A Control Strategy of the Three-Phase Bridge-type ZVT Inverter for AC Motor Drives

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ABSTRACT - In this paper, control strategies of the bridge-type ZVT inverter for AC motor drive application were discussed. The topology of the ZVT inverter is analyzed with a description of the control conditions based on the load current. And a new resonant control algorithm by using load current feedback and modified SVM algorithm for the proposed ZVT inverter is proposed in order to achieve the ZVT switching condition in full control range. The detailed computer simulation and experimental results represent that ZVT and ZCT operation for the main and auxiliary switch, respectively, was achieved.

1. INTRODUCTION

Recently, three phase ZVT (Zero Voltage Transition) inverter is widely used in many AC motor drive applications. The ZVT switching can reject or reduce the over-voltage and over-current spike in the main inverter switches. So, the ZVT inverter is able to reduce the switching losses and severe problems with the reverse recovery of the anti-parallel diodes. And the ZVT inverter has been adopted the system for AC motor drives such as electric propulsion drive because it has many benefits compared to conventional hard switching PWM inverter which are the high efficiency, high reliability, high power density, robustness and low EMI [1]-[6].

Even though a number of ZVT topology have been developed, there are some minor problems which is the increase of the cost and the complexity of the control circuit due to add the excessive components in order to get the ZVT switching condition [1]-[12]. To solve the above problem, the bridge-type ZVT inverter was proposed [1]. This inverter is to reduce the parts count of the resonant snubber based soft-switching inverter, mainly the number of the resonant inductors and blocking diodes. But, it still has some problems, which had been existed by the conventional ZVT inverter. These ZVT topologies are to exist the hard-switching region partly even if the ZVT circuit is designed optimal condition because the resonant period depend on load current. And it can not also use the SVM (Space Vector Modulation) algorithm, directly, to achieve the sinusoidal output current of inverter [9].

Therefore, in this paper, control strategies of the three-phase ZVT inverter are discussed. First, the correlation of the resonant period and load current is analyzed and to achieve the ZVT switching in full control range, a new resonant control algorithm by using load current feedback is proposed. Second, a new modified SVM algorithm for the proposed ZVT inverter is derived through the analysis of the conventional SVM. And computer simulation and experimental results have verified the validity of the proposed control strategies.

2. OVERVIEW OF THE CONVENTIONAL ZVT INVERTER

Several ZVT circuits for AC motor drive application have been proposed to solve the problems, which is efficiency, EMI and power density, associated with the hard-switching in the conventional three phase PWM inverter. These ZVT inverters can be categorized into three configurations: (1) auxiliary resonant commutated pole (ARCP) inverter, (2) resonant transition inverter (RTI) and (3) Delta-configured resonant snubber inverter (Delta-RSI) [1]-[7].

The ARCP inverter topology is able to get the ZVT conditions without increasing the voltage and current stresses of the main switches and without affecting the PWM control used in the conventional hard-switching PWM inverter. The drawback of the ARCP inverter is that the implementation of the ZVT switching requires a stiff dc link capacitor bank, which is center tapped to accomplish commutation and the use of six additional auxiliary switches and three resonant inductors in a three-phase inverter. To overcome this problem, load side ZVT inverter topologies including the RTI and Delta- RSI were proposed by placing the auxiliary circuits on the load side.

The Delta-RSI does not need a center tapped connection from the dc link capacitor bank and has also the advantages of avoidance of over-voltage or over-current penalty in the main switches. But it has still problem, which is the increase of the cost and the complexity of the control circuit due to add the excessive resonant components. Especially, the disadvantage is potential unbalanced inductance between different phase legs due to layout and package.

The RTI with single auxiliary inductor avoids the unbalanced resonant circuit problem and has the advantage of low cost effectiveness compared to the previous topologies due to require adding only one or two auxiliary switches. However, this topology require many transitions to achieve desired state changes and voltage clamping device to prevent over-voltage across the auxiliary resonant switch during current resetting.

