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Design And Analysis Of A Zero-Current Transition (ZCT) Inverter

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Abstract

The development of zero switching loss inverter has attracted much interest for industrial applications. Utilizing the ZCT technique in DC/AC inverter enables all main and auxiliary switches to be turned on and off under zero current conditions.

The ZCT at both turn-on and turn-off not only reduces switching losses significantly but also eliminates the need for passive snubbers due to the much reduced switch stress and cost.

In this paper design and analysis of moderate power ZCT inverter has been presented. Also, the inverter operation has been investigated using a novel control circuit to drive the auxiliary and main switches.

تصميم وتحليل مغير (Inverter) يعمل بتقنية العبور عند التيار الصفري (ZCT)

الخلاصة

إن نشوء مغيرات التيار المستمر إلى التيار المتناوب والتي تعمل بتقنية الغلق - والفتح (Switching) قد اجتذبت اهتمام كبير في التطبيقات الصناعية.

يمكن الاستفادة من تقنية عبور التيار الصفري (ZCT) في مغيرات القدرة (DC/AC) في جعل كل المفاتيح الرئيسة والمساعدة تعمل في لحظة الغلق والفتح تحت شروط التيار الصفري.

إن تقنية عبور التيار الصفري (ZCT) عند الغلق والفتح ليست فقط تقلل مفاقيد المفتاح بل أيضا تمكن المصمم من إزالة دوائر القنص (Snubbers circuit) وتؤدي إلى تقليل الكلفة والإجهاد (Stress) على المفتاح.

تعرض هذه المقالة تصميم وتحليل لمغير (Inverter) يعمل بتقنية عبور التيار الصفري (ZCT) وقد تم فحص عمل المغير المصمم ودرست خواصه باستخدام دوائر سيطرة جديدة لتشغيل المفاتيح الرئيسية والمساعدة.

Index Terms: DC-AC Inverter, Soft Switching and Zero Current Transition.

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1- Introduction:-

High frequency (HF) resonant converter can perform the zero current or zero voltages switching (so called soft switching) operation with lower switching loss and lower electromagnetic interference (EMI) noise than the hard switching operation performed by the conventional pulse width modulation (PWM) converter. [1],[2],[3]

A snubber circiut reduces the switching loss and the switching stresses of switches, but increases the total power loss in the converter [2].

However, a recently developed zero voltage [4] and zero current switching techniques can reduce switching losses with minimum voltage/current stresses and circulating energy. The ZVT technique forcing the voltage of incoming switch to zero before its turn-on to practically eliminate switch turn-on loss. The switch turn-off loss that is usually the dominating switching loss in high power application can not be alleviated effectively with ZVT technique. The ZCT technique can significantly reduce the switch turn off loss by forcing the out going switch current to zero prior to its turn off [5]. A single phase full-bridge inverter [6],[7] using auxiliary commutation is shown in Fig.(1a)The circuit operational waveforms for one switching cycle are illustrated in Fig. (1b) . The current of main switch is reducing to zero prior to the turn-off. However, the auxiliary circuit does not affect the turn-on loss of the main switch.

In this paper, a new inverter scheme with modified control and topology is presented to achieve ZCT at turn-on and turn-off. The proposed inverter has been analyzed theoretically and investigated experimentally. The results obtained have shown better performance of the implemented inverter as compared to the conventional PWM inverter.

2- Analysis of the proposed ZCT single phase inverter:

The drawbacks of ZCT topology[8] shown in Fig. (1) for the turn-on loss of the main switch is not affected by the auxiliary circuit and the peak voltage of resonant capacitor is about twice that of the switches can be overcome by the topology shown in Fig. (2) with series connected auxiliary switches for each leg. Such switches perform the same function as that in the auxiliary resonant commutated pole (ARCP) converter [9] with clamp diodes in the auxiliary circuit tom reduce voltage ringing of the auxiliary switches. The low power diodes

Dc_1-Dc_4 are used to clamp the auxiliary switch voltage.

The operation of ZCT inverter presented here is characterized by soft switching conditions which are achieved by actuating the auxiliary switching circuit in the transient periods.

The simulated waveforms during one switching period are shown in Fig. (2b). There are nine difference stages of the inverter circuit that can be discriminated during one switching period as illustrated in Fig. (3).

On analyzing the inverter operation, the output current i_o is assumed constant during one commutating interval. Because of the symmetry of the circuit configuration, the consideration under the condition of the output current $i_o>0$ can be applied to case of $i_o<0$. Before the mains switch S_1 turn-on the output current i_o is conducted by D_2. The auxiliary current i_x is zero and V_x has a value equal to V_{CO}. The nine inverter circuit stage are as follows.

