The Application of One-Cycle Control Technology in Electric Spring System

To cite this article: Niang Tang *et al* 2018 *IOP Conf. Ser.: Earth Environ. Sci.* **170** 042117

The Application of One-Cycle Control Technology in Electric Spring System

Niang Tang[1], Kai Yang[2, *], Hui Huang[1] and Chi-Kwan Lee[3]

[1]Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou, Guangdong 510080, China
[2]State Key Laboratory of Power Equipment & System Security and New Technology (Chongqing University), Shapingba District, Chongqing 400044, China
[3]Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong

*Corresponding author e-mail: yangkai_UPC@126.com

Abstract. This paper first introduced the function, application and the control algorithm of the electric spring (ES), then the working principle of ES are explained. Aiming at the problems that the existing control algorithms have complex structures and are not conducive to accurate tracking of AC voltage signals on sensitive loads, this paper proposes the ES control strategy based on one-cycle control (OCC) technology. In Matlab/SimulinK, the ES system based on the OCC strategy is modeled and simulated. Through the waveform analysis, it is known that when the power of the photovoltaic system injected into the power grid fluctuates, the ES based on the OCC strategy system can operate in a capacitive, inductive or resistive mode automatically, which can achieve a direct and accurate tracking of a given AC voltage signal under the condition that a small amount of reactive power is injected into the grid, thus the voltage of the sensitive load is stabilized, and at the same time the voltage fluctuations on the grid side voltage can be transferred to non-sensitive loads in series with the ES.

1. Introduction

Since the 21st century, the global photovoltaic industry has developed rapidly. However, due to the influence of temperature and light intensity on photovoltaic, there are obvious instabilities, intermittent and uncontrollable characteristics, etc, it will cause a great impact on the power grid, which will lead to changes in the size and frequency of the voltage at the supply feeder. In order to suppress the voltage fluctuation caused by PV system, the ES device can be used in the system. Through a reasonable control algorithm, the ES automatically suppresses the power fluctuation of photovoltaic systems injected into the grid, thus, the bus voltage fluctuation caused by grid-connected power fluctuations is effectively transferred to the non-sensitive load (such as water heaters, refrigerators, and electric arc furnaces) connected in series with ES[1]. Finally, to ensure the stability of the voltage on sensitive loads (such as precision medical equipment).

In the whole system, a good control algorithm plays a vital role. The [2] combines the PR control strategy with the grid voltage feedforward control strategy to allow the voltage on the sensitive load to follow the given sinusoidal reference voltage at all times. The study in [3], a quasi-PR controller is used as the outer voltage loop to control the voltage on the sensitive load, and the P controller is used as the inner current loop to control the inductor current; [4] decoupled the dq-axis from the AC voltage on the sensitive load and the given AC reference voltage to get the DC component, then, through three PI loops, the DC-link voltage of the inverter, the d-axis and q-axis components of the AC voltage are separately adjusted to ensure that the voltage on the sensitive load can always follow the given sinusoidal reference voltage. The ES control strategy based on PR control in [2-3] and the PI control method based on dq decoupling in [4] can also track the AC signal, but the controller structure is so complex that it is difficult to be realized.

In view of the above problems, the OCC is used to control the ES. In this paper, the working principle of the ES based on the OCC is introduced firstly. Then the ES system based on OCC technology is modeled in the Matlab/SimulinK. Through the analysis of the simulation waveforms, we can find that the ES system based on the OCC can stabilize the voltage on the sensitive load effectively when the power of the photovoltaic energy system injected into the power grid fluctuates (expressed as the voltage fluctuation of the ES).

2. The working principle of ES based on OCC

2.1. The working principle of ES

Fig.1 shows the ES control block diagram based on OCC. The left-dashed box is a single-phase full-bridge voltage source inverter, which is called the electric spring (ES) here. Z2 is a non-sensitive load in the power grid. This type of load has a wide operating voltage, and it can work normally when the voltage applied to it fluctuates within a certain range [5]. Z3 is a sensitive load, which requires a high quality operating voltage. When the working voltage on Z3 has a large fluctuation, it will not work properly.