3. THE BRIDGE-TYPE ZVT INVERTER

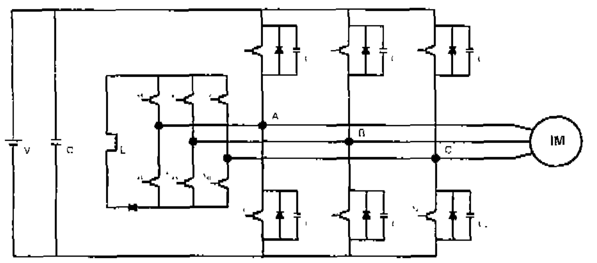


Figure 1. The Bridge-Type ZVT Inverter

To overcome above disadvantages, which is potential unbalance and current resetting problem of resonant inductor, the bridge-type ZVT inverter with a single resonant inductor is proposed in Fig. 1. This topology consists of a conventional hard-switching PWM inverter and a bridge-type ZVT auxiliary circuit to help soft switching of main switch. The bridge-type ZVT auxiliary circuit consists of only one resonant inductor, one blocking diode and six auxiliary switches. The auxiliary branches along with a single inductor are connected across three output terminals.

3.1 Principle of operation

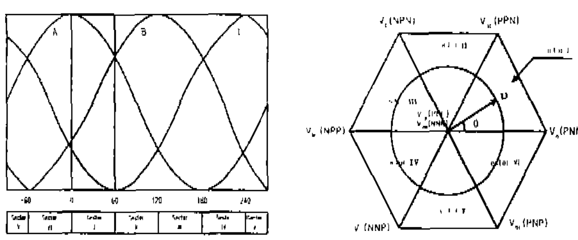
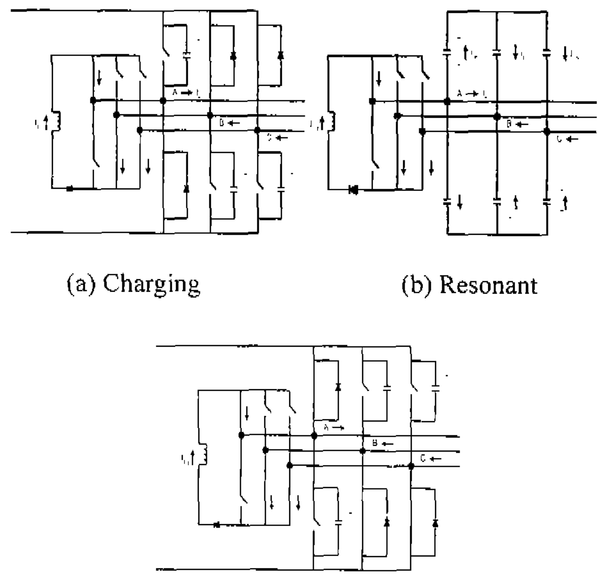


Figure 2. Three-phase voltage and voltage space vectors

The space vector modulation PWM schemes are used in the main inverter control. The phase voltage's waveform and voltage vector's definition is shown in Fig. 2. In the SVM operation, the main switches of the inverter are the eight different switching states. These switching states correspond to the six non-zero discrete voltage vectors, V_a to V_C, and the two zero vectors V_{zp} and V_{zn} as shown in Fig 2. The subscript letters represent the switching state; for example, "PNN" means V_a, in which node A is connected to the positive DC rail and nodes B and C are connected to the negative DC rail. "PPP" means V_{zp}, in which all nodes A, B and C are connected to the positive DC rail. These vectors also called the switching state vectors (SSV).

To understand the operation of the circuit, assume that inverter is operating in sector I at an instance when the current Ia is positive, and Ib and Ic are negative since the operation of the inverter is symmetrical in every 60° interval. In this case, turn-off voltage of the main switches S1, S6 and S2 is snubbed by the capacitor across the main device, as with a snubber capacitor in the conventional PWM inverter. But, when the switches S1, S6 and S2 are turned on, its can not be snubbed by capacitor because the direction of the capacitor discharging current and main current is opposite. To achieve the ZVT condition during turn-on period, the auxiliary resonant branch must be required.

The whole commutation process for the main switches S1, S6 and S2 has three operation modes as shown in Fig. 3. And voltage and current waveforms corresponding operational mode shows in Fig. 4. The step-by-step operation is described as follows.



