IOP Conference Series: Earth and Environmental Science

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Research on Ground Current of High-Power Series Chopper Circuit

To cite this article: Peifei Li *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **252** 032105

Research on Ground Current of High-Power Series Chopper Circuit

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Abstract. The ground current equivalent circuit of the series chopper circuit is proposed. The ground current of the following two switching modes is analysed: The IGBT of the upper chopper circuit is turned on when the IGBT of the lower chopper circuit is in the off state; The IGBT of the upper chopper circuit is turned off when the IGBT of the lower chopper circuit is in the off state. The ground current paths of the two switching modes are analyzed, and the mechanism of ground current crosstalk between the upper and lower chopper circuits in the series chopper circuit is obtained. The analysis is verified by simulation and experimentation.

1. Introduction

Three level NPC inverter is widely used in high-power motor speed control system [1,2], the DC side voltage of the inverter will be pumped up during the motor braking process. Currently, two methods are mainly used to prevent the DC side overvoltage: energy regenerative braking and energy dissipation braking. Energy regenerative braking converts the mechanical energy of the motor into electrical energy and feeds it back to the grid, stores it in a battery or supercapacitor. Energy dissipative braking converts mechanical energy into electrical energy and then dissipates it over the energy dissipation resistor. Energy regenerative braking can effectively utilize energy, which is beneficial to improve the overall efficiency of the system. However, energy regenerative braking requires the energy conversion device have the ability to bidirectionally circulate energy, and the device is complicated. Energy dissipative braking dissipates energy through the energy dissipation resistor to suppress the DC side overvoltage, and the efficiency is lower than energy regenerative braking, but the device is simpler. The series chopper circuit is often used to suppress the pumping of the DC side voltage of the three-level NPC inverter drive system, and adjust the speed of the energy dissipation by adjusting the duty cycle of the IGBT, thereby achieving a smooth control of the DC side voltage.

When the IGBT is turned on and off at a high speed, a large dv/dt is generated, thereby charging and discharging the stray capacitance to generate ground current. Much work was carried out to investigate the ground current, Reference [3] investigated the effects of parasitics on ground current via simulation and measurement. A method using a cancellation winding coupled to inductors was proposed to reduce the ground current of converters [4,5]. A common-mode choke had been used to reduce the undesirable ground current, which is connected in series between the terminals of an inverter and those of a motor [6,7]. The ground current may have an undesirable influence on the motor current control and may result in incorrect operation of residual current-operated circuit breakers[8]. These articles are mainly about the hazard and suppression of ground current. There is little researches on ground current crosstalk between circuits.

In this paper, the ground current model of the series chopper circuit is established. According to the model, the ground current path in different switching modes is analyzed. The ground current crosstalk between the upper chopping circuit and the lower chopping circuit is studied and verified by simulation and experiment.

2. Ground current model

2.1. High-power series chopper circuit

The schematic diagram of the series chopper circuit is shown in Fig. 1. S1 and S2 are the IGBTs of the upper and lower chopper circuits respectively. S1 and S2 adjust E1 and E2 respectively, and S1 and S2 are symmetrical. The results of the study on S1 are applicable to S2. This paper mainly studies the ground current generated by S1 turning on and off when S2 is in the off state.

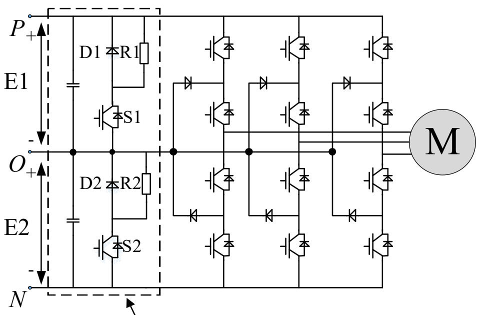

Figure 1. Schematic diagram of the series chopper circuit.

