Methods for Suppressing Spike Voltage of ARCPI Auxiliary Switch

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Abstract. The Auxiliary Resonant Commutated Pole Inverter which is a kind three phase soft inverter. It is very suitable for AC driving. During the developing process, the spike voltage was produced between the auxiliary switch. Research shows that the diode in the auxiliary resonant circuit has a reverse-recovery phenomenon. Aim at this phenomenon, the methods of using clamping diode, double RCD snubber and saturable inductance are adopted. Experiments approve that all the methods can suppress the spike voltage between the auxiliary switch effectively. The method using saturable inductance has the advantage of simple circuit, low power-loss and low effect on ARCPI.

Preface

The AC driving technology was adopted in a novel tank gun control system. It improves the performance of the tank gun control system. In order to reduce the EMI and the power loss of the AC inverter, an auxiliary resonant commutated pole inverter (ARCPI) is designed[1~4]. The topology of the ARCPI circuit is as Fig.1. In ARCPI circuit, the phenomenon of the diode reverse recovery happens in the auxiliary resonant circuit. Great spike voltage is produced during the turn-off period of auxiliary switches. It will threat the safety of switches. Furthermore, severe EMI will be produced and even more severe than the traditional hard switching inverter in some frequency scope. So it is of great importance to suppress the spike voltage of the auxiliary switches.

1 Principle of ARCPI

In order to simplify the analyzing and understanding of the circuit, this paper only demonstrates Bridge A and its auxiliary circuit, because the three phases of ARCPI is independent. Taking the load current out-flowing from Bridge A as an example, the circuit can be divided into 7 modes.

(1) Mode 1 [t₀~t₁] At t₀, the load current flows out from Bridge A, S₁ is off, S₂ is on. The load current iₐ is freewheeling through D₂, Sₓ₁ and Sₓ₂ is off. In this mode, the principle is the same with the traditional hard switching inverter.

(2) Mode 2 [t₁~t₂] At t₁, Sₓ₁ turns on, the voltage on the capacitor Cₓ₂ is Vᵢₙ/2. this voltage acts on the resonant inductor Lₓ₁ through Sₓ₁, Dₓ₂ and D₂. so the current iₓ₁ increases linearly and iₓ₂ decreases linearly. In this mode, iₓ₁<iₐ, D₂ is freewheeling continually.

(3) Mode 3 [t₂~t₃] At t₂, iₓ₁ increases to iₐ, iₓ₂ decreases to 0, D₂ stops freewheeling. After this time, the current will flow through S₂. In this period, iₓ₁ increases continually. At t₃, iₓ₁ increases to a given value Iᵦ₀+iₐ, here we call it as pre-charging current.

(4) Mode 4 [t₃~t₄] At t₃, S₂ turns off. Then the inverter is working in the dead zone of Bridge A. The inductor Lₓ₁ begins to resonant with Cₛ₁ and Cₛ₂. So Cₛ₁ is discharging from Vᵢₙ and Cₛ₂ is charging from 0. When the voltage on the capacitors is Vₛ₁ = Vₛ₂ = Vᵢₙ/2, the current iₓ₁ will reach

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Figure 1. the topology of the main circuit of ARCPI.
the maximum value \( i_{LX1(\text{max})} \). Then the current \( i_{LX1} \) begins to decrease. The voltage on the capacitor \( C_{S1} \) reduces continually until 0 and the voltage on the capacitor \( C_{S2} \) increases until \( V_{in} \).

(5) Mode 5 \([t_4\rightarrow t_5]\) At \( t_4 \), \( V_{CS1} \) reaches to 0 and \( V_{CS2} \) reaches to \( V_{in} \). Due to \( i_{LX1} > i_s \), \( D_1 \) begins to conduct for freewheeling. In this period, the current \( i_{LX1} \) will decrease lineally under the action of voltage \(-V_{in}/2\). After \( t_4 \), the voltage on \( S_1 \) remains 0.

(6) Mode 6 \([t_5\rightarrow t_6]\) At \( t_5 \), \( i_{LX1} = i_s \), so \( i_{D1} = 0 \). After this time, \( i_{S1} \) begins to increase lineally. The current \( i_{LX1} \) decreases continually as mode 5.

(7) Mode 7 \([t_6\rightarrow t_7]\) At \( t_6 \), \( i_{LX1} = 0 \). Due to being blocked by \( i_{LX1} \), \( S_{X1} \) turns off with ZCS. After this time, the principle is the same with the traditional hard switching inverter. The key waveforms are shown as Fig.2.

## 2 The spike voltage of auxiliary switching device

The principle shows that the auxiliary devices can realize the ZCS and ZVS turn-off. But the practical waveforms did not verify this point. Fig.3 shows the waveforms of the auxiliary switching device voltage. We can see from this figure that when the input voltage \( V_{in} = 40V \), the spike voltage of the auxiliary switching device is more than 60V. The current of the resonant inductor is shown in Fig.4. We can see that high frequency vibration is produced in the process of the resonant current returning 0. This indicates that severe EMI have come into being. The cause for this phenomenon is the reverse recovery of the diode. In the resonant circuit, two switches are series reversely connected. Each switch connects with a diode parallelly. The diode can also provides the one direction current path and block another direction current. So the diode is very important for the ARCPI.

