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Authors
Mao, Zhu
Han, Hua
Sun, Yao
et al.

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A Novel DCES based Voltage Control Stragety for Critical Load Supplied by Wireless Power

Zhu Mao, Hua Han, Yao Sun, Mei Su, Qi Zhu, Xiaochao Hou
School of Information Science and Engineering
Central South University
Changsha, China
1799442078@qq.com

***Abstract*—Although the wireless power transfer (WPT) has been used in a wide range of areas, there are many difficulties with the development of WPT. The load voltage quality problem caused by the high susceptibility of the delivered power to the surrounding is still a key issue to be solved. To guarantee a high quality of dc load voltage in WPT system, this paper proposes a novel voltage control strategy based on DC electric spring(DCES). The DCES is controlled to generate a dc voltage to regulate the voltage of critical loads while passing the fluctuating voltage to the non-critical loads. The operating principle and control strategy are analyzed in detail. To verify the effectiveness of the proposed technology in WPT system, simulations are carried out based on MATLAB/SIMULINK.**

Keywords—wireless power transfer(WPT), DC electric spring(DCES), critical load voltage, stabilization.

I. INTRODUCTION

Wireless power transfer (WPT) is a technology to transfer power from a transmitter to a mobile receiver over a relatively large air gap [1]. It was first proposed by Nikola Tesla in 1890s, and it is regarded as an emerging technology to transfer power nowadays. WPT is a hot spot of present research which can be applied effectively in a wide range of areas, such as electric vehicle [2], smart home [3], distributed ocean system [4], implantable medical device [5], etc. Compared with the traditional power transfer means, WPT has many advantages. The traditional power transfer uses the electrical connectors such as plugs and sockets to supply electrical appliances, which brings a lot of threatens. For example, the wire would be abraded for frequent using, and spark might be produced when the plug contacts the socket. These bring a great deal of problems to daily life, even do harm to people themselves. However, the WPT can overcome these shortcomings by reducing the use of electrical connectors. It seems that WPT can ensure more safe and convenient power supply and power consumption in some areas than traditional power transfer.

Although the WPT has brought much convenience to power system, there are some key technologies to be tackled to promote development and application of WPT. Most of all is the fluctuation caused by susceptibility of the delivered power to the surroundings. The fluctuation in the WPT system would affect the normal operation of the electrical appliances. In a WPT system, the fluctuation might be caused by: 1) the uncertainties of the source on the supply side; 2) the variety of the resonate capacitance or the resonate inductance; 3) the stochasticity of transmission distance between primary and secondary coil; 4) metal nearby or other disturbances; 5) the changes of loads; etc. When there is a fluctuation in the WPT system, the voltage of the load side could not remain its previous situation, that might lead to a series of problems. For example, when high permeability of distributed powers access to the grid, the intermittent of renewable sources might cause the fluctuation on the primary side. This fluctuation may result in the voltages of loads deviating from its operation points and even make the system unstable and ruin the electrical appliances in a smart home. As to an electric vehicle supplied by WPT, the voltage of the power system would fluctuate when there is a sharp turn in the process of charging, and the uneven running of the electric vehicle may occur. Thus, the voltage stability of a WPT system is very important.

To stabilize the voltage or power of dc loads, many methods have been used [6]-[7]. With the characteristics of fast response and high power density, the supercapacitor is regarded as an effective method to mitigate high frequency variations of loads and sources [8]. Due to the offset of current ripple in each phase, using interleaved converter is another mean to reduce the input current ripple and suppress the fluctuation of output dc voltage [9], which would be helpful to the dynamic response. As for control algorithm, the nonlinear differential flatness-based control has been proposed for dc bus stabilization [10].

Recently, DC electric spring(DCES) is proposed as an emerging technology to stabilize the bus voltage in dc grids. The feasibility of using DCES for bus voltage stabilization and power balancing in dc grids is reported in [11]. A new topology of DCES based on only DC/DC converters is proposed and analyzed in [12]. There are many advantages of using ES, including stabilizing the voltage fluctuation [13], improving power quality [13], reduction of energy storage requirements [14], etc. So far, the study of applying DCES to WPT system for stabilizing the dc load voltage has not been touched.