2.2. The principle of One-cycle control

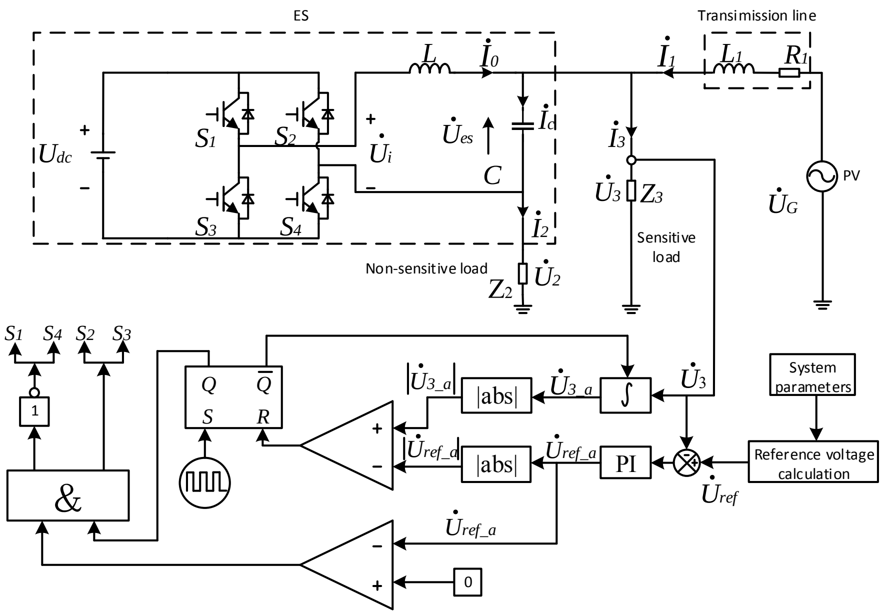

Fig 1. The Control Block Diagram of the ES Based on OCC

The one-cycle controller is mainly composed of six parts: a comparator, an integrator, an RS flip-flop, a clock signal generator, a pulse signal generator and an integral reset circuit [6]. At first, the voltage real-time signal $\dot{U}_3$ on the sensitive load is acquired, and the reference voltage $\dot{U}_{ref}$ is calculated according to the system parameters. As can be seen from Fig. 1, the states of the switches S1-S4 are related to the output signal Q of the flip-flop. Assuming that the real-time voltage value U3>Uref, then the output of the PI ring is negative. When the pulse signal generator pulse signal reaches the RS flip-flop, the integrator starts to integrate the signal $\dot{U}_3$ from 0, the integration result is $\dot{U}_{3\_a}$. After PI adjustment, the difference between $\dot{U}_{ref}$ and $\dot{U}_3$ is $\dot{U}_{ref\_a}$. When $|\dot{U}_{3\_a}|<|\dot{U}_{ref\_a}|$, the reset terminal of RS trigger is low level signal, otherwise, the signal at the reset terminal R of the RS flip-flop is inverted, and the output signal a generates a reset signal and the integrator will reset at this time. When the next pulse signal arrives, the one- cycle controller will repeat the above action until $\dot{U}_{3\_a}=\dot{U}_{ref\_a}$.

When the real-time voltage value U3>U ref, it shows that the voltage on the sensitive load appears high-voltage lift zone. At this time, the switch S1 and S4 are turned off, S2 and S3 are turned on, and the ES works in inductive mode. When the real-time voltage value U3=Uref, the ES does not work and does not provide reactive power for the grid.

