# A New Current Controlled Inverter with ZVT Switching

S. R. Lee, C. H. Jeon, S. H. Ko
School of Electronic and Information engineering
Kunsan National University, Kunsan Korea

***Abstract***

*A single-phase bi-directional inverter with a diode bridge-type resonant circuit to implement ZVT(Zero Voltage Transition) switching is proposed. It is shown that the polarized ramptime current control algorithm, a method that belongs to the family of ZACE(Zero Average Current Error) methods, is a suitable technique to integrate with a typical single-phase ZVT inverter. The proposed current control algorithm is analyzed to design the circuit with auxiliary switch which can operate with ZVT for the main power switch. The simulation results would be shown to verify the proposed current algorithm to turn the main power switch on with ZVT and to operate the inverter bi-directionally*

**Key words :** Bi-directional ZVT inverter, current control

## 1 . INTRODUCTION

Grid connected single phase PV(Photovoltaic) systems, in particular low power systems, are recognized more and more worldwide due to their contributions to clean power generation. Solar technology in the form of PV based inverter controlled remote area power supplies is utilized extensively. Appropriate current control methods for the various inverter topologies are used for grid connected power generation systems. They are also widely used in power application where a sinusoidal signal is required, namely as a UPS(Uninterruptible Power Supply) or as a motor drive[2].

Most inverters use various PWM (Pulse Width Modulation) signal which is filtered to finally produce a low-distortion sinusoidal signal. There are two broad categories of inverter control techniques, voltage control and current control. Each type of control has a specific use. Voltage control is not employed for a grid connected inverter since the voltage on the output is generally dictated by the grid power source. Instead current control is used to export a predetermined amount current control. With the effective value of the grid voltage being approximately constant, this corresponds to a predetermined level of power transferred of the grid. MPPT (Maximum Power Point Tracking) can be utilized with current controlled PV connected inverters by monitoring both PV voltage and current, and maximizing the power by varying the amount of exported power.

The bigger the inverter inductor is the smaller the ripple becomes. However, the disadvantage is that the larger the inductor the larger the size and weight of the inductor and also the greater the cost. Increasing switching frequency of the power switches reduces inductor size but switches frequency is limited by power device technology and power loss. The SSIs(Soft Switching Inverter) topologies can reduce these problems because it can achieve high efficiency and reliability, low EMI for high switching frequency, low cost and compact heat sink. Even though a number of soft-switching circuits have been developed, there exist several problems. The major challenge is to develop control strategy to satisfy the zero voltage switching condition of the main devices and zero current switching condition of the auxiliary switches during transitions.

The current control method is to force the current in the inverter to follow a specific desired value. An ideal current control method would accurately follow then current reference with ZACE(Zero Average Current Error) control method in each switching period. ZACEs provide advantages over conventional control methods such as average current mode control and fixed band hysteresis control.[1] There currently exist several different ZACE control algorithms, such as SGHC(Slope Generated Hysteresis Control) and Ramptime control. SGHC has implementation difficulties due to the intensive processing required in analog and digital format. Also SGHC requires the derivative of the current error to be calculated which can cause problem like noisy. To implement ramptime control is difficult using either discrete electronics or digital signal processing because the division function, to calculate the duty cycle, is required for implementation and it is computationally intensive.

To over come this problem, this paper proposes a new control method to maintain a constant switching frequency based not a determining a hysteresis, band or using a clock, but on the zero crossing of the error signal. Also, it is analyzed to design the circuit with auxiliary switch which can operate with ZVT for the main power switch.

The objective of this paper is to report the integration of the new current algorithm with typical single-phase full-bridge inverter to achieve ZVT. Furthermore, the effectiveness of the proposed current controlled ZVT inverter design is also verified using simulation waveforms for the associated EMI spectral characteristics.

## 2. GRID-CONNECTED ZVT INVERTER

Power electronic deals with conversion and control of electrical energy in order to make it suitable for various applications. The ultimate aim is to process electrical power in a control and efficient manner. To overcome the disadvantages mentioned earlier, the diode bridge-type ZVT inverter is proposed in Figure 1.

