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Analysis on voltage oscillation of a mid-frequency series resonant inverter for DRMP coils on J-TEXT

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HIGHLIGHTS

- The reason of high-voltage oscillation of a series resonant inverter for DRMP coils is analyzed.
- The condition or method for reduction of high-voltage oscillation is discussed.
- The considerations of dead time and switch frequency for reduction of high-voltage oscillation are discussed.

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ABSTRACT

This paper deals with the voltage oscillation of an AC power supply for generating dynamic magnetic perturbation (DRMP) on J-TEXT. The power supply is a series resonant inverter with a matching transformer. It was noted that the high-voltage oscillation at transformer primary side is caused by an interaction between the line inductance and the stray capacitance of the matching transformer at switching transitions. In order to reduce the high-voltage oscillation and consider the requirement for soft-switching technique simultaneously, the switching frequency should be chosen properly by fine-tuning. The dead time should be chosen according to the relative size of minimum required dead time for protection and the optimal dead time.

1. Introduction

In scientific research of controlled nuclear fusion, power supplies based on semiconductor switch are widely used for producing magnetic field. Among them series resonant inverter is the most popular topology for generating dynamic magnetic perturbation (DRMP) [1]. The electrical parameters and topology of the AC power supply for DRMP coils on J-TEXT were described in Ref. [1], and the semiconductor switch of it is Insulated Gate Bipolar Transistor (IGBT). This topology can decrease the switching frequency and the reactive power of load can be compensated locally. In addition, soft-switching technique can be applied to reduce the semiconductor losses and extend lifetime of the switches. The load parameters of this topology are invariable generally and the current of load is adjusted by changing the DC-link voltage of phase-shift full-bridge converter. To improve the magnitude of the output current, a transformer is always used to match the load. Due to the stray capacitances of the matching transformer, high-voltage oscillation always appears at the output of H-bridge since there is no clamping path for the voltage stress at the transformer primary side.

The high-voltage oscillation can cause problems of electromagnetic interference for plasma diagnostic, and damage the driving circuit for solid state switch [2]. Moreover, the high-voltage oscillation can increase the semiconductor losses and voltage stress, and the insulation of the transformer windings could be damaged by this high-frequency voltage oscillation. The electromagnetic interference due to the switching transition can be cancelled by using neither passive EMI filter [3,4] or active EMI filter [5], or by impedance balancing [6]. And by simply adopting snubbers, the voltage oscillation can be suppressed, but the snubbers can cause extra losses and affect the wave form of output current. There are many literatures dealing with the voltage oscillation of high frequency converter, and it was found that the voltage oscillation is due to the parasitic capacitances of semiconductors and leakage

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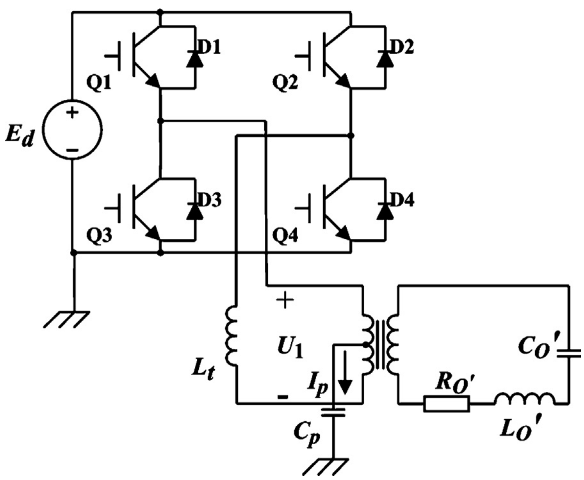

Fig. 1. Common mode current path of a resonant inverter.

inductance of transformer in the circuit [7–9]. But from the analysis of this work, it was found that for a series resonant inverter with matching transformer, the voltage oscillation is different from the situation in high-frequency converter.

The parasitic inductance of DC-link capacitor and the parasitic capacitance of semiconductor switch are usually taken as the reason for voltage oscillation of inverter. But for the inverter with matching transformer, it is not the case. This paper deals with the voltage oscillation of it. Since the transient character of IGBT is very complicated, there is no accurate transient model for it. To facilitate the analysis of it, the IGBT is taken as an ideal switch. Although the ideal-switch model is not accurate, it has little effect on the voltage-oscillation analysis qualitatively. Based on the ideal-switch model, the transition of voltage oscillation is analyzed. Then the method to reduce the voltage oscillation for the mid-frequency series resonant inverter without snubbers is discussed. The design consideration of dead time and the switching frequency for reduction of voltage oscillation is presented. The analysis and experiment results are useful for AC power supply for DRMP coils (Fusion reactor devices), and can also be used in other industry applications.