Based on mechanical spring in physics, the concept of electric spring(ES) was proposed to stabilize ac bus voltage at first. It is an electric device that generates an AC voltage to regulate the voltage of critical loads while passing the fluctuating voltage to the non-critical loads [15]-[18]. In conventional control methods, the control schemes are usually applied on the power-supply side [19]. Compared with the conventional methods, the ES technology is applied on the demand side directly to realize the power balancing between the supply side and demand side [11], [20].

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In this paper, the DCES method is introduced firstly to stabilize the critical load voltage supplied by wireless power. It can be used in smart home, electric vehicle, etc. Compared with ac grids, frequency and phase synchronization are not required in dc grids [21]. The theories and analysis of ES in a dc grid are similar to but easier than that in a ac grid. Using DCES can realize boosting or suppression function when the voltage of dc bus is lower or higher than the predefined voltage. The operating principle of the WPT system with DCES is analyzed and the small-signal dynamic model of DCES is expatiated in section II. The control strategy is introduced in section III. Simulations based on MATLAB/SIMULINK are discussed in section IV to verify the aforementioned analysis.

II. Proposed WPT System with DCES

Fig.1 illustrates the system structure of the proposed WPT system with DCES. The whole WPT system is divided into two parts, the primary side and the secondary side. After power is transferred to the secondary part through the coils, an uncontrolled rectifier is needed to transform the ac voltage into dc voltage, then a LC filter is designed to guarantee the stable dc load voltage.

In Fig.1, the primary coil is represented by an inductor L_p, which is connected with a reactive power compensator, forming a resonant tank. Similarly, the secondary pick-up coil is represented by L_s, which is also connected with a reactive power compensator to form a resonant tank. The reactive power compensators C_p and C_s are designed to form resonance by compensating inductive reactive power, so that more active power can be transferred to the secondary side. The transfer efficiency can be increased as well. The series resistance R_p and R_s represent the overall parasitic resistances of the primary and the secondary side, respectively. The DC inductor L_1 and capacitor C_1 form a filter, ensuring voltage supplied to the load side smoothly and continuously.

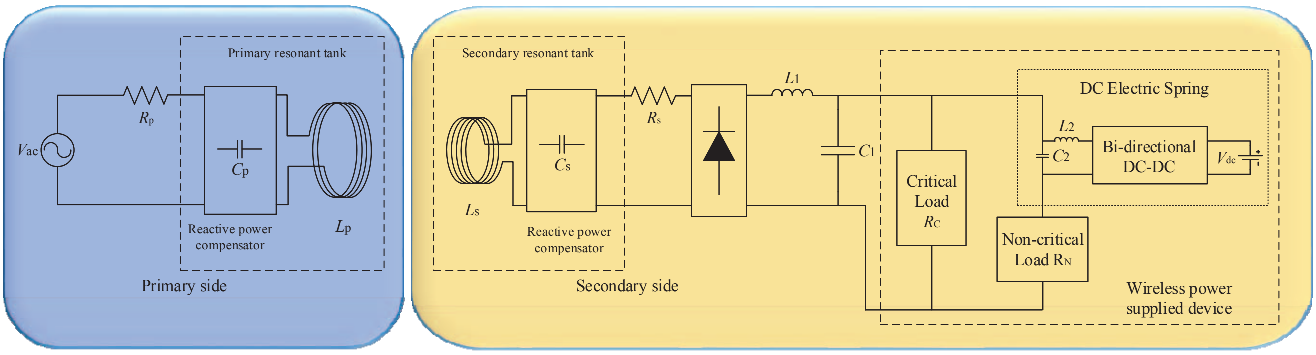


Fig. 1. System configuration of proposed WPT system with DCES.

A. Operating Principle of the WPT system with DCES

The electric loads in the device can be divided into two categories: critical loads and non-critical loads. The critical loads must work on the voltage with little fluctuation, so the voltage of the critical loads must be well-regulated to get a high voltage quality. However, the non-critical loads can tolerate a wider range of voltage and power fluctuation. In this paper, both the critical load and non-critical load are represented by resistors R_C and R_N respectively, as shown in Fig.1. The DCES is connected along with the non-critical load to form a smart load paralleled with the critical load.

As introduced in section I, uncertainty of power supply or load, or the variety of transmission distance may result in voltage fluctuation of the critical load. In these cases, the DCES is able to pass the fluctuation to the non-critical load, and generate a dc voltage to regulate the voltage of critical load. The DCES consists of bidirectional DC/DC converter connected to a series of batteries. When the critical load voltage V_C is lower than the predefined value V_{C_ref}, the batteries are discharged through the bidirectional DC/DC converter. Such operation makes sure power flows from batteries to critical load, which is voltage boosting mode. When V_C is higher than V_{C_ref}, the batteries are charged, which is called voltage suppression mode.