Fig. 2 is the circuit diagram of the high-power series chopper circuit considering main stray parameters. L1 and L2 are the inductances of the connecting cables of the energy dissipation resistor R1, and L3 and L4 are the inductances of the connecting cables of R2. The DC power supply is connected to the IGBT through the busbar, and the inductance and resistance are small, for this reason, the connection impedance between them is ignored. C1 and C2 are the stray capacitances of R1 and R2 respectively. R1 and R2 are often arranged close together, the connection inductance and resistance are small, for this reason, the resistance and inductance between C1 and C2 are ignored. Since R1 and R2 are the same, it can be considered that C1 and C2 are equal, L1, L2, L3, and L4 are equal. The experiment platform parameters studied in this paper are shown in Table 1. L1, L2, L3, L4, C1 and C2 are all measured by an impedance meter. The research methods of this paper are applicable to series chopper circuits with other parameters.

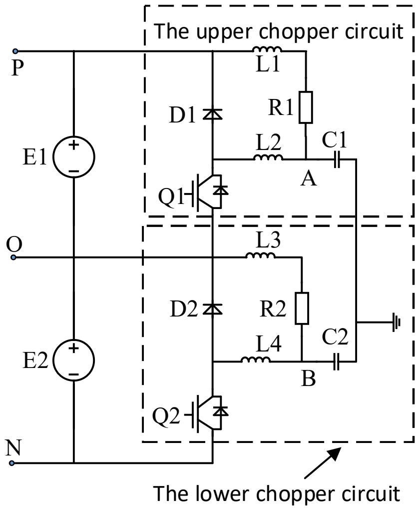

Figure 2. Series chopper circuit considering main stray parameters.

Table 1. The main parameters of the series chopper circuit studied in this paper

E1, E2	1100V
L_1, L_2, L_3, L_4	2uH
C_1, C_2	0.11uF
R_1, R_2	0.4Ω
Power of R1 and R2	3.03MW
IGBT(S1, S2)	FZ3600R17HP4_B2
Diode(D1, D2)	DZ3600S17K3_B2

2.2. Turning on S1 when S2 is in off state

In the high-power series chopper circuit, the connecting cable of the energy dissipation resistor is usually long, so the circuit time constant is large, the IGBT turn-on transient duration is much smaller than the circuit time constant. Therefore, the IGBT can be considered as an ideal switch. Taking O as the reference potential, when S1 is in the off state, the potential of point A is E, the potential of point A is the same as the potential of O after S1 is turned on. The potential of point A changes after S1 is turned on. The current flowing through R1 after S1 is switched on is shown in Fig. 3. When IGBT is turned on, the voltage excitation generated at point A is shown in equation (1).

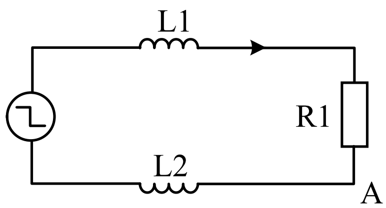

Figure 3. Current flowing through the energy consuming resistor R1 after S1 is turned on.

$$V1(s) = -\frac{E(sL+R)}{s(2sL+R)} \tag{1}$$

After S1 is turned on, D1 is in the reverse-off state, the ground current does not flow through it; S2 is in the off state, and its freewheeling diode is in the reverse-off state, ground current does not flow through it. Fig. 4 shows the current path when S1 is turned on and S2 is in the off state. When analyzing the ground current, the voltage source can be regarded as a short circuit, so the ground current equivalent circuit can be obtained as shown in Fig. 5.

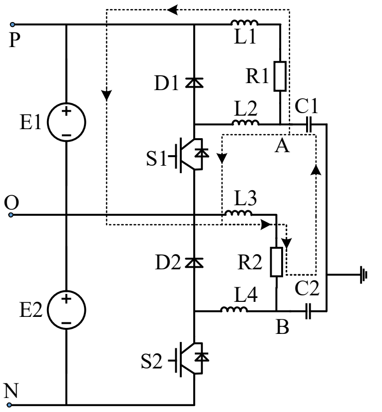

Figure 4. Ground current path when S1 is turned on and S2 is in the off state.