(a) Turn-On Transition I(t_0,t_1):-

At t_o, S_{x1} is turned on initiating the turn-on transition. The auxiliary resonant tank consisting of L_x and C_x start to resonate and the auxiliary current i_x resonates from zero to positive peak at t_1, while current in the diode D_2 is reduced to zero. So that, S_1 is turned on under ZCT condition at t_1 and turn- on loss is reduced significantly.

(b) Turn-On Transition II (t_1, t_2): -

The current rises rate of the switch S_1 after turn-on is limited by the resonant inductor. After t_1, i_x decreases rapidly toward zero at t_2 because the supply voltage Vs/2 will oppose the flow of the resonant current.

(c) Turn-On Transition III(t_2,t_3):-

At t_2, ix returns to Zero. So that the switch S_{x1} turns off at ZCT condition at t_2. Since the resonant capacitor voltages V_x is positive, then the auxiliary circuit continues resonating and negative i_x is conducted by the clamp diode Dc_2. This stage vanishes when the current I_x returns again to zero.

(d) Switch on. Stage (t_3,t_4):-

When i_x returns to Zero again at t_3, Dc_2 is turned off naturally. Then the auxiliary circuit stops resonating and disconnected from the main circuit functionally. The converter resumes its PWM operation the duration of this stage is determined by the PWM control.

(e) Turn-off Transition I (t_4,t_6):-

Before the main Switch is turned off, the auxiliary switch S_{x2} is turned on at t_4. The resonant tank starts to resonate again. The resonant path includes L_x, C_x and the (V_S/2) input voltage. Current i_x is negative and its magnitude increases from Zero to peak and than decreases. When i_x returns to Zero at t_5, S_{x2} is turned off under ZCT condition. Since resonant capacitor voltages V_x is less than (-Vs/2) then switching on the auxiliary switch S_{x1} at t_5 allows the auxiliary circuit to continue resonating after t_5. The positive i_x is conducted by S_{x1} and D_{x2}. Hence the current of the main switch S_1, (i_0 - i_x), is decreasing for i_x increase. The interval of this stage is terminated at t_6 when i_x reaches i_0.

(f) Turn-off Transition II (t_6,t_7):-

At t_6, i_x reaches i_0 and the main switch current is reduced to zero .So, the switch S_1 is turned off under the ZCT condition. As i_x keeps increasing after t_6 the surplus current will flow through the parallel diode of S_1 and clamp the voltage a cross S_1 to Zero. So ,the gate signal of S_1 can be removed without causing much turn off loss.

(g) Turn-off Transition III (t_7, t_8):-

At t_7, i_x falls to i_0 and the parallel diode of S_1 stops conducting. Hence the capacitor C_x recharges through the load at an approximately constant current of i_0. These mode ends when the capacitor voltages becomes equal to (Vs/2) at t_8 and tends to over charge due to the energy stored in inductor L_x.

(h) Turn-off Transition IV (t_8, t_9)

At t_8, V_x is charged to (Vs/2) and the diode D_2 starts conducting. So, the resonant tank begins to resonate again. As i_x resonates toward zero, the current in the main diode increases gradually and i_x returns to zero at t_9 for S_{x1} is turned off at ZCT condition.

(i) Clamp diode on stage (t_9, t_{10}):-

At t_9, V_x is being charged to positive voltages above (Vs/2) and the clamp diode Dc_2 conducts the auxiliary current i_x. This current resonates from Zero to negative peak and returns back toward zero at t_{10}. At the end of this stage the resonant capacitor voltage V_x is equal V_{co} which is the same value as the initial voltage.

3- Design of the ZCT circuit: -

The design of the auxiliary circuit requires determination of the capacitance C_x and Inductance L_x. The auxiliary circuit should be designed to a chive zero current switching with maximum main current while keeping the power loss in auxiliary circuit minimized [10]. Since turn-off transition is more critical than the turn-on transition the following design procedure is mainly based on the switch turn-off requirements. To reduce the switch loss the duration of turn-off Transition II, T_{off} =(T_7-T_6), should be long enough for most storage charge of the main switch to recombine. In the following analysis the design is based on maximum output current I_o. From the state plane trajectory of Fig. (4) we can get.

$$\mathbf{T_{off} = T_7 - T_6} \quad (1)$$

$$\mathbf{T_{off} = 2\left(\cos^{-1} m\right)\sqrt{LxCx}}$$

$$\mathbf{T_{off} = \left(T_o \cos^{-1} m\right)/\pi} \quad (2)$$

Where: $\mathbf{m = \frac{I_o}{I_{PK}}}$, $\mathbf{T_o = 2\pi\sqrt{LxCx}}$

I_{pk} is the resonant peak of i_x during turn-off. Assuming V_x is zero at t_4 without loosing much accuracy, we can estimate I_{pk} to be[1] .

$$I_{PK} = \frac{Vs/2}{Z_O} \quad \text{Where:} \quad Z_O = \sqrt{\frac{Lx}{Cx}}$$