B. Small-Signal Dynamic Model of DCES based WPT system

The circuitry of a DCES embedded in a device supplied by wireless power is shown in Fig.2. V_1 is the output dc voltage of the uncontrolled rectifier through the LC filter, R_L represents the line impedance, V_a is the output voltage of the bidirectional DC/DC converter.

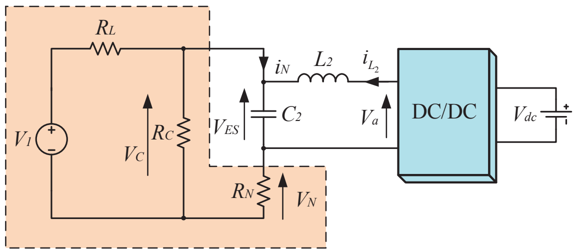


Fig. 2. Equivalent circuit of a DCES embedded in a device supplied by wireless power.

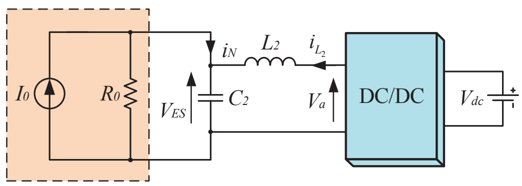


Fig. 3. Simplified circuit of Fig. 2.

Fig. 2 is further simplified to Fig. 3, the circuit in the dashed line in Fig. 2 is equivalent to that in Fig. 3. R_0 is obtained according to the Norton's theorem.

$$R_0 = \frac{R_L R_C + R_C R_N + R_N R_L}{R_L + R_C} \tag{1}$$

$$I_0 = V_1 \times \frac{R_C}{R_L R_C + R_C R_N + R_N R_L} \tag{2}$$

Using Kirchhoff's voltage and current laws (KVL and KCL), the state equation of the DCES is derived as follows

$$\begin{cases} L_2 \dfrac{di_{L_2}}{dt} = V_a - V_{ES} \\ C_2 \dfrac{dV_{ES}}{dt} = i_{L_2} + \dfrac{V_C - V_{ES}}{R_N} \end{cases} \tag{3}$$

where L_2 and C_2 are the inductor and capacitor of the DCES, i_{L_2} is the current of L_2, V_{ES} is the output voltage of DCES.

With Laplace transform, the corresponding small-signal model equation of (3) is obtained, shows in (4)

$$\begin{cases} sL_2 \hat{i}_{L_2}(s) = \hat{V}_a(s) - \hat{V}_{ES}(s) \\ sC_2 \hat{V}_{ES}(s) = \hat{i}_{L_2}(s) + \dfrac{\hat{V}_C(s) - \hat{V}_{ES}(s)}{R_N} \end{cases} \tag{4}$$

where $\hat{V}_a(\mathrm{s})$, $\hat{V}_{ES}(\mathrm{s})$, $\hat{i}_{L_2}(\mathrm{s})$, $\hat{V}_C(\mathrm{s})$ are the small-signal ac values of $V_a(\mathrm{s})$, $V_{ES}(\mathrm{s})$, $i_{L_2}(\mathrm{s})$, $V_C(\mathrm{s})$, respectively.

KCL in Fig. 3 is expressed as

$$sC_2 \hat{V}_{ES}(s) = \hat{i}_{L_2}(s) + \hat{I}_0(s) - \frac{\hat{V}_{ES}(s)}{R_0} \tag{5}$$

The critical load voltage can be solved from (4) to (5) as follows

$$\hat{V}_C(s) = \frac{(R_0 - R_N)\hat{V}_a + (s^2 L_2 C_2 R_N + sL_2 + R_N) R_0 \hat{I}_0}{s^2 L_2 C_2 R_0 + sL_2 + R_0} \tag{6}$$

Through (6), it is inferred that the ES system can be regarded as a single phase DC/DC converter with an active load. I_0 represents the equivalent current source. When there is a fluctuation transferred from WPT system, the value of I_0 varies at a certain range.

III. Control Strategy of the WPT System with DCES

In this section, the control strategy of the whole system is discussed. The control of WPT system and DCES are introduced respectively.