(a) Charging (b) Resonant

(c) Discharging

Figure 3. Operational modes of the proposed inverter

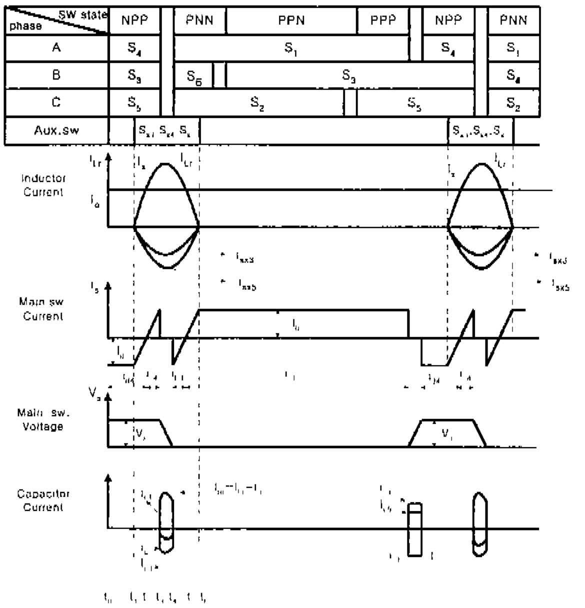


Figure 4. Voltage and current waveforms corresponding operational modes

(1) **Charging Mode**: The initial condition assumed is for a positive output phase A current which is freewheeling through D3, D4 and D5 with S3, S4 and S5 conducting. At t_1, turn on auxiliary switches S_{x3}, S_{x4} and S_{x5} as shown in Fig 3(a). The resonant inductor current, I_{Lr}, increases linearly. When the resonant current equals the load current at time t_2, the freewheeling current in D3, D4 and D5 becomes zero. The inductor current exceeds the load current after t_2 and then it is provide through switches S3, S4 and S5 instead of D3, D4 and D5. When the inductor current increases to I_x at t_3, turn off devices S3, S4 and S5.

(2) **Resonant Mode**: At t_3, the current path is established by the stored energy of inductor and capacitors as shown in Fig. 3(b). At that point, the capacitors C3, C4 and C5 serve as lossless snubbers to allow zero voltage turn-on of the main switches S3, S4 and S5. Capacitors C3, C4 and C5 are charged DC bus voltage, V_S, and C1, C2 and C6 are discharged to zero voltage at t_4 by the stored energy of the resonant inductor.

(3) **Discharging Mode**: At the end of the resonance period at t_4, turn on main switches S1, S2 and S6 as shown in Fig. 3(c). From this time, the inductor current start to decrease, and the resonant current except load current is diverted to diodes D1, D2 and D6. At t_5, the inductor current equals the load current, and the diode current is diverted to the main switch. So, switches, S1, S2 and S6 can be turned on at zero voltage condition. The switch current continues to increase while the inductor current decreases linearly. When the inductor current decreases to zero at time t_6, auxiliary switches, S_{x3}, S_{x4} and S_{x5} can be turned off at zero current condition.

3.2 Design considerations

The design of the main power stage of the proposed inverter is basically similar to a conventional PWM inverter. But, an important difference is the use of resonant component, capacitor C_r and inductor L_r. The resonant capacitor is used in parallel with each main switch to reduce turn-off loss in the ZVT inverter. For AC motor drive applications, especially, the dv/dt characteristic of main switch of the inverter needs to meet the IEEE standard-522. By using this standard, the device dv/dt is recommended 220V/us. So, the proper value of the capacitor can be found in following expression.

$$\frac{1}{Cr}\int\frac{Io}{2}dt = V_s \tag{1}$$

The inductance, L_r is very important for the ZVT operation because the magnitude of the resonant inductor determines turn-on di/dt of main switch and inductor charging time. A large inductance helps eliminate the diode reverse recovery problem, but results in more conduction loss in the auxiliary circuit and more duty cycle loss. The resonant inductor current can be determined by

$$I_{Lr} = \frac{Vs}{Lr}t_{cg} \tag{2}$$

Where t_{cg} is inductor charging time, $t_{cg} = t_3 - t_1$, as shown in Fig. 4.

Otherwise, the charge of the resonant inductor needs to be sufficient to discharge the resonant capacitor to ensure ZVT switching. That is, the inductor current, I_{Lr}, must be charged to a level higher than the load current to satisfy the following charge balance requirement;

$$\frac{1}{2}L_r I_{rc}^2 = C_r V_s^2 \tag{3}$$

Where I_{rc} is the resonant current, $I_{rc} = I_{Lr} - I_o$, and Vs is the DC bus voltage.

4. THE PROPOSED CONTROL STATEGY

The all topology of the previous mentioned ZVT inverter has a inherent problem which is not to achieve the ZVT switching for the full control range due to depend on the load current, and to be adopted the standard SVM algorithm directly due to the structure of ZVT topology. In this paper, a new control strategy for the bridge-type ZVT inverter is proposed in order to improve the above mentioned problem. The detail description for the control strategy of the ZVT inverter is divided two subsections, how to select resonant control pattern and modified SVM algorithm, and the control concept of this strategy is shown in Fig. 5.

