

Three Phase PWM Inverter based on state analysis method

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Abstract - Output voltage waveforms according to all kinds of combination of main circuit structure, load quality and control manner for output voltage are analyzed systematically at ideal condition in voltage-source PWM inverter so that all kinds of existing quality of combination and the rule of influence to output voltage waveform for voltage-source PWM inverter are obtained and a state analysis method is presented for a voltage-source PWM inverter. The ideal output voltage waveform of the voltage-source PWM inverter is determined by the combination of all kinds of valid main circuit states. The output voltage waveform of a single-phase half bridge voltage-source PWM inverter is analyzed in detail by the state analysis method and the corresponding control strategy is obtained, which is extended to the single-phase full-bridge voltage-source PWM inverter and the three-phase bridge-type voltage-source PWM inverter. According to the analysis of dead-time problem, non-dead-time control strategy is presented.

Key Words: State analysis method, voltage-source, PWM inverter, output voltage waveform, non-dead-time control etc.

1. INTRODUCTION

Use of renewable energy resources for generation of electrical energy has gaining importance from last few decades. Among all types of renewable energy resources used for electricity generation, solar energy is gaining more attention. Solar energy generation module is larger in size as it has various components like rectifier, Power factor corrector and DC/AC or DC/DC converter for supplying load. Inverters with switching power topology have some bad circuit behaviours like rippled generating voltage input and harmonics in its output [1]. In high power application areas three phase inverters are used. It converts input DC voltage in an output voltage with variable frequency. In MW range industrial applications use of three phase PWM inverters are gaining popularity. There are two types of PWM inverters depending on their energy storage components. Voltage source PWM inverters are having mature control strategies and it is being used in micro grid system, solar power and bidirectional energy storage systems [2]. Three phase voltage source inverters are used widely as it can share large voltage to series devices with lower harmonics as compared to two level inverters. Now the GTO devices are replaced by IGBTs in inverters as it has higher switching frequency and voltage current ratings. There are various PWM techniques used in inverter model and among them SPWM or sinusoidal pulse width modulation technique is widely used because its circuit is simple and it has rugged controlling schemes.

SPWM has the capability of producing pulses with constant amplitude and variable duty cycles for each period. By controlling width of the pulses of SPWM the desired output voltage and reduction of harmonics are achieved from the inverter [3]. In inverter circuit distorted sinusoidal pulses because of the presence of harmonics can be produced while using nonlinear loads. These harmonics need to be reduced as these can adversely affect the network like: heating of conductors, heating of transformer windings, fuse and circuit breaker false operation and reduction of life of the network. Now for reduction of lower order harmonics if filter circuit is going to use then it will be larger in size and very costly while for higher order harmonics the filter needed will be smaller in size and will be economical to use. So, for harmonic reduction SPWM techniques will be used in case of lower order harmonics reduction and filter circuit will be designed for reduction of harmonics with higher order [4].

1.1 The Basic Principle of State Analysis Method:

The main circuit of the voltage-source PWM inverter without load is shown in Figure, which consists of some half bridges. One half-bridge consists of two up-down bridge arms in series and each of bridge arms consists of a controlled device and an anti-parallel diode in parallel. The main circuit state of the voltage-source PWM inverter is determined by the combination of on-off states of switch devices, and each switch device has on/off two states. Therefore, the states of main circuit consisting of N bridge arms have 220 combinations in theory [6-8].

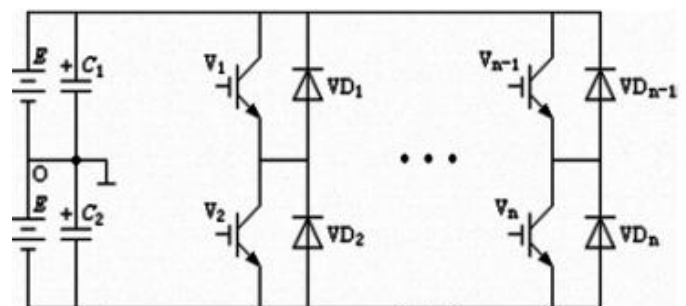


Figure 1: Main circuit of voltage-source PWM inverter

Some states of the voltage-source PWM inverter are invalid. For example, to avoid short-circuit, the up-down bridge arms of the same half-bridge cannot be shoot-through, therefore corresponding states are invalid. On the same bridge arm, because the current directions allowed getting through the controlled device and the anti-merge diode are opposite, at most one device can be on at one time. The states that both the controlled device and the anti-merge diode on the same bridge arm are on are invalid. Therefore the ideal output voltage waveform of the voltage-source PWM inverter is

determined by the combination of various valid main circuit states.