A. Control strategy of the WPT system

As is shown in Fig. 1, the left part of whole system is a WPT system. The main problem of the WPT is to maximize the transfer efficiency. In some researches on WPT, the ac source on the primary side is obtained by a dc source connected with an inverter, as shown in Fig. 4. The capacitor C_p, C_s are series with L_p, L_s respectively to form resonance.

$$\omega_0 = \frac{1}{\sqrt{L_p C_p}} = \frac{1}{\sqrt{L_s C_s}} \tag{7}$$

The resonant capacitor C_p and C_s, which match the coil inductances L_p and L_s at the operating frequency ω_0 according to (7), are applied both on the primary and secondary side.

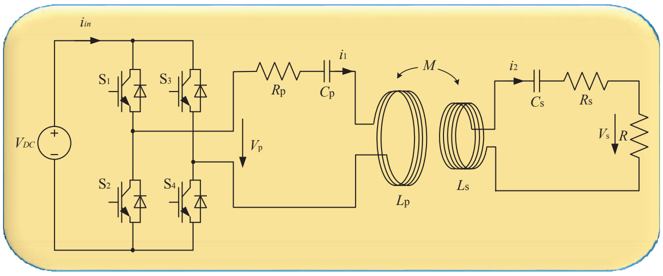


Fig. 4. The completed diagram of the WPT system.

The inverter is operated under the control of phase shift modulation scheme [22]. θ is defined as the phase shift between the two inverter legs. With all higher harmonics and losses are neglected, the fundamental inverter output voltage V_p in dependence on the phase shift θ can be obtained according to (8) by means of the Fourier transform

$$V_p = \frac{2\sqrt{2}}{\pi} V_{DC} \sin(\frac{\theta}{2}) \tag{8}$$

Under the phase shift control, the IGBTs of the leading inverter legs can be switched on the condition of zero current with turn-on switching losses. In contrast, the IGBTs of the lagging inverter legs can be operated on the condition of zero voltage with turn-off switch losses.

B. Control strategy of the DCES

When there is a fluctuation in the WPT system, the normal operating mode of critical loads would be broken. In the discussion of the control strategy of the DCES, the WPT part can be simplified to a ac source V_s. The DCES in Fig. 5 is implemented with a half-bridge inverter, which is connected with the inductor L_2 to act as a DC/DC converter. From this diagram, each switch is paralleled with a snubber circuit to protect the switching element from overvoltage and overcurrent.

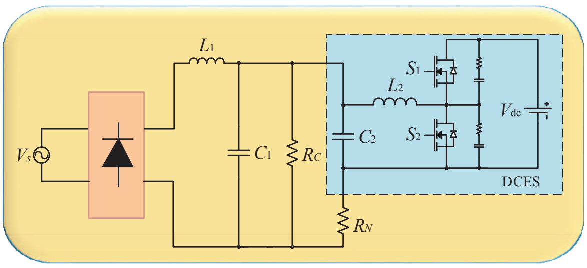


Fig. 5. Simplified model of the devices with DCES.

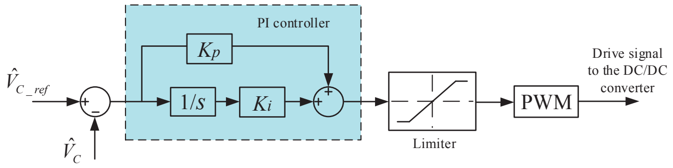


Fig. 6. Control block diagram of the DCES.

$$G_{pi}(s) = K_p + \frac{K_i}{s} \tag{9}$$

Fig. 6 shows the control diagram of the DCES. A typical PI controller is used to control the DCES to maintain the voltage of the critical load. Its transfer function is represented in (9). K_p and K_i are the proportional and integral coefficients of the PI controller, respectively. $\hat{V}_{C\_ref}$ is the small-signal value of the reference of V_C. Whenever there is fluctuation in the voltage of critical load, an error signal between $\hat{V}_{C\_ref}$ and $\hat{V}_C$ would be generated, which is processed by PI controller and PWM generator to generates drive signal to feed the DC/DC converter.

IV. Simulations and Discussions

To verify the aforementioned analysis, simulations are conducted using MATLAB/SIMULINK. The simulation circuit is shown in Fig. 1 and parameters are given in Table I. In this section, the variety from both supply side and load side are considered and discussed.

