltage regulation principle of ES introduced above, it is feasible to apply ES to traction train auxiliary power supply system to stabilize the critical load voltage.

3. Voltage Stabilizing Model of the ES in Auxiliary Power Supply System

The simplified schematic of voltage stabilizing model using the ES in auxiliary power supply system is shown in Figure 5. Z_L represents the line impedance. *Disturb* represents the voltage fluctuation of PCC caused by the instability of the system voltage. *NC* represents the noncritical load such as water heater. *C* represents the critical load related with the safety of the passengers and the train. The voltage $\overrightarrow{V_{ES}}$ across the ES is adjusted by signals: $\overrightarrow{V_C}$, V_{ref}, $\overrightarrow{I_{NC}}$, and the enable signal.

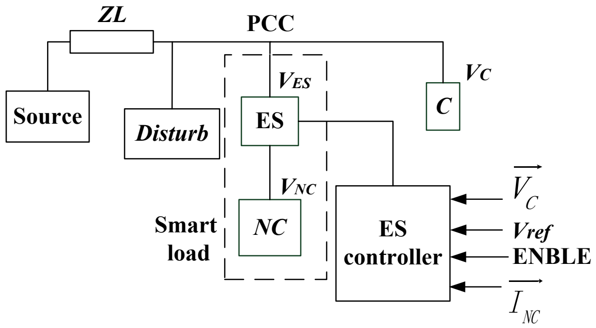

Figure 5. Simplified schematic of voltage stabilizing model using the ES

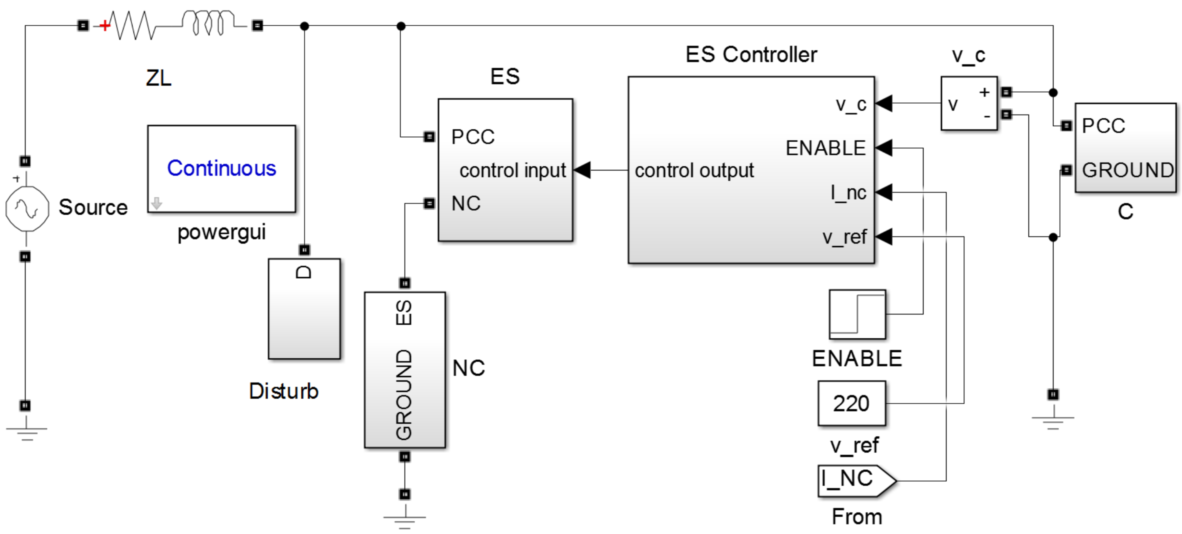

Figure 6. Simulink simulation diagram

The auxiliary power supply system on the train has a variety of voltage levels. A simulation model of the AC220V subsystem is established in Matlab/Simulink. It is used to test the performance of the voltage regulation of the ES. The whole simulation model is shown in Figure 6. The source is AC200V. *ZL* is the system line impedance. *Disturb* is used to make the system voltage fluctuate.

4. Simulation Analysis

In order to verify the performance of the ES used to mitigate system voltage fluctuation, the rapidity and stability tests are carried out. The operating mode of the ES is also analyzed. Except the AC220V subsystem, the voltage stabilization performance of the ES also has the same reference for AC loads in other voltage levels in auxiliary power supply system.

4.1. Rapidity Test of the ES

This simulation is set to 1 second. It is used to simulate that the system voltage drops at 0.4 seconds because of the start of the air conditioning equipment. If the ES is not activated, the measured value of the critical load V_C is shown in Figure 7. V_C drops from 220V to 204V. For equipment requiring constant voltage, such voltage drop will greatly affect their normal operations, may result in significant losses in severe cases.

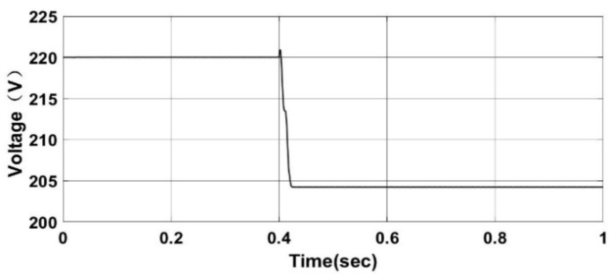

Figure 7. Measured value of the critical load voltage V_C without the ES

Under the same disturbance, after the ES is activated, the measured value of the critical load voltage V_C and the noncritical load voltage V_{NC} are shown in Figure 8, Figure 9 respectively. It can be seen that with the operation of the ES, the critical load voltage is adjusted to 220V rapidly within about 0.05 seconds. It is less than the time of the system voltage fluctuation caused by the start of the air conditioning equipment in [5]. Yet the noncritical load is in low voltage operation. This shows that the ES can quickly respond to the disturbance, and transfer the system voltage fluctuations to the noncritical load, stabilizing the critical load voltage.