2.3. The method to calculate the reference voltage

The calculation of the reference voltage in the ES control strategy based on OCC is also very important, which determines the working mode of the ES in the current state. In order to simplify the calculation, we assume the sensitive and non-sensitive loads are purely resistive loads. The phasor relationship of the voltage and current between the ES operating in capacitive mode and inductive mode is shown in Fig.2.According to the relationship between the various variables, we can get the relational expressions between the angles in the phasor diagram in the inductive mode as follows:

$$\theta_1 = \tan^{-1}(\frac{wL_1}{R_1 + R_2}) \tag{1}$$

$$\theta_0 = \tan^{-1}(\frac{R_1}{wL_1}) \tag{2}$$

$$\theta_3 = \frac{\pi}{2} - \frac{\theta}{2} - \theta_0 - \theta_1 \tag{3}$$

Through the cosine and sine theorem we can get the following equation in the triangles containing Ur and UG:

We can get:

$$\theta = \sin^{-1}(\frac{U_G - U_r^2 - q}{\sqrt{p^2 + q^2}}) - \tan^{-1}(\frac{q}{p}) \tag{4}$$

$$\theta_4 = \sin^{-1}(\frac{U_S \cos(\theta/2)\cos(\theta/2 + \theta_0 + \theta_1)\sqrt{R_1^2 + (wL_1)^2}}{R_2 U_G}) \tag{5}$$

Among them:

$$p = \frac{U_r U_3}{R_2}\sqrt{R_1^2 + (wL_1)^2}\cos(\theta_0 + \theta_1) \tag{6}$$

$$q = \frac{U_3^2[R_1^2 + (wL_1)^2]}{2R_2^2} + \frac{U_r U_3}{R_2}\sqrt{R_1^2 + (wL_1)^2}\sin(\theta_0 + \theta_1) \tag{7}$$

$$U_r = \frac{U_3^2\sqrt{(R_1 + R_2)^2 + (wL_1)^2}}{2R_3^2} \tag{8}$$

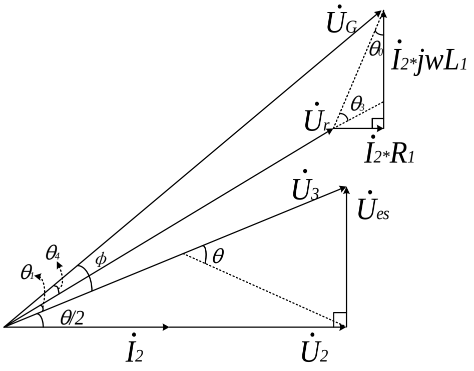

Fig 2. (a) Inductive mode

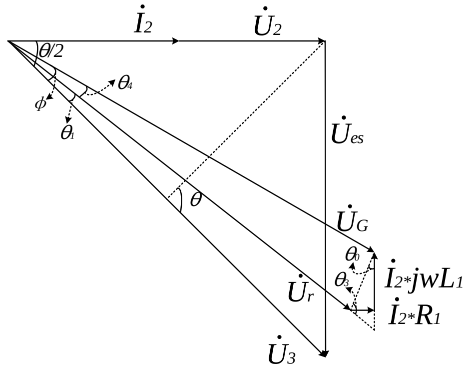

Fig 2. (b) Capacitive mode

Based on the above calculation results, we can obtain that when the ES operates in the inductive mode, the voltage $\dot{U}_G$ leads to the $\dot{U}_3$ by phaseφ, which satisfies the following relationship:

$$\Phi=\theta_1+\theta_4 \tag{9}$$

When the ES operates in capacitive mode, the phase angle relationship between $\dot{U}_G$ and $\dot{U}_3$ also satisfies the above relational equation. The difference is that the angle θ at this time is negative. Let φ be together with the given voltage amplitude on the sensitive load to make up the voltage reference $\dot{U}_{ref}$ .Using the one-cycle control method, the voltage value on the sensitive load can follow the reference voltage $\dot{U}_{ref}$ in real time.

3. Simulation verification on Matlab/Simulink platform

In order to verify the feasibility of the ES control strategy based on the one-cycle control technology, a simulation model should be built in MATLAB/Simulink. The system parameters used in the model are shown in Table 1.

Table 1. The simulation parameters of system

Project	**Parameter value**	**Project**	**Parameter value**
Voltage *Udc*	480*V*	Resistance *R1* of transmission line	0.1Ω
Sensitive load *R3*	60Ω	*Kp*	20
Non-sensitive load *R2*	5Ω	K_i	1
Inductance *L* of the low-pass filter	10*mH*	Pulse generator cycle *Ts*	1e-5*s*
Capacitance *C* of the low-pass filter	200*uF*	Pulse width of pulse generator	50%
Inductance *L1* of transmission line	2.4*mH*		

When the power of the PV grid-connected system is changed, the grid-side voltage will also change. In order to simplify the model, the change in the grid-connected power is simulated using the variation of the grid-connected voltage UG of the photovoltaic system.