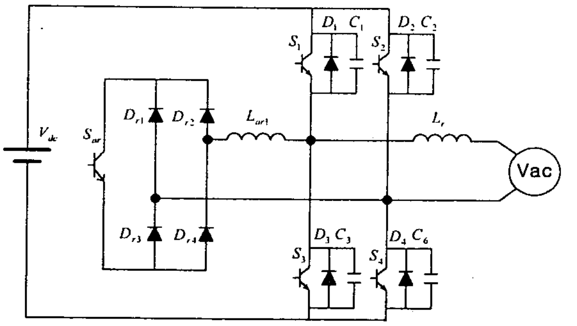
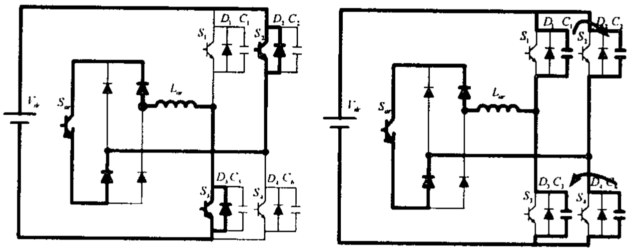


Fig.1 Grid-connected ZVT inverter

The structure of the proposed inverter topology contains a traditional single stage VSI, consisting of four main switches and four anti-parallel diodes. And four resonant capacitors can be externally added to the inverter. The auxiliary resonant circuit consists of only one auxiliary switch, one resonant inductor and four blocking diodes. The circuit is connected with output terminal of the grid in parallel. The main advantage of the proposed topology is the reduction of the auxiliary switch

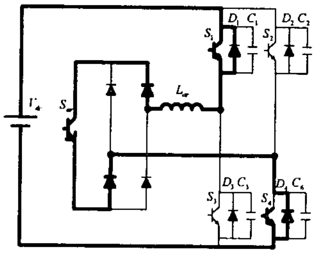
### 1) Principle of Operation

The principle of operation of the proposed inverter is that the resonant branch circuits operate to provide a zero-voltage condition to the switches during turn-on, and the switch turn-off voltage is snubbed by the capacitor across the main device, as with a snubber capacitor in the conventional PWM inverter. Since the resonant capacitor slows down the switch voltage rise during turn-off, the turn-off loss is largely reduced. The prosed inverter ZVT switching operation for the main switch S1 and S4 has three operation modes shows Fig. 2. Three operation modes is described as follows.



(a)Charging mode

(b) Resonant mode



(c) Discharging mode

Fig. 2. ZVT operation modes of proposed inverter

(1) **Charging mode** : The initial condition assumed is for a positive output current which is freewheeling through D2 and D3 with S2 and S3 conducting. Turn on auxiliary switch Sar as shown in Fig. 2(a). The resonant inductor current Ia, increases linearly. When the resonant current equals the load current , the freewheeling current in D2 and D3 becomes zero. The resonant inductor current exceeds the load current and then it is provide through switches S2 and S3 instead of D2 and D3. When the auxiliary inductor current increases turn off devices S2 and S3.

(2) **Resonant mode** : All main switches are turn –off . The current path is established by stored energy of resonant inductor and snubber capacitors as shown in Fig. 2(b). At that point, the capacitors C2 and C3 serve as lossless snubbers to allow zero voltage turn-on of the main switches S2 and S3. Capacitors C2 and C3 are charged DC bus voltage, Vdc, and C1 and C4 are discharged to zero voltage by the stored energy of the resonant inductor..

(3) **Discharging mode** : At the end of the resonance period, turn on main switches S1 and S4 as shown in Fig. 2(c). Main switches S1 and S4 can be turned on at zero voltage condition. The switch current continues to increase while the resonant inductor current decreases linearly. When the resonant inductor current decreases to zero auxiliary switch can be turned off at zero current condition.

### 2) Design of Auxiliary Circuit

The ZVT inverter for Grid-connected system is ZVT condition depending on the load current. So, ZVT inverter have to design in consideration of load current. This paper design a input voltage DC 380[V], output current 15[A] ZVT inverter module.

(1) During time of snubber capacitor charging and discharging ( $\Delta t_c$ ) : 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

$$\frac{1}{C_r}\int\frac{I_0}{2}dt = V_s \quad (1)$$

$\Delta t_c$ is obtained by the following to (1)

$$\Delta t_c = \frac{2C_rV_s}{I_o} \qquad (2)$$

In order get to the ZVT switching of main switch , the capacitor discharging time $t_{cg}$ must be satisfied by

$$t_{cg} \le t_d \qquad (3)$$

Where $t_d$ is dead time of main devices. If output current $I_o$ decrease to the limit designed value, the proposed ZVT topology cannot satisfy ZVT condition because capacitor charging time is, accordinng to relationship in load current from (2), greater than dead time of main device.