TABLE I. Parameters of Circuit and Contrllers

Description	*Parameter*	*Value*
Reference of critical load voltage	V_{C_ref}	50V
Battery voltage	V_{dc}	100V
DC source on the primary side	V_{DC}	200V
Line resistance	R_p , R_s	5 Ω
Inductor of the primary resonant tank	L_p	24 μ H
Capacitor of the primary resonant tank	C_p	46 μ F
Inductor of the secondary resonant tank	L_s	10 μ H
Capacitor of the secondary resonant tank	C_s	110 μ F
Operating frequency of resonant tank	ω_0	30KHZ
Resistance of critical load	R_C	50 Ω
Resistance of non-critical load	R_N	10 Ω
Inductor of the filter in DCES	L_2	1mH
Capacitor of the filter in DCES	C_2	1 μ F

A. The variety on the supply side

When there are only disturbances on the primary side, the power transferred to the secondary side varies as well, and the output voltage of the secondary side is shown in Fig.7.

The voltage waveforms in Fig. 7 is divided into two parts. In the first part, at t = 0~1s, the power transferred to the secondary side is stable. In the second part, the supply-side voltage with a fluctuating profile is applied at t = 1~2s.

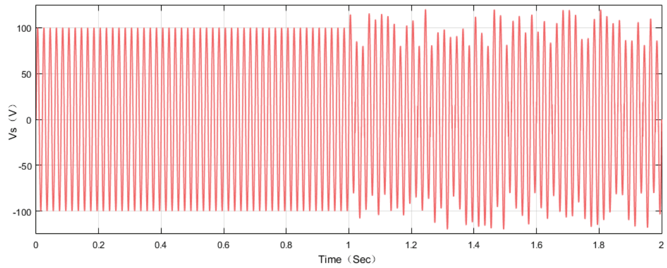
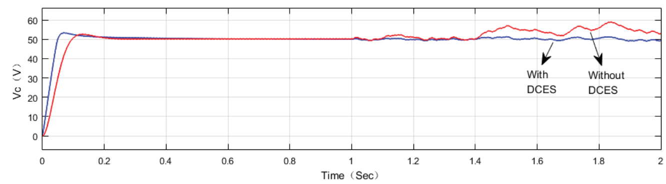
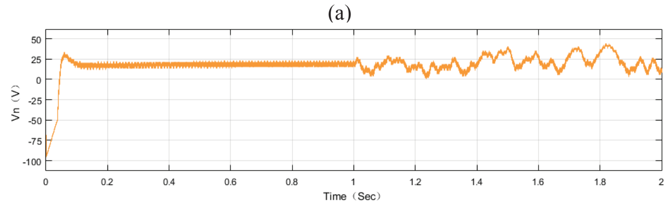


Fig. 7. Output voltage of the secondary side.

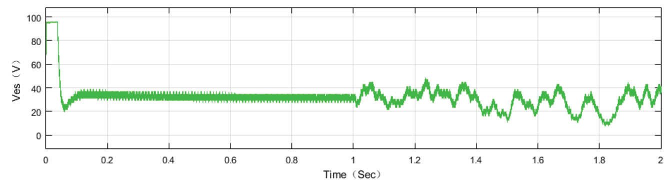
Fig. 8(a) shows the voltage curve of V_C without and with DCES operated on the secondary side. At t = 0~1s, the device works in a normal condition, and the voltage of the critical load is stable and kept at 50V. When the disturbance appears at t = 1s, the output voltage of the WPT system varies. The voltage of critical load could not remain at the previous value without DCES. The maximum deviation reaches nearly 10V, which occupied 20% of the set critical load voltage. However, with the DCES operates, the fluctuation is passed to the non-critical load, and a dc voltage is generated to regulate the voltage of critical load, so that the critical load voltage still remains around 50V. The maximum deviation is regulated in 1.5V, 3% of the set critical load voltage. Fig.8(b) and (c) shows the voltage waveforms of the non-critical load and DCES, respectively.



(a)



(b)



(c)

Fig. 8. The voltage with variety on the supply side (a) The voltage curve of the critical load without and with DCES operated. (b) The voltage curve of the non-critical load. (c) The voltage curve of the DCES.