To verify that the ES system based on single-cycle control has good support for the voltage on the sensitive load when the photovoltaic grid-connected power is suddenly reduced. Here, let the photovoltaic grid-connected voltage UG reduce from 240V to 190V at 0.3s. Simulating the system can obtain the waveform shown in Fig.3-5.

Fig.4 shows the voltage simulation waveforms of various parts of the system when the photovoltaic grid-connected voltage suddenly decreases with the ES. Fig.4-5 are the RMS voltage waveforms of the sensible load when ES is added or not added to the system when the photovoltaic grid-connected voltage suddenly decreases. When the PV grid-connected voltage decreases suddenly, it can be seen from Fig.4 that the phase angle of U2 leads Ues, The ES works in capacitive mode and absorbs some capacitive reactive power from the grid, and at the same time shifts the voltage fluctuation to the non-sensitive load.

Similarly, in order to verify that the ES system based OCC has a good suppression for the voltage on the sensitive load when the photovoltaic grid-connected power is suddenly increases. Here, let the photovoltaic grid-connected voltage UG increase from 205V to 252V at 0.3s. Simulating the system can obtain the waveform shown in Fig.6-8. It can be seen that when the photovoltaic grid-connected voltage UG increases, the ES system based on OCC plays a good role in suppressing the voltage U3 on the sensitive load.

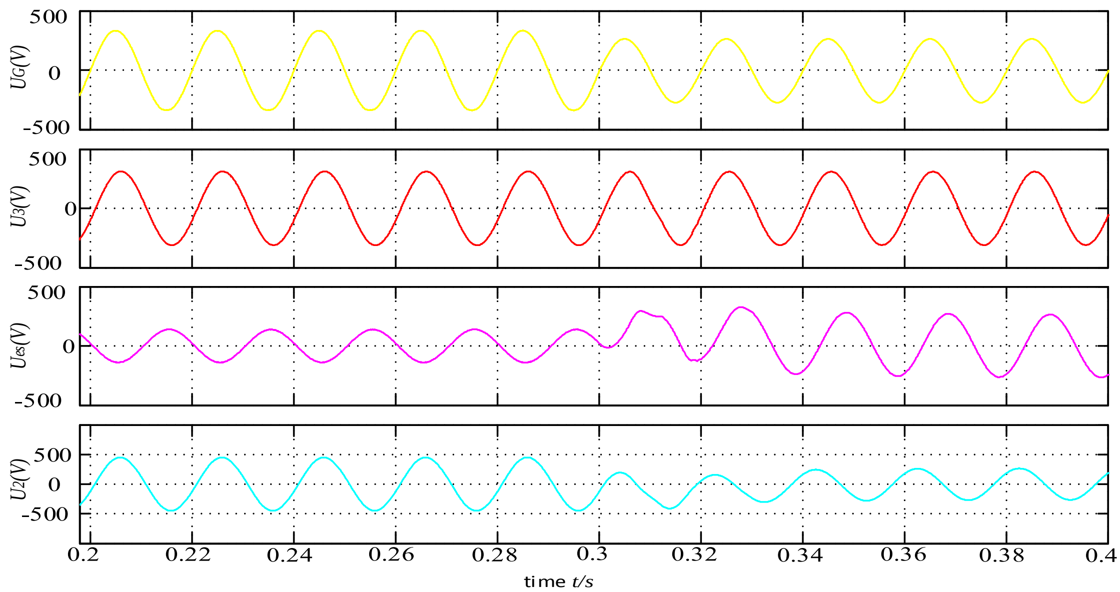

Fig 3. The simulation waveforms of various parts of the system when UG decreases suddenly (with ES)