1.2 Single-phase Half-bridge Voltage-source PWM Inverter:

Figure 2 shows main circuit of a single-phase half-bridge voltage-source PWM inverter which has two bridge-arms, and each bridge arm consists of a controlled device and an anti-parallel diode. On the DC side, there are two capacitors in series, and the coupling point of the two capacitors is the midpoint of DC source. Load connects between the midpoint of DC source and the coupling point of two bridge arms. The advantage of half-bridge inverter is simple in structure, and its disadvantage is that the amplitude of AC voltage is half of that of DC voltage. In Fig.2, we define the current from the coupling point of up up-down bridge arms to the midpoint of DC source is positive [5].

The current in inductive load cannot change abruptly, therefore the ideal output current waveform of the voltage source PWM inverter is continuous sine wave. The current and voltage of inductive load aren't consistent in phase. If the current and voltage have the same direction, the diode in main circuit is off; otherwise it is on and make current continue. According to the on-off states of the controlled device and the diode in main circuit, every main circuit state is obtained. Meanwhile, the on-off states of the controlled device and the diode in main circuit are determined by the control signal and the direction of the current, and the interval of being the same current direction is determined by the power factor of the load.

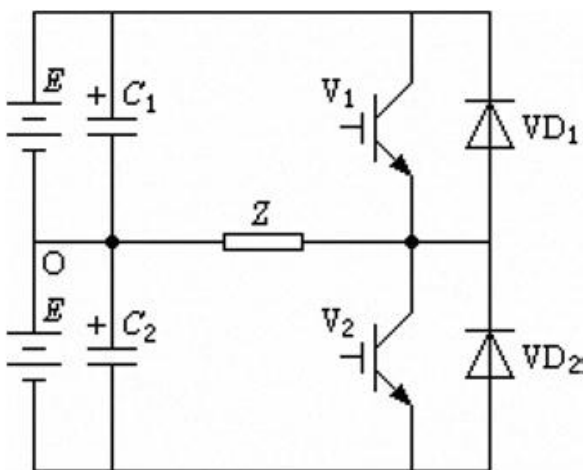


Figure 2: Main circuit of single phase half bridge voltage PWN inverter

Although the PWM output voltage waveform of all kinds of voltage-source PWM inverter is arbitrary, they consist of the limited main circuit states based on some rules. As shown in Figure 3, the ambipolar output voltage waveform can be realized by the combination of the main circuit states of the voltage-source PWM inverter in inductive load.

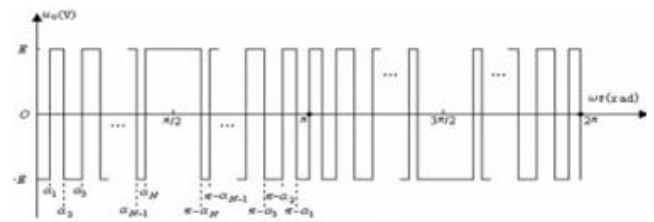


Figure 3: Double polarity output voltage waveform

The main circuit states of single-phase half-bridge voltage-source PWM inverter depend on the combinations of on/off states of controlled device and diode, which have $2^4=16$ possibilities in theory, as shown in table I. In table I, we define that connection is "on", then disconnection is "off". All the tables below are in the same way. However, in practical application, the valid main circuit states of single-phase half-bridge voltage-source PWM inverter are less than 16 kinds. For example, the condition that the up-down bridge arms cannot be shoot-through makes the states 3, 7, 11, 12, 13, 14 and 15 invalid; the condition that the controlled device and diode in the same bridge-arm cannot be on at the same time makes the state 5 and 10 invalid. In ideal instance, the current in inductive load is continuous. It means that there is no zero-current interval (not including current zero-point). Since the current must have the corresponding route, at least one switch device of the main circuit must be on, which makes the state 0 invalid. If both VD_1 and VD_2 are off, the direction of current is negative. When V_2 is on, the current must pass it. In this case, V_1 is off and the state 6 is invalid. In the same way, the state 9 is invalid, too. By the analysis above, in inductive load and ambipolar output voltage control mode, the invalid states of single-phase half bridge voltage-source PWM inverter are 4 kinds. As shown in table II, all of them are the state in which one parts is on and others are off.