The value of T_{off} in designing the resonant circuit depends on the switching devices. Generally T_{off} should be much longer than the current fall time of the main switch [11], [12], [13]. A longer T_{off} can be achieved by either increasing I_{pk} or increasing T_o. Our design objective is to minimize the conduction loss caused by the soft switching action for given T_{off}. From the state plane shown in Fig.(4) we have:

$$\frac{1}{2}\omega_O T_{off} = \theta \qquad (3)$$

$$\text{and}, \ \theta = \cos^{-1}\frac{I_O}{I_{PK}} = \cos^{-1} m \qquad (4)$$

Using the above equations and definitions it can be shown that: -

$$\omega_O = \frac{1}{m}\,\frac{I_O}{CxVs/2} \qquad (5)$$

Substituting for T_o using eq.(5) in to eq.(2) yields:

$$T_{off} = 2mCx\frac{Vs/2}{I_O}\cos^{-1} m \qquad (6)$$

Let $T_n = \frac{CxVs/2}{I_O} = \frac{Q}{I_O}$ be the available turn-off time, then:

$$T_{off} = 2mT_n \cos^{-1} m$$

$$T_{off} = 2\theta T_n \cos\theta \qquad (7)$$

The per unit turn-off (T_{off}/T_n) as a function of current ratio m is plotted in fig.(5). The optimum design condition is obtained at the maximum per unite turn-off time at shown in fig. (5). The criterion can be accurately calculated by setting the derivative of eq. (7) equal to zero and solving the resulting transcendental equation.

$$\frac{dT_{off}}{d\theta} = 2T_n(\cos\theta - \theta\sin\theta) = 0$$

$$\theta = \cot\theta \qquad (8)$$

By numerical solution of eq. (8) we get:

$$\theta = 0.86\,\text{rad} = 49.3^\circ$$

$$m = 0.652$$

Once m=M is chosen; Lx and Cx can be calculated as follows:-

$$Lx = \frac{MT_{off}Vs}{4I_O\cos^{-1} M} \qquad (9)$$

$$Cx = \frac{I_O T_{off}}{MVs\cos^{-1} M} \qquad (10)$$

A practical converter will have much more complex loss models for its component and the optimum design can only be achieved through experiment. The conduction duration of the auxiliary switch is always 75 % of the resonant cycle. The main switch can be turned on or off around the resonant peak of i_x.

4-Experimental Results: -

The half bridge ZCT inverter shown in fig.(6) has been built and tested. The control circuit of the main and auxiliary switches is illustrated in fig. (7). Also the synchronized pulses required to control the operation of the designed ZCT inverter are given in fig.(2). Load voltage of (50Hz) frequency has been obtained with switching frequency of (1.6KHz) and resonant frequency of (20KHz). The output voltage can be controlled with uniform pulse width modulation (UPWM) techniques.

Power MOSFET's (type VN4000A) are used for all main and auxiliary switches. Fig.(8),Fig.(9) and Fig.(10) show the experimental waveforms. It can be seen that the circuit waveforms comply with theoretical on analysis and simulation. Fig. (8) (a, b, c, d, e and f) shows synchronized control pulse of the two main switch S_1, S_2 and two auxiliary switch Sx_1 and Sx2. Fig. (9a) show the output voltage for R load only and fig.(9b) shows the output voltages for (RL) load.

Fig. (10) shows the practical auxiliary circuit voltage and current respectively, whereas fig. (10c) illustrated the current of the main switch S_1. It can be seen that these waveforms are in good agreement with that obtained in the theoretical analysis.

5-Conclusions: -

In this paper analysis of the steady-state operation of moderate power inverter has been presented and design algorithm to determine the components of the resonant tank has been developed.

The designed inverter has been implemented using power MOSFET switches and novel control circuit to produce a.c. power of (50HZ) frequency.

The theoretically depicted waveforms and these obtained experimentally are in good agreement, which means that switching loss and stress are reduced significantly.

The snubber can be reduced or eliminated in the ZCT inverter and its cost may be reducing while its efficiency, EMI emissions, reliability, and dynamic performance are improved. Experimental results prove that significant efficiency improvement can be achieved ZCT circuit.

References

1- Hengchun Mao. Fred C. Y. Lee, xunwei zhou, Heping Dai, Mohammet Casun and Dushan Boroyerich. "Improved zero current transition converters for high power application," IEEE Trans. Ind. Applicat. , Vol.33, No.5 pp.1220-1281, September/ October 1997.

2- Deepakray M. Divan. "The resonant dc link converter-anew concept in static power conversion," IEEE Trans. Ind. Applicat. Vol.25, No.2 , pp.319-325, March/April 1989.