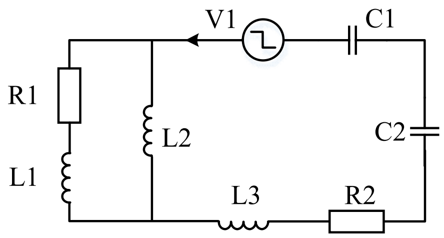

Figure 5. Equivalent circuit of Fig. 4.

From the above equivalent circuit, the current response under the excitation of voltage V1(s) can be obtained as follows:

$$I(s) = -\frac{EC(sL+R)}{3s^3L^2C+4s^2RLC+(4L+R^2C)s+2R} \tag{2}$$

The pole-zero map of equation (2) is shown in Fig. 6. Equation (2) has three poles, one real pole p2 and one pair of complex conjugate poles p1, the real pole is negative, far from the imaginary axis, a pair of complex conjugate poles are to the left of the imaginary axis, and are closer to the imaginary axis. Equation (2) has a real zero. For this reason, the dominant pole of equation (2) is a pair of complex conjugate poles p1, and the conjugate poles can be expressed as the sum of the real part and the imaginary part.

$$p_1 = -\sigma \pm j\omega_d \tag{3}$$

Similar to the second-order system, the damping coefficient can be defined as:

$$\varsigma = \frac{\sigma}{|p_1|} = \frac{\sigma}{\sqrt{\sigma^2+\omega_d^2}} = \frac{\sigma}{\omega_0} \tag{4}$$

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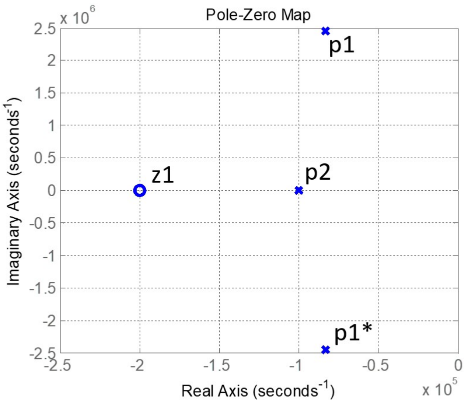

Figure 6. The pole-zero map of equation (2).

From the circuit parameters of table 1. $0 < \varsigma < 1$ can be obtained. For this reason, the ground current system is an underdamped system, and the ground current will resonate.

When the ground current resonates and the current direction is opposite, S2 is in the off state, and its freewheeling diode is in the reverse-off state, and the ground current does not flow through it. Fig. 7 shows the ground current path, the equivalent circuit can be obtained as shown in Fig. 8.

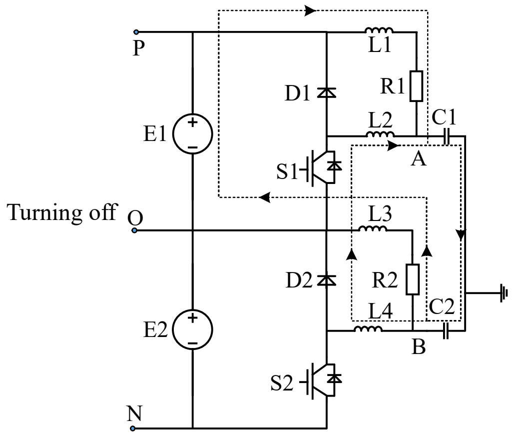

Figure 7. Reverse ground current path when S1 is turned on when S2 is in the off state.

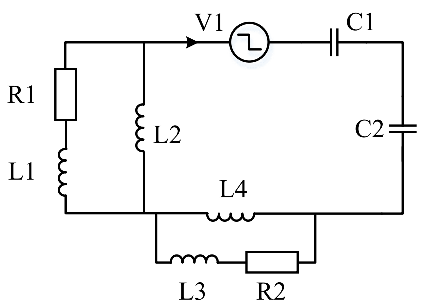

Figure 8. Equivalent circuit of Fig. 7.