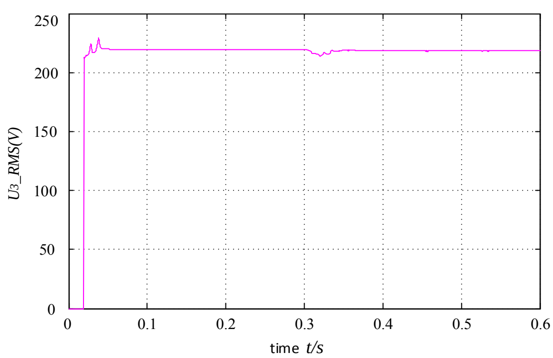

Fig 4. The RMS voltage on sensitive load when UG decreases suddenly (with ES)

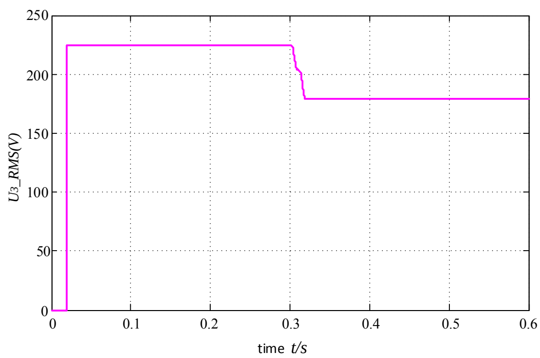

Fig 5. The RMS voltage on sensitive load when UG decreases suddenly (without ES)

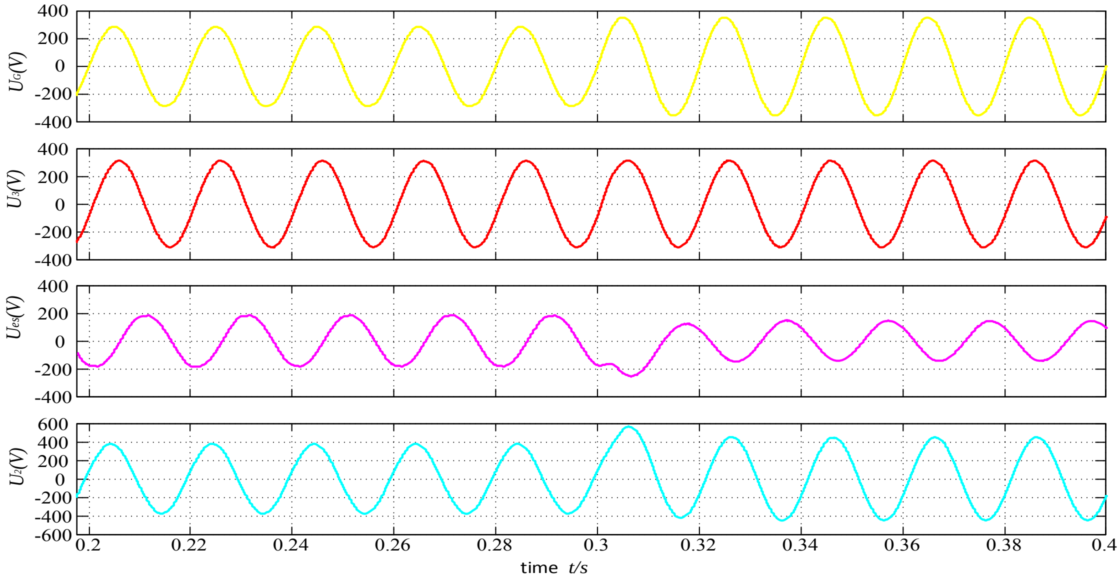

Fig 6. The simulation waveforms of various parts of the system when UG increases suddenly (with ES)