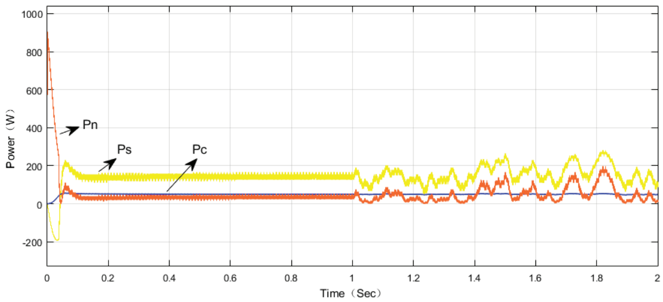
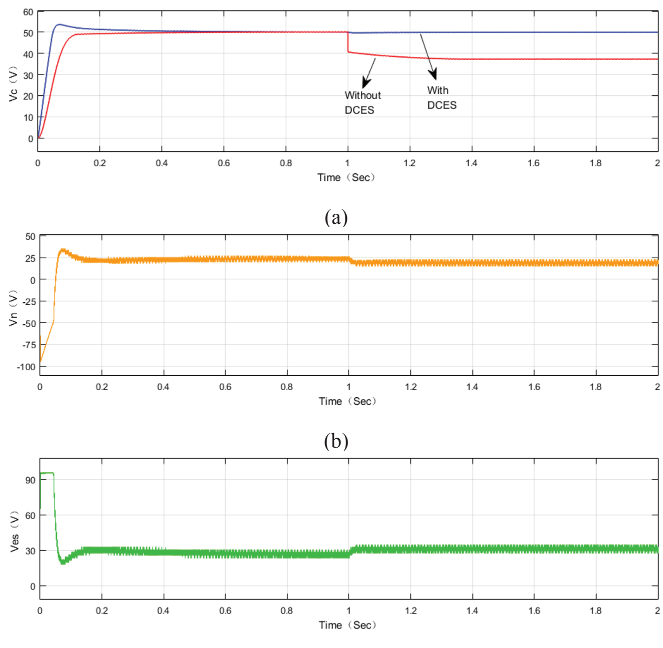


Fig. 9. The power waveform of secondary side Ps, critical load Pc, non-critical load Pn.

With DCES operated, the power waveforms of secondary side, critical load, non-critical load are given in Fig.9, named P_s, P_c, P_n, respectively. It can be seen that even there is a disturbance on the supply side, the power of critical load is remained steady. The power fluctuation can be passed to the non-critical load, which explains the phenomenon that P_n varies following P_s.

B. The variety on the load side

When one of the critical loads changes, the voltage waveforms of the other critical loads, non-critical load, DCES are shown in Fig.10. There is no load variety in the first 1s. At t = 0~1s, the loads work as usual, and the voltage of the other critical loads kept at 50V. However, when a change on the load side occurs at t = 1s, it can be seen from Fig.10(a) that the voltage of other critical loads still keeps around the previous value 50V with DCES operated while decreases over 10V without DCES. It can be confirmed that with DCES operating, one of the critical loads changes would not affect the normal working of the other critical loads, they could still work under the voltage with high electric quality.



(c)

Fig. 10. The voltage with variety on the load side (a) The voltage curve of the critical load without and with DCES operated. (b) The voltage curve of the non-critical load. (c) The voltage curve of the DCES.

Fig.10(b) gives the voltage curve of the non-critical load, it shows that when one of the critical loads changes, the fluctuation of voltage would be passed to the non-critical load, which results in the voltage of the non-critical load droops at t = 1s. At = 1~2s, the voltage of the non-critical load would stay on a new level. Fig.10(c) gives the voltage of DCES, which generates voltage to regulate the voltage of the other critical loads remain unchanged so that they can work normally.

The two kinds of fluctuation from the supply side and the load side can represent the typical fluctuations appear in the WPT system. The effectiveness of DCES is verified by simulations.

V. Conclusion

A novel DCES based voltage controller is proposed to improve the quality of the critical load voltage supplied by wireless power. This DCES is controlled to stabilize the voltage of critical loads by passing the fluctuating to the non-critical loads when any fluctuation occurs in the WPT system. The small signal mathematical model of a WPT system with the proposed DCES is established, and a PI controller is designed to improve the stability and steady-state performance of system.

The simulation results show that no matter the fluctuation is from the supply side or the load side, the DCES can work effectively and keep the voltage stabilization of the critical load. The feasibility of the DCES is verified.

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