From the above equivalent circuit, the current response under the excitation of voltage V1(s) can be obtained as follows:

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$$I(s) = -\frac{EC(sL+R)}{2s^3L^2C + 2s^2RLC + 4sL + 2R} \tag{5}$$

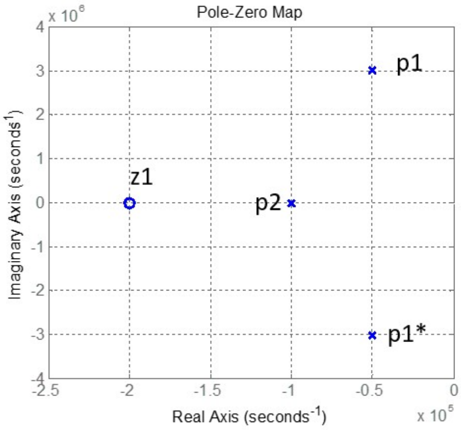

Figure 9. Pole-zero map of equation (5).

The pole-zero map of equation (5) is shown in Fig. 9. Similarly, we can know that the ground current system is also an underdamped system when it is reversed.

It can be seen from the above analysis that turning on S1 when S2 is in the off state, the forward and reverse ground current path are both underdamped systems, and for this reason, the current will resonate. The ground current flows through D2 when it is reversed.

2.3. *Turning off S1 when S2 is in off state*

Taking O as the reference potential, when S1 is in the on state, the potential of point A is consistent with the potential of point O. After the S1 is turned off, the potential of point A is E. The potential of point A changes after S1 is turned off. The current flowing through R1 after S1 is switched off is shown in Fig. 10. When IGBT is turned off, the voltage excitation generated at point A is shown in equation (6).

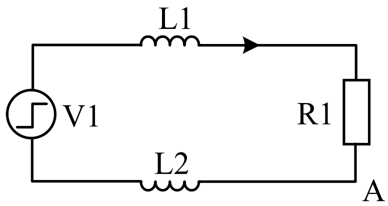

Figure 10. Current flowing through the energy consuming resistor R1 after S1 is turned off.

$$V1(s) = \frac{E(sL+R)}{s(2sL+R)} \tag{6}$$

Fig. 11 shows the current path when S1 is turned off and S2 is in the off state. the equivalent circuit of Fig. 11 is shown in Fig. 12.

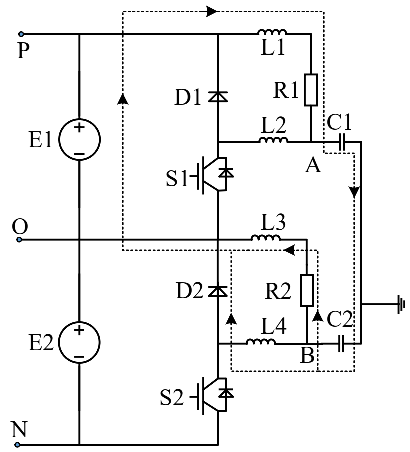

Figure 11. Ground current path when S1 is turned off and S2 is in the off state.

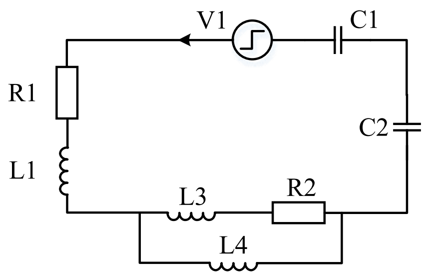

Figure 12. Equivalent circuit of Fig. 10.

From the above equivalent circuit, the current response under the excitation of voltage V1(s) can be obtained as:

$$I(s)=\frac{EC(sL+R)}{3s^3L^2C+4s^2RLC+(4L+R^2C)s+2R} \tag{7}$$

The pole-zero map of equation (7) is shown in Fig. 13.