3- Muneaki Ishida, Hitosh. Fujino, and Tukamas, Hori "Real time output voltage control method of Quasi-ZCS series resonant HF lineked Dc-Ac converter," IEEE Trans. On power electronics, Vo.10, No.6, pp.776-783, November 1995.

4- Carlos A. Canesion and Ivo. Barbi "Novel Zero-current switching

PWM converters," IEEE Trans. Ind. Applicat. Vol.44, No.3 PP.372-381 June 1997.

5- Ahmed cheriti, Kamal Al-Haddad, Dessaint, A. Meynard and Din kar Mukhedkar "A rugged soft commutated PWM Inverter for ac drives," IEEE Trans. On power electronics , Vo.7 , No.2 pp.385-392 ,April 1992.

6- Ramesh Oruganti and Fred. C.Lee "Resonant power processors part I-state plane analysis," IEEE Trans. Ind. Applicat. , Vol.IA.21 , No.6 , pp.1453-1460 , Nov./ Dec. 1985.

7- Jung. Goocho, Chang-Yong Jeong and Fred C. Lee "Zero voltage and zero-current-switching full-bridge PWM converter using secondary active clamp," IEEE Trans. On power electronics Vol.13, No.4, PP.601-607, July 1998.

8- Willium McMurray "Thyristor commutation in dc choppers a comparative study," IEEE Trans. Ind. Applicat. Vol.IA.14, No.6, pp.547-558 November/ December 1978.

9- Akio-Tobu, Toshihisa Shimizu Gunjikimura, Mitsua Shioya, and Shigeru. Sano. "Auxiliary resonant commutated pole inverter using two internal voltage-point of dc source," IEEE Trans. Ind. Applicat. ,Vol.45 , No.2 pp.200-206 , April. 1998.

10- Deepakraj. M. Divan and Gary Skibinski "Zero-switching loss inverter for high-power application," IEEE Trans. Ind. Applicat. Vol.25, No.4, pp.634-643, July/August 1989.

11-M.H. Rashid "Power electronics circuit, devices and applications, " by prentica-Hall, 1988.

12-B.W. Williams "Power electronics devies, drivers and applications, " by Macmillan Education LID 1987.

13-S. B. Dewan and A. Straughen "Power semiconductor circuit," by John. Wiley and Sons. Ine. 1975.