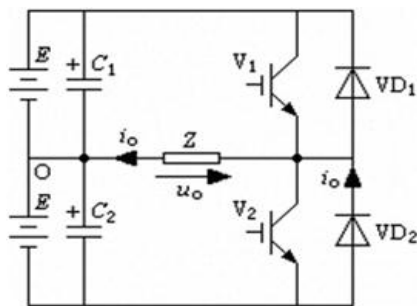
State of main source	V_1 states	V_2 states	VD_1 states	VD_2 states
0	off	Off	Off	off
1	off	Off	Off	on
2	off	Off	On	off
3	off	Off	On	on
4	off	On	Off	Off
5	off	On	Off	On
6	off	On	On	Off
7	off	On	On	On
8	on	Off	Off	Off
9	on	Off	Off	on
10	on	Off	On	Off
11	on	Off	On	On
12	on	On	Off	Off
13	on	On	Off	On
14	on	On	On	Off
15	on	On	On	On

Table I: The main circuit states of single-Phase half-Bridge voltage-Source PWM Inverter In theory

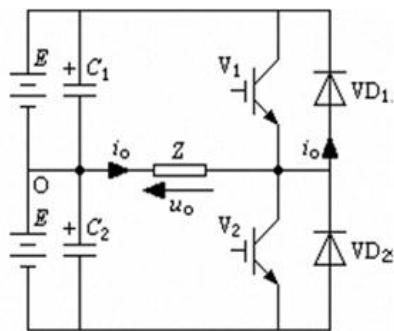
Valid states of main circuit	1	2	4	8
Directions of load current	+	-	-	+
Directions of load voltage	-	+	-	+
V_1 states	off	off	off	on
V_2 states	off	off	on	off
VD_1 states	off	on	off	off
VD_2 states	on	off	off	off

Table II: The Main Circuit States of Single-Phase Half-Bridge Voltage-Source PWM Inverter in Inductance

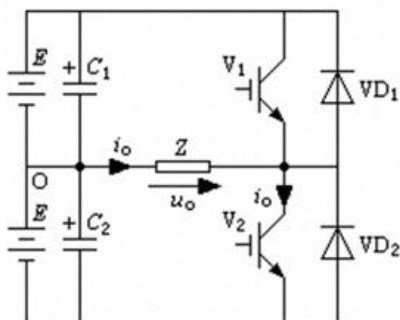
The direction of load voltage and load current corresponding to each of states in table II is shown in Figure 4;



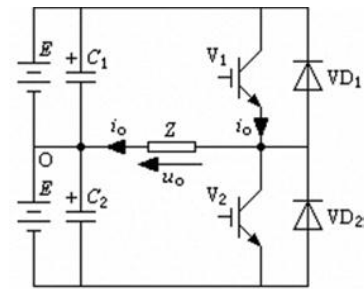
(a) State 1



(b) State 2



(c) State 3



(d) State 4

Figure 4: The direction of voltage and current about all states in Table II

2. Single-phase Full-bridge Voltage-source PWM Inverter:

Figure 5 shows main circuit of a single-phase full-bridge voltage-source PWM inverter, which has four bridge-arms. Therefore, we can think it is made up of two half-bridge circuits. A large enough capacitance should be located at the side of DC, but we can have an assumed DC-source midpoint for an easy analysis, and divide it into two capacitances in series. The advantage of full-bridge inverter is that the output amplitude of AC voltage is equal to that of DC voltage. Meanwhile its shortcoming is that it includes too many parts. In Figure 6, it is defined that the current from the joint of 1&2 to the joint of 3&4 is positive [9].