2. EMI due to voltage oscillation

As shown in Fig. 1, E_d is the DC-link voltage of phase-shift full-bridge converter and C_p is the parasitic stray capacitance between transformer windings and the earth. A common-mode voltage varies every switching of the inverter, and the common-mode voltage changes from $-1/2\ E_d$ to $1/2\ E_d$ if there is no high-voltage oscillation and the frequency is determined by the commutation time. If there is high-voltage oscillation, the common-mode voltage amplitude and frequency would be larger. Through the parasitic stray capacitor C_p, the voltage oscillation can produce high-frequency oscillatory common-mode currents at the instant of every switching. The oscillatory currents can create a magnetic field and radiate electromagnetic interference (EMI) noises throughout, thus producing a bad effect on electronic devices such as data acquisition equipment [4]. The high-frequency common-mode currents escaping to earth through parasitic stray capacitors can also produce conducted noise with the circuit sharing the same ground path. In the frequency range of the voltage oscillation, the parasitic capacitive coupling between primary and secondary windings can be quite high so as to create paths for the noise current via the control electronics. And the coupling of stray capacitances between the power supply, the torus and the diagnostics can cause big noises in the probes by this high-voltage oscillation [2].

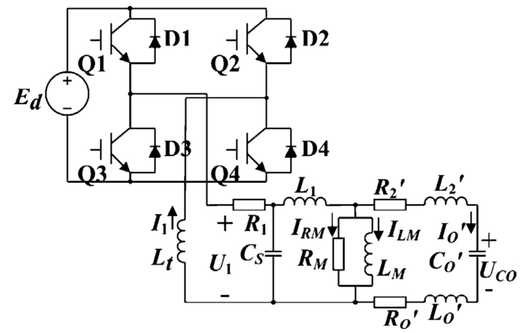

Fig. 2. Equivalent circuit for switching transition

3. Analysis of inverter voltage oscillation

3.1. Equivalent circuit

According to the analysis in Ref. [7–9], the voltage oscillation is caused by the interaction between the leakage inductance of transformer and the parasitic capacitance of semiconductor at switching transitions. But from the following analysis, it will be found that the voltage oscillation across the transformer primary side for the series resonant inverter is caused by an interaction between the line inductance and the stray capacitance of the matching transformer at switching transitions. The model of transformer with stray capacitance can be simplified to a low-order model [10], and the equivalent circuit for switching transition is shown in Fig. 2. As the parasitic inductance of DC-link capacitor has little effect on the transient analysis of voltage oscillation at transformer primary side, the DC-link capacitor is taken as an ideal DC-voltage source. Fig. 2 shows the series resonant inverter including parasitic components, i.e., the switch internal antiparallel diode; the transformer primary and secondary leakage inductance: L_1 and L_2'; the resistance of transformer primary and secondary windings: R_1 and R_2'; the transformer magnetizing inductor and resistor: L_M and R_M; the parasitic capacitor of the transformer windings: C_s; the load capacitor, inductor and resistor: C_o', L_o' and R_o'; the line inductance: L_t. For the sake of the voltage-oscillation analysis at the primary side, the equivalent circuit reflected to the primary side is used, as shown in Fig. 2, where $U_{CO}' = U_{CO} \times n$, $I_O' = I_O/n$, $L_2' = L_2 \times n^2$, $R_2' = R_2 \times n^2$, $R_O' = R_O \times n^2$, $L_O' = L_O \times n^2$ and $C_O' = C_O/n^2$. Because the load of AC power supply for DRMP is the DRMP coils [11], the load parameters can be taken as invariant approximately when not considering the change of coupling with plasma and vacuum vessel. So the resonant frequency of the circuit is constant when not considering the small variation of circuit parameter due to environment factors.

As similar to the analysis in Ref. [7], in order to perform voltage-oscillation analysis, several assumptions are made as follows: (1) Switches are ideal and the parasitic inductance and capacitance are ignored, except for the internal antiparallel diode. (2) The inductance of L_M is very large and capacitance of C_s is very small, so L_M can be taken as current source in the switching transition. (3) The resistances of transformer windings and the line are much smaller than magnetizing resistance, so they can be ignored in analyzing the voltage oscillation. (4) The internal antiparallel diode is ideal diode so the resistance and forward voltage are ignored and the parasitic capacitance of it is also neglected in the analysis. Based on these assumptions, the detailed analysis focused on the voltage oscillation at transformer primary side is described as follows.

3.2. Definition of two operating regions

Normally the inverter operates at point near the resonant frequency, and it is very hard to set the switching frequency exactly as