(2) Energy balance : The charge of the resonant inductor needs to be sufficient to discharge the snubber capacitor to ensure ZVT switching;

$$\frac{1}{2}L_rI_{toff}^2 \ge C_rV_s^2 \qquad (4)$$

where is $I_{toff} = I_{Lr} - I_o$. So, resonant current $I_{toff}$ is minimum when a situation of load current maximum. Therefore, the inductor current, $I_{Lr}$, must be charged to a level higher than the load current to satisfy the following charge balance requirement from (4). The inductor value $L_r$ can be design when inductor charging time is 2[us] and inductor current $I_{Lr} = 2I_o$.

## 3. CURRENT CONTROL ALGORITHM

The grid-connected single-phase system employs the proposed ZVT inverter shown Fig. 1. This can avoid problems of a non-zero mid point voltage due to the unbalance individual battery voltage. A lower rated current and lower rated voltage of switches can also be used in this configuration.

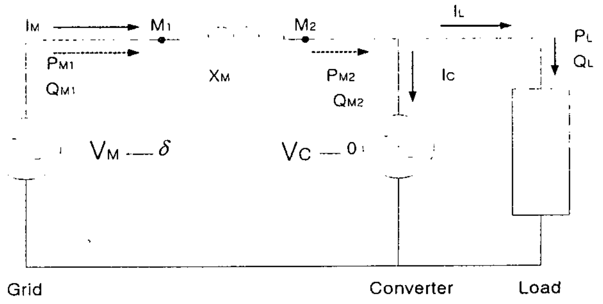


Fig.3 power flow equivalent circuit

Fig. 3 shows single-phase equivalent circuit. Power flow can be controlled by directly controlling the real and reactive components of the current.

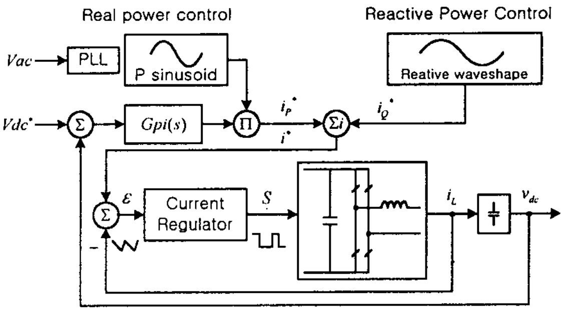


Fig 4. Inverter control with inner current control loop

Current controlled power flow consists of the inner and outer control loops shown Fig 4. In the outer loop, a desired current reference waveform is created. In the inner current control loop, the actual inductor current is forced to follow the reference waveform. The inductor current is measured with an instantaneous measurement, and is subtracted from the sinusoidal reference current $i*$ to given an error signal $\varepsilon$. The current control technique uses th error singal to produce a PWM pattern ouput switch signal $S$ which is used to directly control the switch in the inverter in such a way as to force the inductor current $i_L$ to follow the reference value $i*$.

Ramptime current control was developed in an effort to find a ZACE method with a fixed switching frequency. This method uses only the current error signal to determine switching instants, and aims to maintain a narrow switching frequency band.

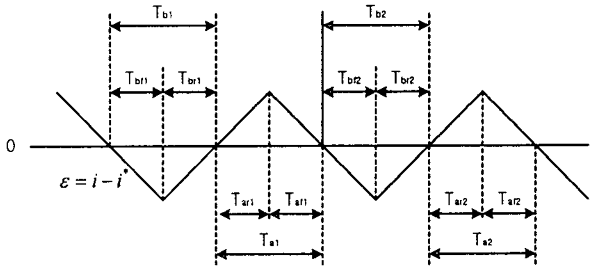


Fig.5 Current error signal with time periods

Ramptime control is explained by reference to the current error signal in Fig. 5. Assuming a fixed inductance, and negligible variance in the current reference within in switching period, constant slopes over that switching period. Ta is the period of time when $i_\varepsilon$ is above zero and Tb is the period of time when $i_\varepsilon$ is below zero. If Ta is can be made equal to Tb, then area of the current error signal above zero will equal the area of the current error signal below zero, and the average value of the current error signal over that switching period will be zero. To maintain ZACE and a fixed switching frequency, the desired value of each half switching period is:

$$T_a^* = T_b^* = \frac{T_{sw}}{2} \qquad (4)$$

where , * : indicates a desired value

Ramptime current control assumes that the error current is made up of linear segments and calculates the next switching instant using duty cycles and time information. One of disadvantage of this technique is any error made miscalculation of the next switching instance Also, ramptime control require accurate calculation of the duty cycle for the previous half switching cycle to minmize errors. To solve the problem, this paper presented polarized ramptime current control algorithm. In PRT(polarized ramtime) current control, the previous same-side excursion of the current error signal is used in the determination of a switching instant, rather than the immediately previous opposite-side excursion. Referring to Fig.5, to determine $T_{ar2}\#$, the immediatelu previous $T_{arl}{}^\wedge$ and $T_{al}{}^\wedge$ are used. Similarly, to determine $T_{bf2}\#$, the immediatelu previous $T_{bfl}{}^\wedge$ and $T_{bl}{}^\wedge$ are used.