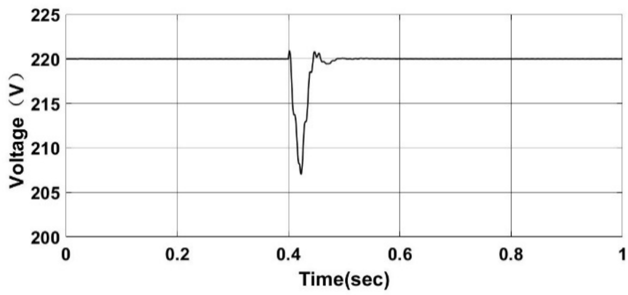

Figure 8. Measured value of the critical load voltage V_C with the ES activated

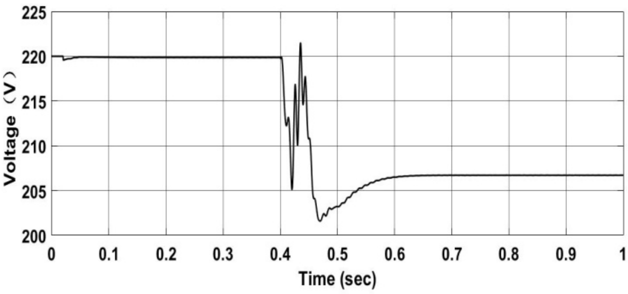

Figure 9. Measured value of the noncritical load voltage V_{NC} with the ES activated

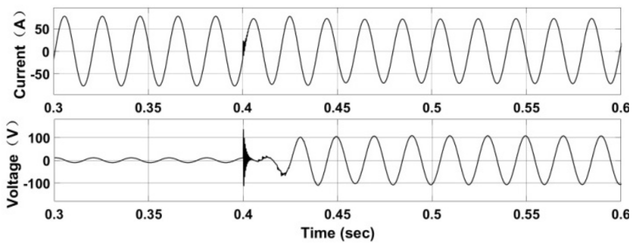

Figure 10. Waveforms of the ES voltage and the noncritical load current with the ES activated

With the ES activated, the waveforms of the ES voltage $\overrightarrow{V_{ES}}$ and the noncritical load current $\overrightarrow{I_{NC}}$ between 0.3 seconds and 0.6 seconds are shown in Figure 10. It can be seen that before the system voltage drops, the ES voltage is almost zero. When the system voltage drops, the ES injects a voltage lagging the noncritical load current by 90°. The ES emits reactive power to the system to lift the critical load voltage to its rated value. At this time, the ES works in capacitive mode.

4.2. Rapidity Test of the ES

In order to verify the stability of the ES, this simulation is set to 100 seconds. It is used to simulate that the system is subjected to random interference. When the ES is not activated, the measured value of the critical load voltage V_C is shown in Figure 11, it is seen that the voltage fluctuates between 203V and 235V.

When the ES is activated, the critical load voltage will almost remain 220V as shown in Figure 12. The ES can stabilize the critical load voltage for a long time, greatly improving the reliability of its operation.

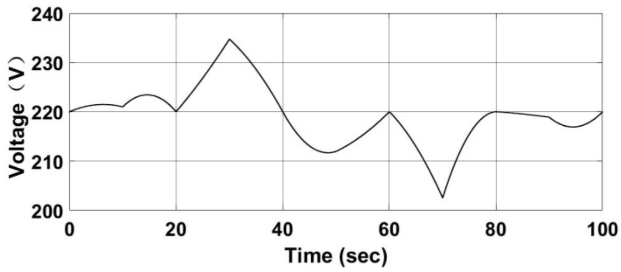

Figure 11. Measured value of the critical load voltage V_C without ES (in stability test)

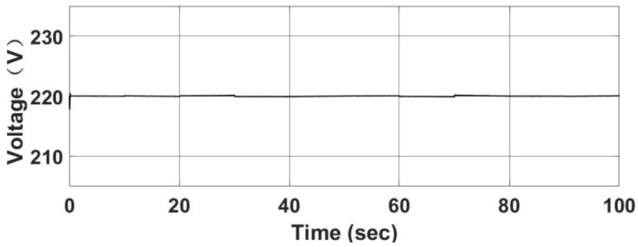

Figure 12. Measured value of the critical load voltage V_C with ES activated (in stability test)

5. Conclusions

This paper introduces the operation principle and control method of the ES, and applies the ES to traction train auxiliary power supply system to stabilize the voltage of the critical load. A Matlab/Simulink simulation is established to test the rapidity and stability of the operation of the ES. From these two tests, it can be seen that the ES can respond to the system voltage fluctuation rapidly and stably, adjusting the critical load voltage to its rated value. So, using the ES to improve the power supply quality of the important loads in traction train auxiliary power supply system is feasible.

Acknowledgements

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