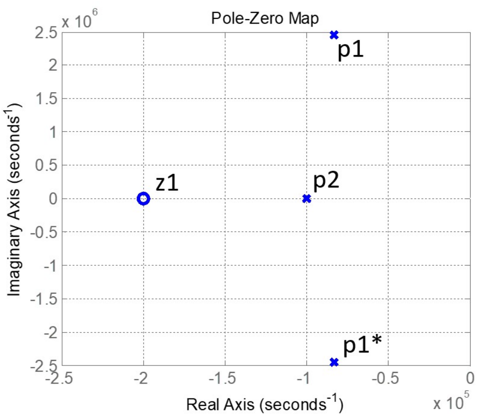

Figure 13. Pole-zero map of equation (7).

Similarly, the ground current system is an underdamped system, and the ground current will resonate.

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When the ground current resonates and the current direction is opposite, S1 and S2 are in the off state, and their freewheeling diodes is in the reverse-off state, the ground current does not flow through them. Fig. 14 shows the ground current path, the equivalent circuit can be obtained as shown in Fig. 15.

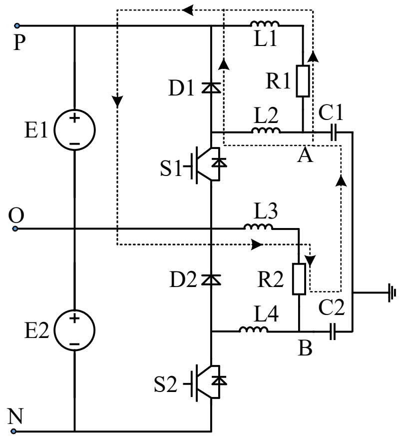

Figure 14. Reverse ground current path when S1 is turned off and S2 is in the off state.

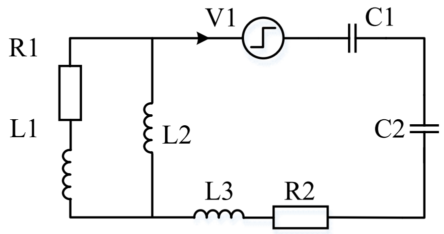

Figure 15. Equivalent circuit of Fig. 13.

From the above equivalent circuit, the current response under the excitation of voltage V1(s) can be obtained as follows:

$$I(s)=\frac{EC(sL+R)}{3s^3L^2C+4s^2RLC+(4L+R^2C)s+2R} \tag{8}$$

The zero-pole map of equation (8) is shown in Fig. 16. The analysis shows that S2 is in the off state and S1 is turned off, the forward and reverse ground current path are both underdamped systems, and for this reason, the current will resonate. The ground current flows through D2 when it is opposite.

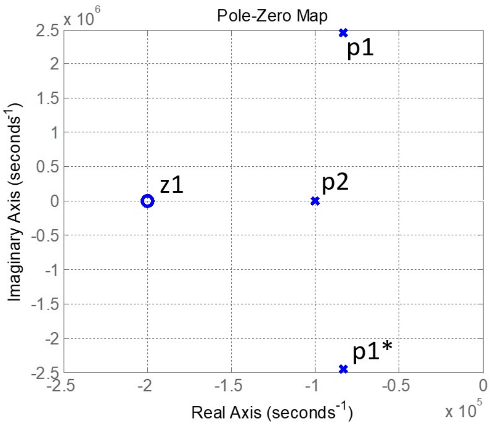

Figure 16. Pole-zero map of equation (8).

3. Simulation and experiment verification

In order to verify the correctness of the proposed ground current equivalent circuit and analysis, a series chopper circuit experiment platform was built. The experiment platform is shown in Fig. 17. The main parameters of the test platform are shown in Table 1.

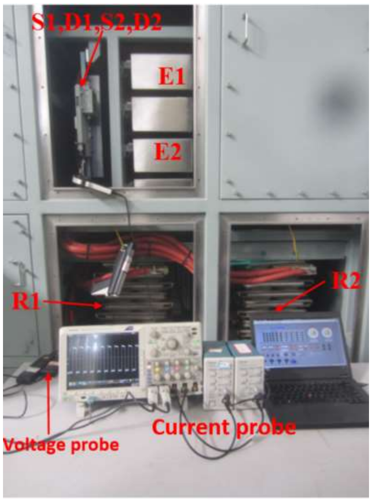

Figure 17. Photo of the experiment platform.