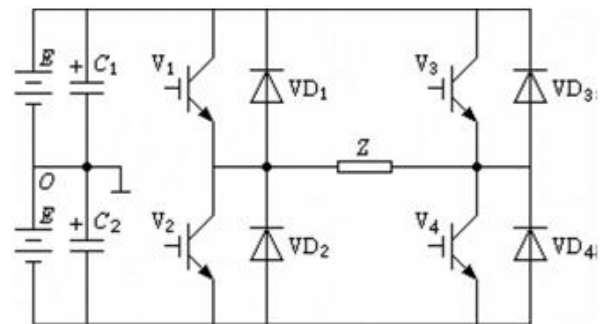


Figure 5: Main circuit of single phase full bridge voltage source PWM inverter

The main circuit states of single-phase full-bridge voltage-source PWM depend on the combinations of on/off states of controlled device and diode, which have $2^6=256$ kinds in theory, but the valid main circuit states are much less than 256 kinds in practice because up down bridge arms in the same group cannot be shoot-through. Under the situation of inductive load and ambipolar output voltage control mode, we can imitate the analysis of the half-bridge one, and then we can conclude single-phase full-bridge voltage-source PWM inverter has four valid states, as shown in table III.

Valid states of main circuit	1	2	3	4
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Directions of load current	+	+	-	-
Directions of load voltage	+	-	-	+
V ₁ states	On	off	off	Off
V ₂ states	Off	off	on	Off
V ₃ states	Off	off	on	Off
V ₄ states	On	off	off	Off
VD ₁ states	Off	off	off	on
VD ₂ states	Off	on	off	Off
VD ₃ states	Off	on	off	Off
VD ₄ states	Off	off	off	On

Table III: States of Single-phase Full-bridge Voltage-source PWM Inverter main circuit in inductance

If we make single-phase full-bridge voltage-source PWM inverter realize ambipolar output under the situation of inductive load, then we may control it in the similar way of half-bridge one.

3. Three-phase Bridge-type Voltage-source PWM inverter:

Figure 6 shows main circuit of a three-phase bridge voltage source PWM, which has six bridge-arms. Therefore, we can think it is made up of three single-phase half-bridge circuits. In Fig.6, we defined that the current effusing from each half bridge midpoint is positive [10].

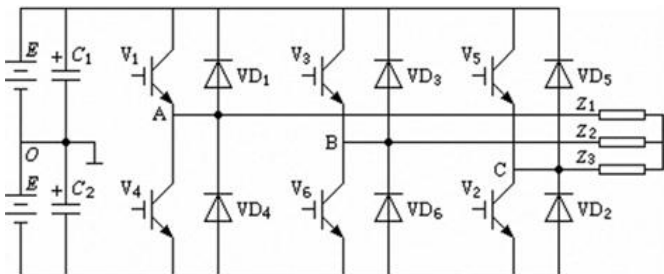


Figure 6: Main circuit of three-phase bridge-type voltage-source PWM inverter

The main circuit states of three-phase bridge-type voltage-source PWM inverter have $2^{12}=4096$ possibilities in theory, but the valid main circuit states is much less than 4096 kinds in practice. In inductive load, the state of three-phase bridge-type voltage-source PWM inverter depends on the current direction of each phase and the on-off state of each bridge arm. The current directions of three-phase have 8 combinations in all, but two kinds of these are that the three current is in the same direction, which disobey Kirchhoff's current law, thus there is no time to correspond with these two combinations in the ideal three phase output current.

Therefore, eliminating them, there are six valid combinations of current directions. In ambipolar output, there is one and the only on-bridge-arm to each phase in one time. Which is used, the controlled device or the diode depends on current direction of each phase and voltage direction of each phase load, so switch devices have 8 combinations corresponding to the combination of each current direction [11].

Throughout the analysis above, main circuit of three phase bridge-type voltage-source PWM inverter have 48 valid states in inductive load. When the voltage of one phase is positive, the up bridge arm of the corresponding half-bridge is on, and the down bridge arm is off; when the voltage of one phase is negative, the up bridge arm of the corresponding half-bridge is off, and the down bridge arm is on. Each half-bridge has one controlled device valid and the other at the same half-bridge is unused corresponding to the combination of the same current direction of inverter. We can blank off its drive signal, so we need not add dead-time at the same current direction and realize non-dead-time control.

4. Conclusions:

The state analysis method can be applied to analyze PWM inverter and obtain the valid states and the working of main circuit. The number of the on-switch-devices in the valid state of voltage source PWM inverter is equal to the number of half-bridge in main circuit. By state analysis method, we can obtain the non-dead-time control strategy of the output voltage waveform of voltage-source PWM inverter, which provides reference for the further research of ideal output voltage waveform and practical output voltage waveform in the voltage-source PWM inverter.

5. REFERENCES

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