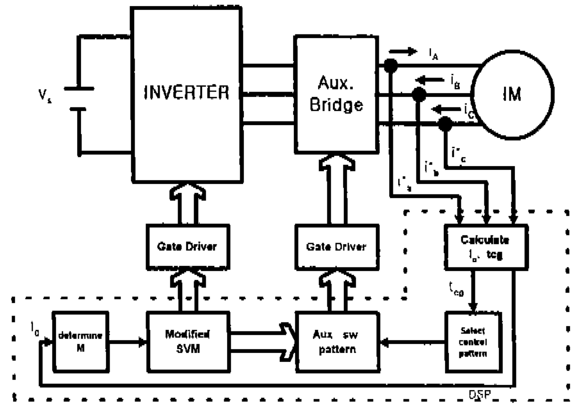


Figure 5. The control concept of the proposed ZVT inverter.

4.1 How to select resonant control pattern

The bridge-type ZVT inverter is designed to satisfy ZVT switching for the main devices and ZCT commutation for the auxiliary switches during resonant period. But, if the load current would not be constant value such as AC sine waveform, the proposed ZVT inverter could not meet these requirements during the full .control range. Because the discharging time of the stored energy of the resonant capacitor depend on the load current of the proposed ZVT inverter. That is, from (1), the relationship between the dead time of the main devices and the capacitor discharging time can be expressed by

$$t_{cg} = \frac{2C_r V_s}{I_L} \quad (4)$$

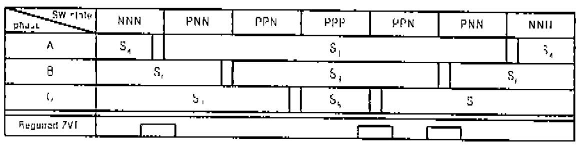
If the turn-off voltage of main switch could be snubbed by capacitor across the main device, the capacitor discharging time t_{cg} must be satisfied by

$$t_d \geq t_{cg} \quad (5)$$

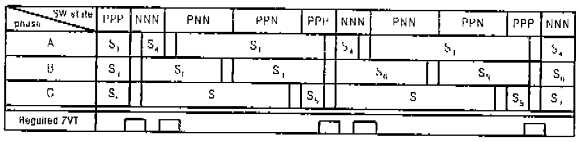
Where, t_d is the dead time of main devices. Generally, in case of AC motor drive applications, the proposed ZVT topology cannot satisfy the condition of (5) during full control range because load current is the sinusoidal value 'such as the sine waveform. That is, turn-off voltage of the main switch cannot be sufficiently snubbed by the capacitor across the main device around the zero crossing point of the load current because the capacitor charging time is greater than the dead time of the main device. Otherwise, in case of resonant mode, the required resonant time is constant, $\pi\sqrt{LC}$, and is already designed the proper value, which is smaller than the dead time, t_d. The resonant time is independent in load current. In this paper, therefore, the resonant control algorithm corresponding to the load current is proposed. This algorithm is that if the dead time is smaller than the capacitor charging time, the ZVT resonant circuit is controlled during both turn-on and turn-off of main device. But, if the dead time is greater than the capacitor charging time, the resonant circuit is normally controlled during turn-on of main device. The proposed ZVT inverter is achieved ZVT switching for the main devices and ZCT commutation for the auxiliary switches during every transition period of the full control range.

4.2 Modified SVM for ZVT inverter

The typical SVM schemes for the conventional PWM inverter are categorized in two types; analog and digital based SVM as shown in Fig. 6. To accommodate the analysis of the SVM scheme's operation, assume that inverter is operated in sector I of the voltage space vector at an instance when the current I_a is positive, and I_b and I_c are negative as mentioned in Fig. 2. In this case, turn-on voltage of the main switches S3, S4 and S5 is snubbed by the capacitor across the main device, as with a snubber capacitor in the conventional PWM inverter. But, when the switches S1, S6 and S2 are turned on, its can not be snubbed by capacitor because the direction of the capacitor discharging current and main current is opposite. In this transition time of main device, to achieve ZVT switching condition, the auxiliary resonant branch for ZVT have to be operated whenever main switches S1, S6 and S2 are turned on. In this structure of both SVM schemes, however, even though the auxiliary resonant branch for ZVT is controlled, the ZVT switching condition cannot be achieved when main switches S1, S6 and S2 is turned on because the resonant circuit path is not formed. Therefore, to be operated the ZVT resonant branch completely, the switching state vector (SSV) with leading phase angle 180° compared to the transitioned SSV is required before the transitioned SSV is occurred. For example, from zero SSV, V_{zn} (NNN) to SSV, V_a (PNN) transition, it should be changed from zero SSV, V_{zn} (NNN) into SSV, V_{bc} (NPP) before the SSV, V_a (PNN) is occurred as shown in Fig. 7. And the changed SSV, V_{bc} (NPP) is turned on for a short time without affecting output load current.