$$T_{ar2}\# = \left[\frac{T_{arl}{}^\wedge}{T_{al}{}^\wedge}\right]\left[\frac{T_{sw}}{2}\right] \qquad (5)$$

$$T_{bf2}\# = \left[\frac{T_{bfl}{}^\wedge}{Tb^\wedge}\right]\left[\frac{T_{sw}}{2}\right] \qquad (6)$$

where , ^ : indicates a measured value
#: indicates a calculated value

The implementation of PRT current control illustrated in the functional block diagram of Fig. 6.

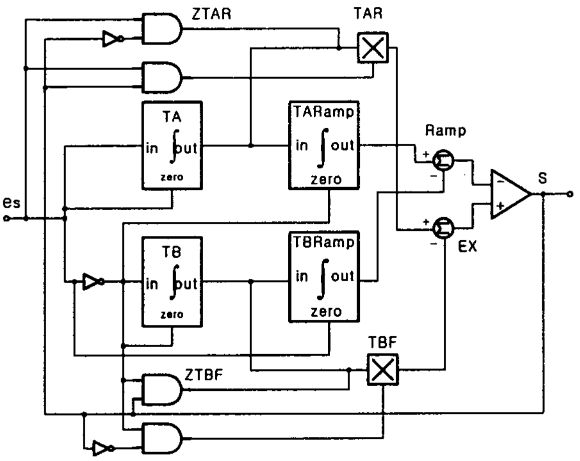
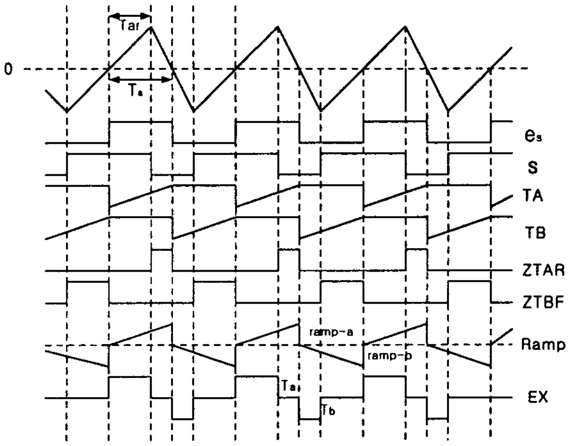


Fig. 6 PRT current control functional diagram

$\varepsilon_s$ is a binary signal indicating the polarity of current error signal $\varepsilon$. $\varepsilon_s$ is high when $\varepsilon$ is positive, and low when $\varepsilon$ is negative. $S$ is a binary signal used as a command for the power circuit main switches. Fig. 7 shows PRT current control timing wavefroms

TA : an integrator to measure Ta
TAF : an integrator to measure Taf
TA RAMP : an integrator for creating a ramp with a slop proportional to Ta
TB : an integrator to measure Tb
TBF : an integrator to measure Tbf
TA RAMP : an integrator for creating a ramp with a slop proportional to Tb



.Fig. 7 PRT current control timing waveforms

## 4. SIMULATION RESULTS

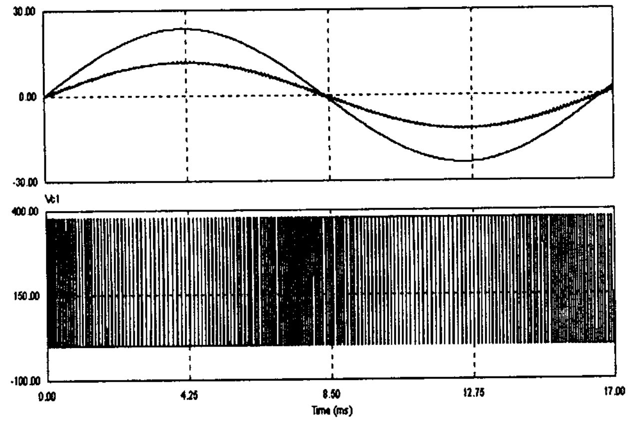
The simulation was done with Pspice and PSim simulator in order to verify the ZVT operation of the proposed topology and control algorithm. R-L values of the load for simulation were determined to be the output current 15A.

