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A Novel Topology of Zero-Current Transition (ZCT) Voltage-Source PWM three-phase Inverter

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Abstract:

Soft-switching technique can substantially improve the performance of power converters, mainly due to the increase of switching frequency, that result in better modulation quality. This is more concerned particularly in the high power applications, where devices [gate turn off (GTO) or something else similar] can not operate over a few hundreds of hertz in conventional hard switching converter structures. High frequency resonant converter can perform the zero-current or zero-voltage switching (so, called soft switching) operation, which produces lower switching loss and lower EMI noise than the hard switching operation performed by conventional PWM converters.

In this paper, design and analysis of moderate power ZCT three-phase PWM inverter has been presented. Also, the designed inverter and its novel control circuit is implemented experimentally to investigate its characteristics with this new zero-current transition ZCT technique.

صنف جديد لتقنية الانتقال عند التيار الصفري (ZCT) لمغير ثلاثي الأطوار

الخلاصة:-

إن أداء مغير للقدرة عند الترددات العالية (حيث تستخدم الترددات العالية للحصول على تضمين افضل) يمكن تحسينه باستخدام تقنية الغلق – الفتح الناعمة (soft-switching). إن تطبيق هذه التقنية يكون مهم عند القدرة العالية حيث لا تستطيع آلة الغلق – الفتح المستخدمة (مثل GTO وما يشابهها) العمل عند الترددات العالية اكبر من عدة مئات من الذبذبات /الثانية في حالة المغيرات التقليدية. مغيرات الرنين التي تعمل عند الترددات العالية بإمكانها أن تؤدي عملية الغلق – الفتح عند التيار الصفري أو الفولتية الصفرية (ما يسمى بالغلق – الفتح الناعم) عند فقد قدرة قليل وضوضاء (EMI) قليلة مقارنة مع المغيرات تضمين عرض النبضة التقليدية (PWM).

تعرض هذه المقالة تصميم وتحليل لمغير ثلاثي الطور معتدل القدرة يعمل بتقنية الانتقال عند التيار الصفري، وقد تم التنفيذ المختبري للمغيرات المصممة ودوائر السيطرة عليها بقصد تفحص خصائص هذه المغيرات التي تستخدم هذه التقنية الجديدة.

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

1- Introduction:-

High-performance inverters have always received the interest of considerable researchers. Due to many advantages of high efficiency, high operational frequency, small size and low switching stresses, soft switching topologies have brought the new trend to the industrial applications of next generation [1],[2],[3].

The development of zero switching loss inverter has attracted much interest for industrial applications. Utilizing the zero current transition ZCT technique in DC/AC inverter enables all main and auxiliary switches to be turned on and off under zero current conditions[1]. The zero current transition at both turn-on and turn-off not only reduces switching losses significantly but also eliminates the need for passive snubers[2], due to the much reduced switch stress and cost.

A three-phase ZCT PWM voltage source inverter using auxiliary commutation is shown in Fig.1(a). The circuit operational waveforms for one switching cycle are illustrated in Fig.1(b), when the current of the main switch is reduced to zero prior to its turn-off. However, the turn-on loss of the main switch is not affected by the auxiliary circuit. The auxiliary switch turn-off current (at instant t_3) is the same as the output current I_o, i.e., the same as the main switch turn-off current in the hard-switched converter. Therefore, this scheme is not suitable for high-power applications.

In this paper, new ZCT inverter schemes are proposed and analyzed to further improve the ZCT technique in Fig.1. With modified control and topology, all main switches and auxiliary switches are switched on and off under zero-current conditions, so the switching losses and stresses are reduced significantly.

2- Analysis of the proposed ZCT three-phase inverter:

The drawbacks of ZCT topology 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. This voltage stress can be reduced by the topology shown in Fig.2(a). In this topology, two series-connected auxiliary switches are used for each leg with the low power diodes Dc_1-Dc_6 used to clamp the auxiliary switch voltage.

The operation of ZCT inverter presented here is characterized by soft switching [4] 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.2(b). 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 main switch S_1 turns on the output current I_o is conducted by D_2. The auxiliary current i_x is zero and the resonant capacitor voltage V_x has a value equal to V_{CO}. The nine inverter circuit stages are as follows.

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

At t_0, S_{x1} is turned on initiating the turn-on transition. The auxiliary resonant tank consisting of L_x and C_x starts to resonate and the auxiliary current i_x resonates from zero to positive peak at t_1, while the current in the diode D_2 is reduced to zero. So, S_1 is turned on under ZCT condition at t_1 and the 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, i_x returns to zero. So 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 and the duration of this stage is determined by the PWM control.