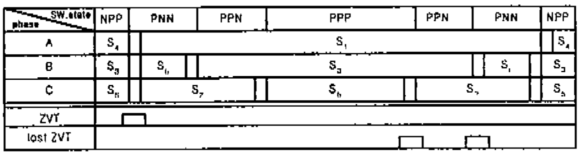


(a) Analog based SVM

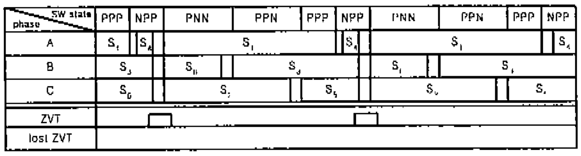


(b) Digital based SVM

Figure 6. The typical SVM schemes for the conventional inverter.



(a) Analog based SVM



(b) Digital based SVM

Figure 7. Modified SVM schemes for the ZVT inverter.

In Fig 7 (a), even though the SSV sequence of the analog based SVM is modified properly, it has still the commutation period with losing ZVT condition. But, the modified SVM scheme of digital based SVM, which is shown in Fig. 7 (b), operate perfectly without ZVT lost condition. Therefore, in this paper, the digital based modified SVM scheme is adopted for the proposed ZVT inverter, which is shown in Fig. 5.

5. SIMULATION AND EXPERIMENTAL RESULTS

The simulation was done with Pspice simulator in order to verify the ZVT operation of the proposed topology and control algorithm. The load using the simulation was adopted the R-L load with phase current 50A. Two possible SVM algorithms mentioned above, the digital based modified SVM technique was selected due to perfectly implementation with ZVT operation.

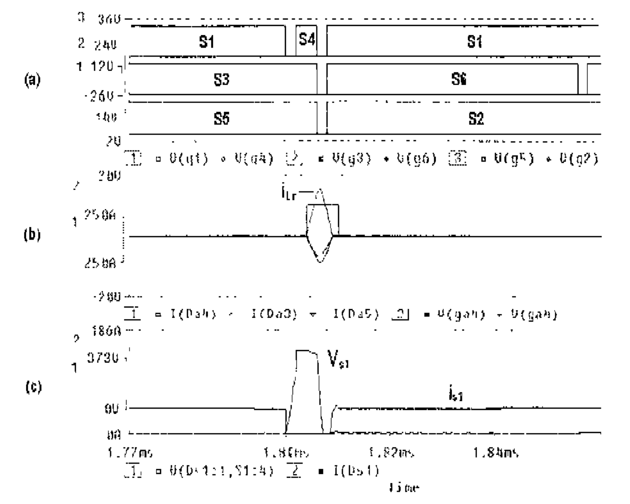
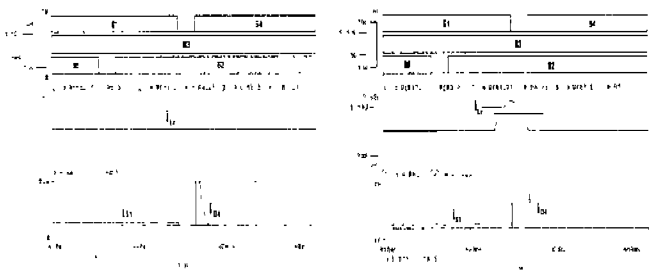


Figure 8. Simulation waveforms of the proposed inverter during commutation

Fig. 8 shows the corresponding waveforms of the proposed ZVT inverter during commutation when the SSV is located in sector 1. Figure 8 (a) is the waveforms of the gate signal sequences of the inverter main devices based on the modified SVM. Figure 8 (b) shows the resonant current of auxiliary switches S_{x3}, S_{x4} and S_{x5}, and its gate drive signal. The inductor current of S_{x4} is the same as the sum of the current of S_{x3} and S_{x5}. Figure 8 (c) is the across voltage and current waveforms of the phase A switches during commutation period. This shows to be commutated the main device with the ZVT switching condition by the modified SVM scheme, which is changed from zero SSV, V_{zn} (NNN) into SSV, V_{bc} (NPP) before the SSV, V_a (PNN) is occurred in the conventional SVM scheme. And also shows to be switched the auxiliary switch with the