The simulation waveform when S1 is turned on and S2 is in the off state is shown in Fig. 18, Fig. 19 shows the experiment results. The simulated waveform when S1 is turned off and S2 is in the off state is shown in Fig. 20, Fig. 21 shows the experiment results. VD1 is the voltage across D1, ID2 is the current flowing through D2, and IG is the ground current.

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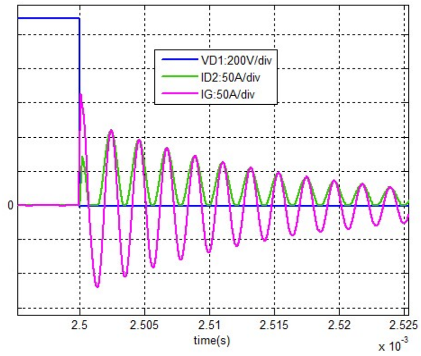

Figure 18. The simulation waveform when S1 is turned on and S2 is in the off state.

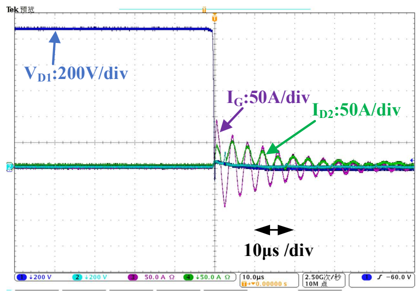

Figure 19. The experiment results when S1 is turned on and S2 is in the off state.

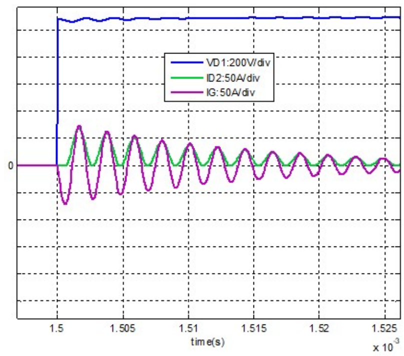

Figure 20. The simulation waveform when S1 is turned off and S2 is in the off state.

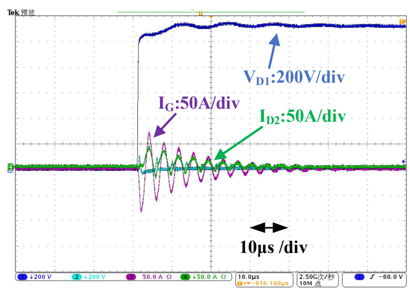

Figure 21. The experiment results experiment results when S1 is turned off and S2 is in the off state.

It can be seen from Fig. 18 and Fig. 19 that when S1 is turned on and S2 is in the off state, the simulation waveform is in good agreement with the experiment results. The ground current flows through D2 when it is reversed.

When S1 is turned off and S2 is in the off state, the simulated waveform is also in good agreement with the experiment results, as shown in Fig. 20 and Fig. 21. The ground current flows through D2 when it is opposite.

Turning on S2 when the ground current flows through the freewheeling diode D2 may cause D2 to be hard-off. The freewheeling diode used in the high-voltage and high-power applications is generally a PIN-structured diode, and the PIN-structured diode is in the hard-off process may produces large voltage resonances and voltage spikes, which generate strong electromagnetic interference and increase the loss of freewheeling diodes. In severe cases, the freewheeling diodes will fail due to voltage spikes. That is, the ground current generated when the upper chopper circuit IGBT is turned on will flow through the freewheeling diode in the lower chopper circuit, and affects the operation of the lower chopper circuit, this is the ground current crosstalk phenomenon in series chopper circuit.

4. Conclusion

In this paper, the ground current equivalent circuit of series chopper circuit in two switching modes is proposed. Based on the equivalent circuit, the ground current is analyzed, and the mechanism of current crosstalk between the upper and lower chopper circuits is obtained. Based on the equivalent circuit, the ground current can be predicted. It provides a theoretical basis for eliminating ground current crosstalk between the upper and lower chopper circuits.

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