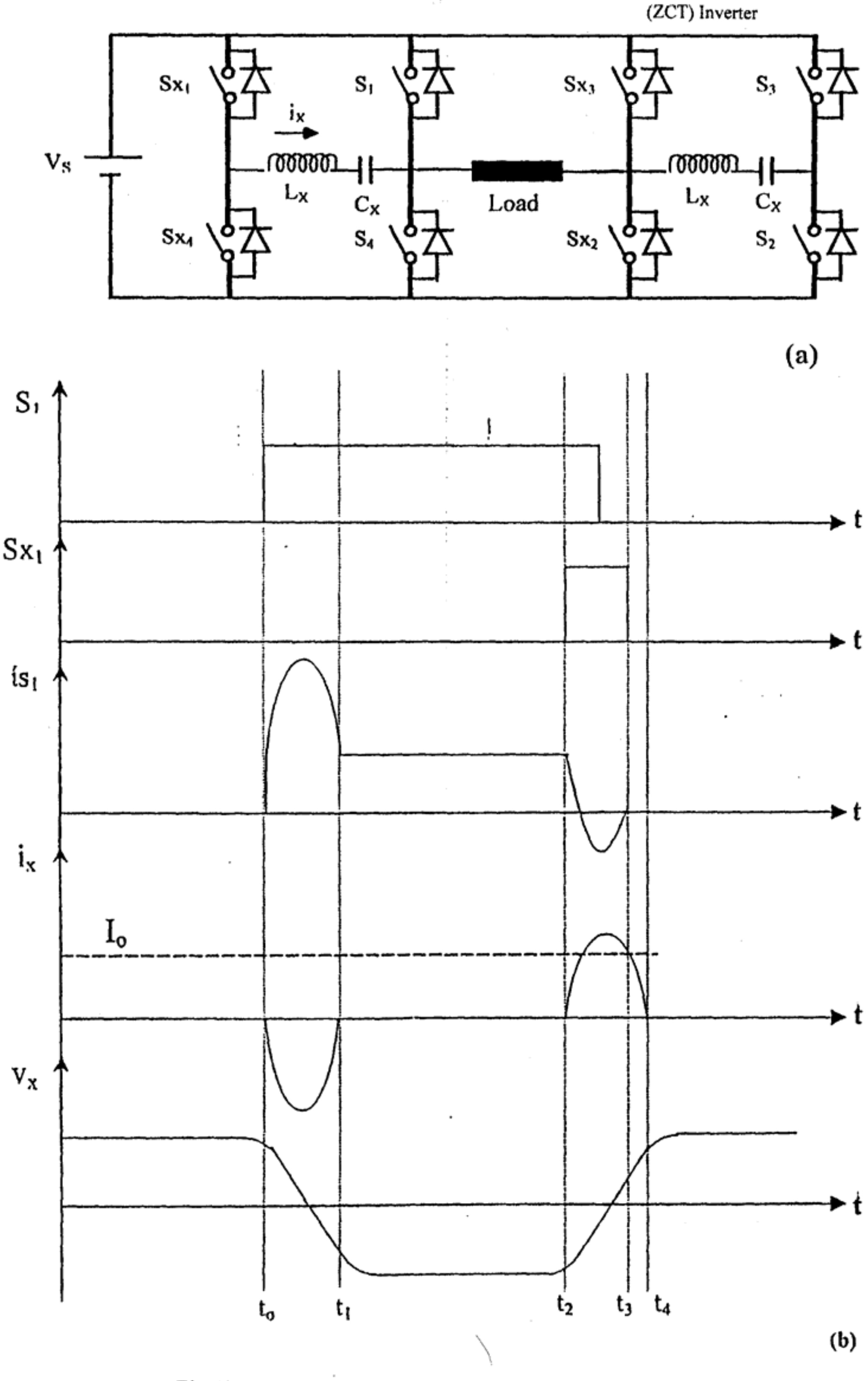
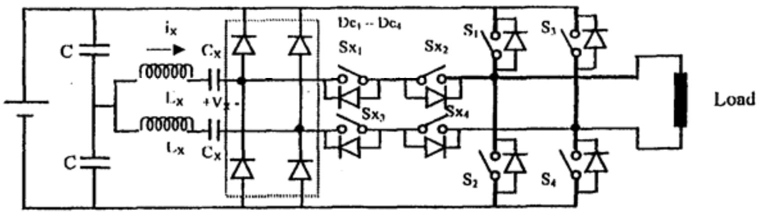
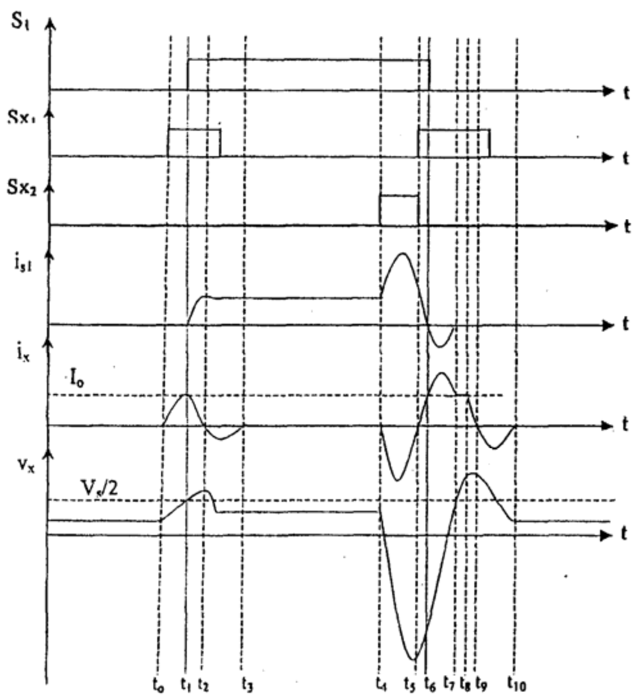


Fig.(1):- Single phase full bridge inverter.
(a) Topology.
(b) Operational waveforms in one switching cycle of S_1.



(a)



(b)

Fig.(2): Modified ZCT single phase full bridge inverter.
(a) Topology.
(b) Operational waveforms in one switching cycle of S_1.