(a) Without resonant control (b) with resonant control

Figure 9. An effect on the resonant control algorithm

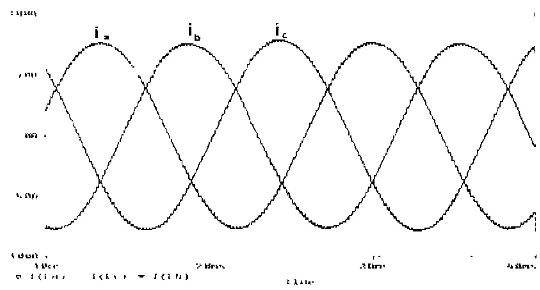


Figure 10. Output current waveforms of the proposed inverter

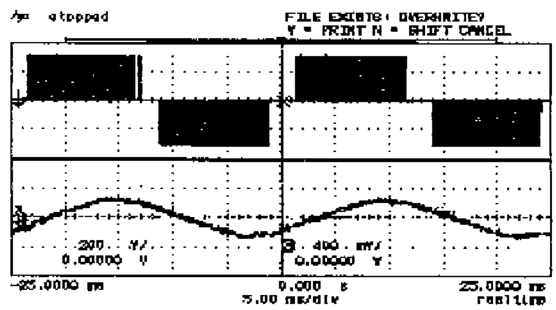


Figure 11. Experimental output current waveforms of the proposed inverter

ZCT condition, naturally. Otherwise, the usefulness of the proposed resonant control algorithm is shown in Fig. 9. This is the across voltage and current waveforms of the phase A switch, S1 and the anti-parallel diode D4 of switch S4, when the load current is small and the capacitor charging time is greater than the dead time of the main device. In this case, when the ZVT auxiliary resonant branch is not operated during turn-off commutation period of switch S1, the capacitor cannot be fully discharged and the remained energy of capacitor works on surge current of diode D4 as shown in Fig. 9 (a). But, if the ZVT resonant branch is controlled at this point by the feedback the load current, the capacitor can be fully discharged and the surge current of main switch is not occurred as shown in Fig. 9 (b). The output three-phase current waveform of the proposed ZVT inverter is shown in Fig. 10. The adopted SVM technique have been changed the SSV from zero vector V_{zn}, NNN to voltage vector V_{bc}, NPP for a short period in sector I. In other sector, the above modification concept is also adopted. However, the output current can get the smoothing sinusoidal waveform like the conventional SVM scheme. The simulation result represents that the proposed ZVT inverter clearly satisfies ZVT operation of main switch, and also ZCT operation of auxiliary resonant switch during commutation based on the modified SVM and the proposed resonant control algorithm.

And, in order to testify the bridge-type ZVT inverter topology and the proposed control algorithm, a three-phase 1-KW bridge-type ZVT inverter has been built to drive a 1/8-hp induction motor. Fig. 11 shows the output current waveform of the proposed inverter with the induction motor load. The switching frequency was 10KHz and the fundamental frequency was 40Hz. The current ripple is largely reduced with high frequency switching. The output current of the proposed inverter shows the sinusoidal waveform like the simulation result. This means the proposed control algorithm operates well without affecting load current.

6. CONCLUSIONS

In this paper, control strategies of the bridge-type ZVT inverter for AC motor drive application were discussed. To resolve the problems of the proposed ZVT topology, the correlation of the ZVT operation and load current during commutation period was analyzed. And a new resonant control algorithm by using load current feedback was proposed in order to achieve the ZVT switching condition in full control range. Another, a new modified SVM algorithm for the proposed ZVT inverter was derived through the analysis of the conventional SVM. For practical implementation of these algorithms, two possible logical control strategies were discussed and simulated for the bridge-type ZVT inverter. And, in order to testify the bridge-type ZVT inverter topology and the proposed control algorithm, a three-phase 1-KW bridge-type ZVT inverter has been built to drive a 1/8-hp induction motor. The detailed computer simulation and experimental results represent that ZVT and ZCT operation for the main and auxiliary switch, respectively, was achieved.

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