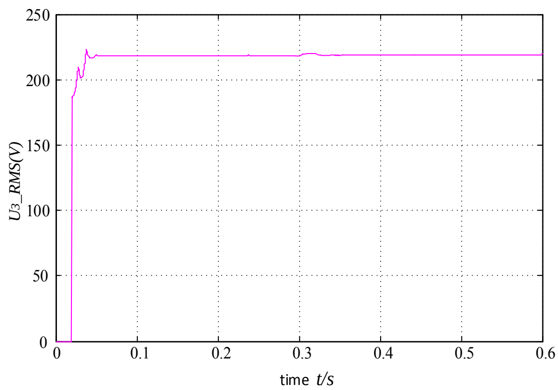

Fig 7. The RMS voltage on sensitive load when UG increases suddenly (with ES)

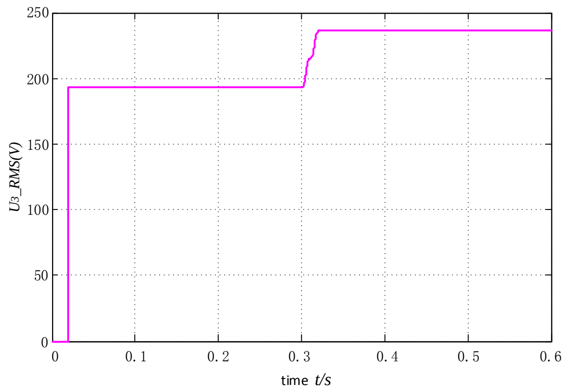

Fig 8. The RMS voltage on sensitive load when UG increases suddenly (without ES)

4. Summary

Aiming at the problems that the existing ES control strategy is complex and it is not conducive to tracking AC signals on sensitive loads, this paper proposes a ES control strategy based on single-cycle control technology. By modeling and simulating the ES system based on the OCC strategy in Matlab/SimulinK, we obtained:

(1)The ES control strategy based on OCC has advantages over other control algorithms: it has a very simple structure, eliminates tedious decoupling links and PR links, and can quickly achieve accurate tracking of given AC signals.

(2) When the power of photovoltaic system injected into the power grid fluctuates (expressed as the voltage fluctuation of the power grid), the ES system based on OCC can automatically operate in a capacitive or inductive mode, which can stabilize the voltage on the sensitive load while injecting a small amount of reactive power into the grid. At the same time, it can transfer the voltage fluctuation on the grid side to the non-sensitive load connected in series with the ES.

5. Acknowledgments

In this paper, the research was sponsored by the China Southern Power Grid Technology Project (GDKJQQ20152051).

References

[1] N. R. Chaudhuri, C. K. Lee, B. Chaudhuri, and S. Y. R. Hui, Dynamic modeling of electric springs, IEEE Trans. Smart Grid, vol. 5, NO. 5 SEPTEMBER 2014.
[2] CHENG Ming, WANG Qingsong, ZHANG Jianzhong. Theoretical Analysis and Controller Design of Electric Springs [J]. Proceedings of the CSEE, 2015, 35 (10): 2436-2444.
[3] Q. Wang, M. Cheng, Z. Zhen, and Z. Wang, "Steady-state analysis of electric springs with a novel δ control," IEEE Trans. Power Electro. vol. 30, no. 12, pp. 7159–7169, Dec. 2015.
[4] CHENG Yisheng, LU Zhengang, WANG Keyou. Analysis on Steady-state Operating Range and Off-limits Malfunction Mechanism of Electrical Spring [J]. Automation of Electric Power Systems, 2017, 41 (14): 147-152.
[5] Hui S Y R, Lee C K, Wu F. Electric springs—A new smart grid technology [J]. IEEE Transactions on Smart Grid, 2012, 3 (3): 1552-1561.
[6] Simulation of three-phase three-wire APF with modified one-cycle control based on space vector. Jidong Wang, Meicui Qin,Guanqing Yang. Innovative Smart Grid Technologies-Asia (ISGT Asia) 2012 IEEE. 2012
[7] Lee C K, Chaudhuri B, Hui S Y R. Hardware and control implementation of electric springs for stabilizing future smart grid with intermittent renewable energy sources [J]. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2013, 1 (1): 18-27.
[8] YAN S, LEE C K, YANG T B,et al. Extending the operating range of electric spring using back-to-back converters: hardware implementation and control [J]. IEEE Trans on Power Electronics, 2017, 32 (7): 5171-5179.