The simulation condition and parameters of the proposed ZVT inverter are given Table 1.

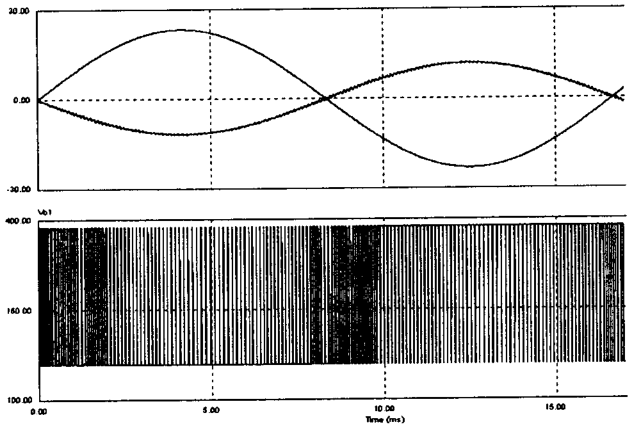
Table 1. Simulation condition and parameters

| Parameter | Value |
|---|---|
| $V_{an}$ | 220 V |
| $V_{dc}$ | 380 V |
| $I_a$ | 15 A |
| $f_{sw}$ | 20 KHz |
| $f_l$ | 60 Hz |
| $L_r$ | 20 mH |
| $L_{ar}$ | 20 uH |
| $C_r$ | 15 nF |

Figure 8 and 9 shows the simulation results of the proposed topology for grid connected power generation systems. Figure 8 (a) is the waveforms of the voltage and current of the inverter during positive state. Figure 8 (b) is the waveforms of the voltage and current of the inverter during negative state.



(a) Positive State



(b) Negative State

Fig 8. Waveforms of the voltage and current of the proposed ZVT inverter

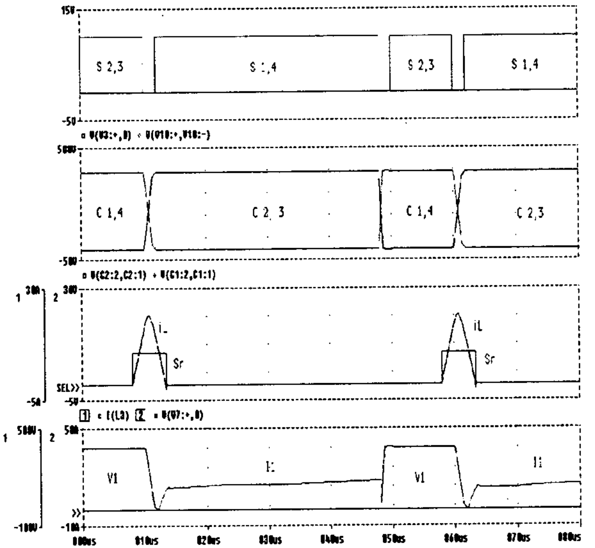


Fig. 9. Waveforms of ZVT operation of proposed inverter

Figure 9 (a) is the waveforms of the gate signal sequences of the inverter main devices based on the proposed control method. Figure 9 (b) shows the voltage of main switches. Figure 9 (c) shows the resonant current of auxiliary switch. Figure 9 (d) is the voltage and current waveforms of the main switches during commutation period. The simulation result indicates that the proposed ZVT inverter clearly satisfies the zero-voltage operation during transition of main switches and also bi-direction operation.

Figure 10 shows the current harmonic spectrum from zero to 60 kHz. The widely of the switching frequency band is much greater than expected.

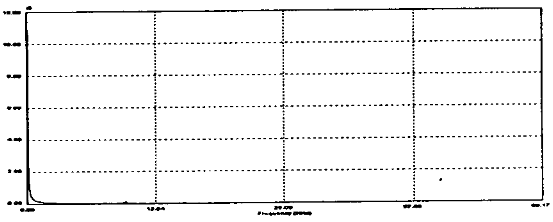


Fig 10 Fourier transform current harmonic spectrums

## 5. CONCLUSION

In this paper, the diode bridge-type ZVT inverter for grid-connected power applications, which is used PRT current control method to overcome problem of conventional current control method as mentioned above, was proposed. And current control algorithm of the proposed ZVT inverter, was discussed. The detailed simulation results show that ZVT operation for the main devices, in full control range, was achieved. PRT current control method offers a good mix of minimum ac ripple current, with full controllability and transient response, and a narrow switching frequency band.

## Acknowledgments

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