## 3 Methods for suppressing the spike voltage

### 3.1 The clamping zener diodes

![Figure 5. ARCPI with clamping zener diodes.](image)

![Figure 6. ARCPI with Dual RCD snubber circuit.](image)
The existence of the spike voltage is due to none path for the inductor energy to dissipate\(^5\). So the clamping zener diodes shown in Fig.5 can dissipate the energy and suppress the spike voltage. Although the ARCPI with clamping zener diodes can suppress the spike voltage to some extent, every phase of the inverter has more than 4 power devices. This increases the difficulty of circuit layout, meanwhile the reliability of ARCPI is decreased.

### 3.2 Dual RCD snubber circuit

The RCD snubber circuit is the common circuit for suppressing the spike voltage\(^6\). Because the resonant circuit of ARCPI has two switches to realize the dual direction current flow, every switches should be added a RCD snubber circuit in order to absorb the spike voltage generating by the dual direction current flow. The circuit is shown as Fig.6.

This paper has tested the ARCPI with the dual RCD snubber circuit. Some key waveforms of the auxiliary resonant circuit are recorded. Fig.7 shows the waveforms of the \(S_{X1}\) voltage and \(L_{X1}\) current. Fig.8 shows the waveforms of \(S_{X1}\) and \(S_{X2}\) voltage. We can conclude from the above waveforms: ARCPI with Dual RCD snubber circuit has realized the suppressing of spike voltage during the dual direction flowing of the inductor current. However, the dual RCD snubber circuit also has some influence on the main circuit. When the two auxiliary switches are both off, the snubber capacitor will be resonant with the resonant inductor, the voltage of the snubber capacitor will increase.

![Figure 7. SX1 voltage and LX1 current waveforms of dual RCD circuit.](image)

![Figure 8. The voltage waveform of the auxiliary switch.](image)

### 3.3 The saturation inductor

The simplest method for suppressing the spike voltage is that the saturation inductor is connected serially in the auxiliary resonant circuit\(^7\). It is shown as Fig.9. The principle is: when the current of the saturation inductor increase from 0, just as shown as the process from state 2 to state 3 in Fig.10. In this process, the magnetic permeability of the saturation inductor is very high and its inductance is great. So it will restrain the current variability. When the current is normal, just as the process from state 3 to state 4 in Fig.10. The saturation inductor is saturated. The inductance is so little that it no effect on the main circuit. But when the current flows from normal to 0 and then increase in reverse direction, just as the process from state 5 to state 6 in Fig.10, the saturation core retreats saturation state and the inductance is great. So the current variability is little. That will suppress the spike voltage.
voltage. Fig.11 shows that the practice inductor current of ARCPI with the saturation inductor. The waveforms verified that the analysis is true and are correspond with the states in Fig.10 respectively.

In the reverse recovery time, the saturation inductor must bear the reverse voltage in order to suppress the reverse recovery current. There is the formula: \[ \Phi_c = 2B_s A_c \geq U_r t_{rr} \]

In the formula, \( \Phi_c \) is the whole magnetic flux of the saturation inductor, its unit is Wb; \( U_r \) is the voltage on the saturation inductor, its unit is V; \( t_{rr} \) is the reverse recovery time, its unit is s. In the design, choose \( U_r = 150V \), the auxiliary switch is SGL160N60UFD and the reverse recovery time \( t_{rr} = 105ns \). According to the formula, \( \Phi_c \) should be 15.75 \( \mu \)Wb. Meanwhile, in order to get little \( di/dt \) value at the beginning and end of the resonant process, the saturation inductor should meet the demand as follows: big initial magnetic permeability, low saturate magnetic flux density, narrow magnetic hysteresis. Based on this analysis, cobaltic amorphous core is the best choice. In this paper we choose the Beijing Shouzi company’s CAH142104 cobaltic amorphous core. Its magnetic flux is 12.99\( \mu \)Wb. so in order to meet the using demand, 2 circle wires are winded on the core.

Fig.12 is the SX1 voltage and inductor current waveforms. From these waveforms, we can see that the cobaltic amorphous core can suppress the spike voltage effectively. Meanwhile, the power loss of the core is very little and the efficiency of the APCPI is improved further.

4 Conclusion

By comparing the three spike-voltage-suppressing methods, we can conclude that in the ARCPI circuit, the saturation inductor is the best method. It is the simplest and the influence is the least, the effect of the spike-voltage-suppressing is good and the loss is the least. So in the practice design, the saturation inductor method is adopted to suppress the spike voltage in ARCPI.

References