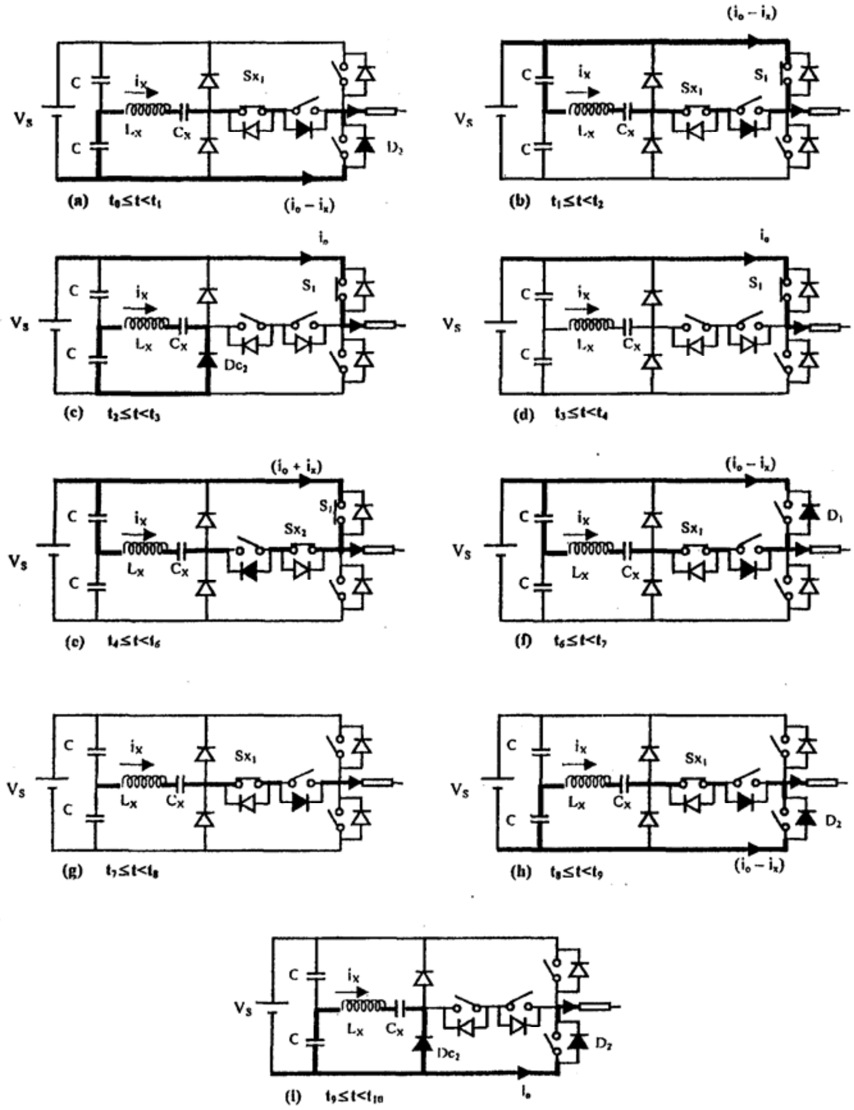


Fig.(3) Operating stages in the soft-switching commutation.

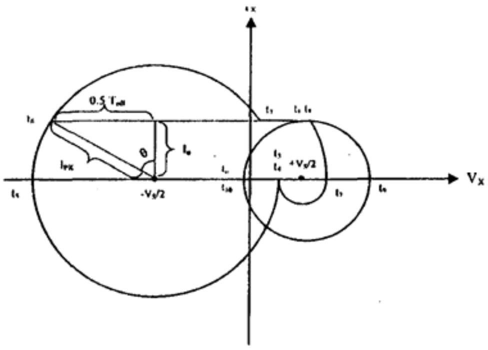


Fig.(4):- State plane trajectory

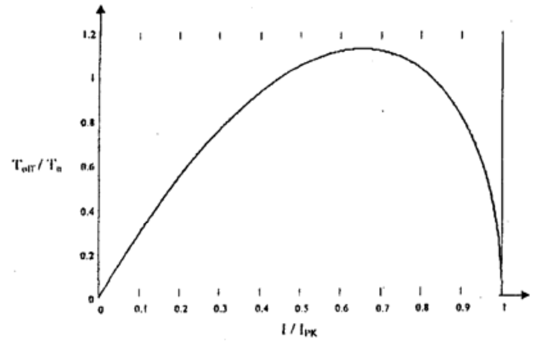


Fig.(5):- Turn off time in basic circuit as a function of current ratio parameter m.

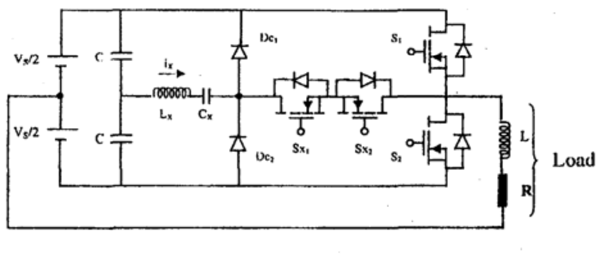


Fig.(6):- Single-phase half-bridge inverter with ZCT.

The implement:

V_S=50V L_X=0.1297mH (Ferrite core)

I_o=1A C_X=0.488μF (Ceramic capacitance)

C_1=C_2=100 μF

all diodes of the type BYX 71

all trausistor of the type VN 4000A power

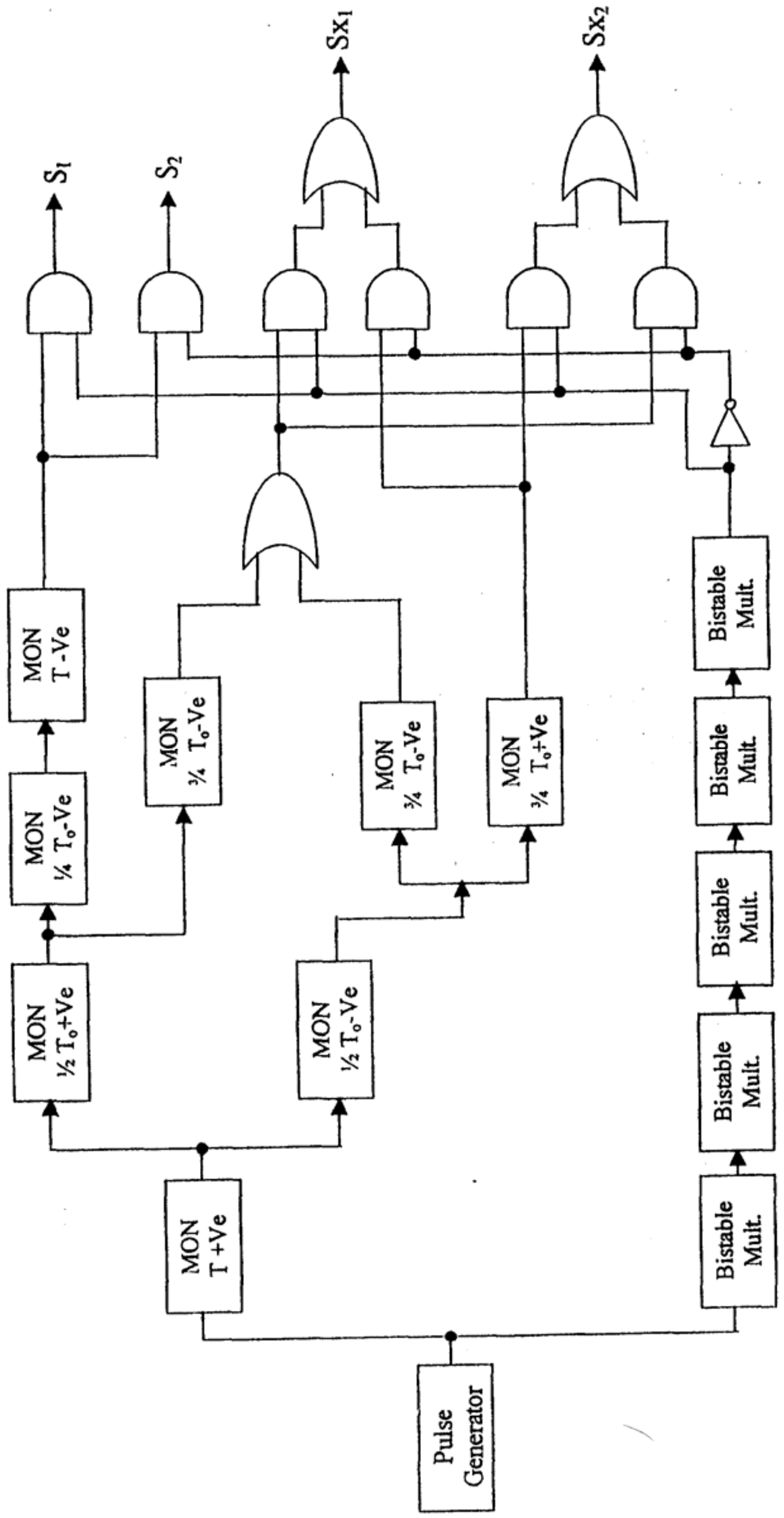
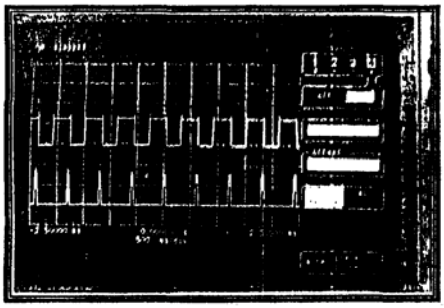


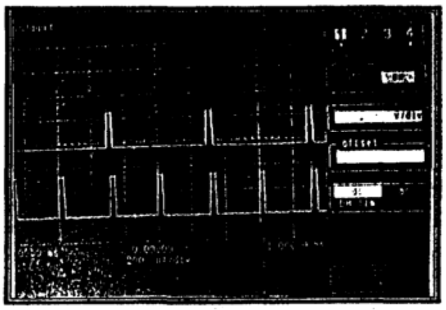
Fig.(7):- The control circuit of the two main switches S_1 and S_2 and two auxiliary switches Sx_1 and Sx_2.

Fig.(8)



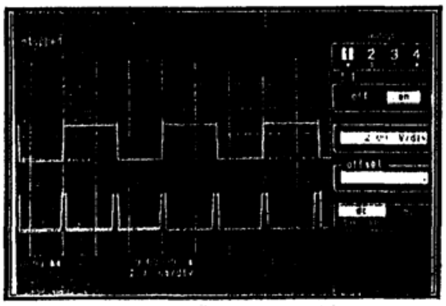
2 V/div
500 µsec/div

a- Control voltage for multiple pulse modulation upper for S_1, lower S_{x2}



2 V/div
200 µsec/div

b- Control voltage for multiple pulse modulation upper for S_{x2}, lower S_{x1}

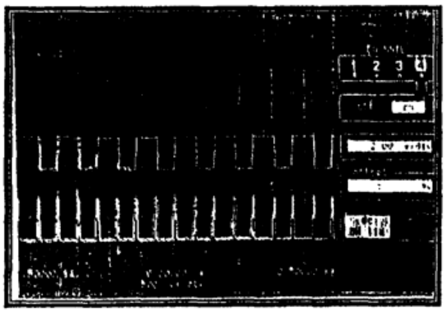


2 V/div
200 µsec/div

c- Control voltage for multiple pulse modulation upper for S_1, lower S_{x1}

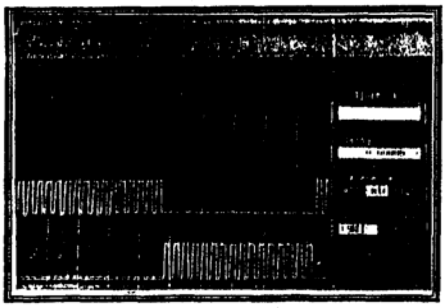
2 V/div
500 µsec/div

d- Control voltage for multiple pulse modulation upper for S_2, lower S_{a1}



2 V/div
500 µsec/div

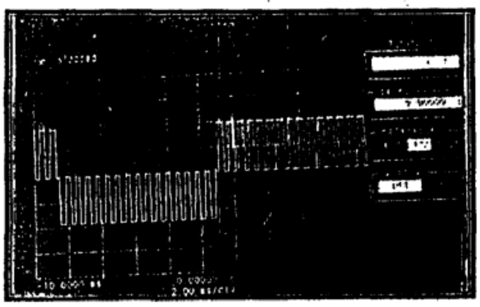
e- Control voltage for multiple pulse modulation upper for S_2, lower S_{a2}



2 V/div
2 msec/div

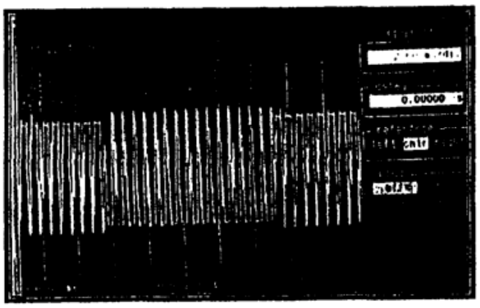
f- Control voltage for multiple pulse modulation upper for S_1, lower S_2

Fig.(9) :-



25 V/div
2 msec/div

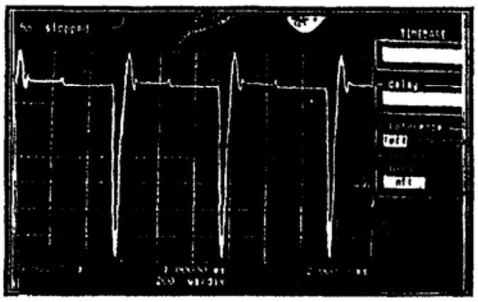
a- Output voltages inverter for multiple pulse modulation resistive load only.



25 V/div
2 msec/div

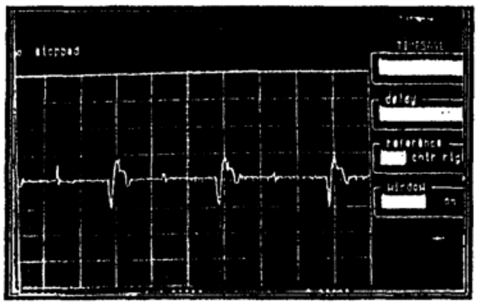
b- Output voltages inverter for multiple pulse modulation inductive load.

Fig.(10) :-



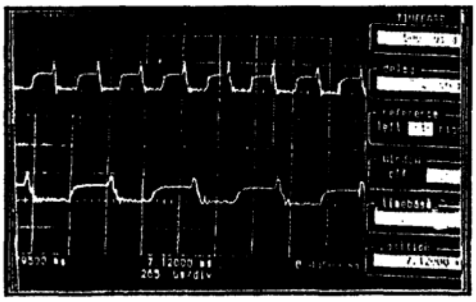
25 V/div
200 µsec/div

a- Resonant capacitor voltage V_r.



1 A/div
200 µsec/div

b- Resonant inductor current i_r.



Upper
1 A/div
500 µsec/div

Lower
1 A/div
256 µsec/div

c- i_{s1} current of switch S_1.