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

Before the main Switch S_1 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 then decreases. When i_x returns to zero at t_5, S_{x2} is turned off under ZCT condition. Since the 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. This mode end when the capacitor voltage becomes equals 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 where 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 the determination of the capacitance C_x and inductance L_x. The auxiliary circuit should be designed to achieve zero current switching with maximum main current while keeping the power loss in the auxiliary circuit a minimum [5]. 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 such that most storage charge of the main switch will be recombined. In the following analysis the design is based on maximum output current I_o. From the state plane trajectory [6] of Fig.4 we can get.

$$T_{off} = t_7 - t_6 \qquad \text{-------(1)}$$

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

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

Where: $m = \dfrac{I_o}{I_{PK}}$,

$$T_o = 2\pi\sqrt{LxCx}$$

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].

$$I_{PK} = \frac{Vs/2}{Z_O}$$

Where:

$$Z_O = \sqrt{\frac{Lx}{Cx}}$$

The value of T_{off} used 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 [7]. 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:

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

and ;

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

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

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

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

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

Let $$T_n = \frac{CxVs/2}{I_o} = \frac{Q}{I_o}$$

be the available turn-off time[8], then:

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

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

The per unit turn-off time (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 as 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.

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

$$\theta = \cot\theta \qquad \text{-----(8)}$$

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

$\theta = 0.86\,\text{rad} = 49.3°$

$m = 0.652$

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

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

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

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 three-phase 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 (600Hz) and resonant frequency of (10KHz).

Power MOSFET's (type VN4000A) are used for all main and auxiliary switches. Figs.8-10, show the experimental waveforms. It can be seen that the circuit waveforms comply with theoretical on analysis and simulation. Fig.8 (a, b and c) shows the synchronized control pulses of the main switches and auxiliary switches. Fig.9(a) shows the output three-phase line-to-neutral voltages V_{an},V_{bn} and V_{cn} for resistive load only. Fig.9(b and c) shows the output phase and line voltages respectively for resistive load. Whereas ,Fig.9(d and e) shows those voltages for inductive load. Fig.10 (a) shows the current of the main switch S_1. As it can be seen in this figure, the current is increasing at the beginning of the turn-off stage due to the resonant inductor current and then decreasing at the end of this stage to zero.The resonant capacitor voltage and inductor current waveforms are shown in Fig.10(b and c) respectively. It can be seen that waveforms are similar to those obtained from the theoretical analysis.

Fig.11 shows the measured efficiency of the implemented three-phase inverter for different values of the input voltage. The efficiency has been calculated for the hard switching and soft switching conditions of the inverter. It can be seen that the measured efficiency of ZCT PWM inverter is higher than of the conventional PWM inverter at heavy load.

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 reduced while its efficiency, EMI emissions, reliability, and dynamic performance are improved. Experimental results prove that significant efficiency improvement can be achieved using the ZCT circuit.

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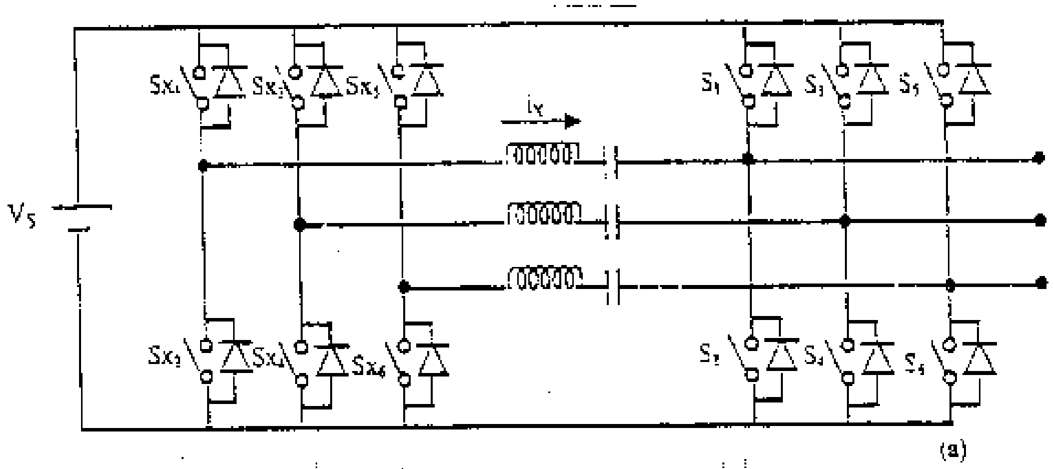


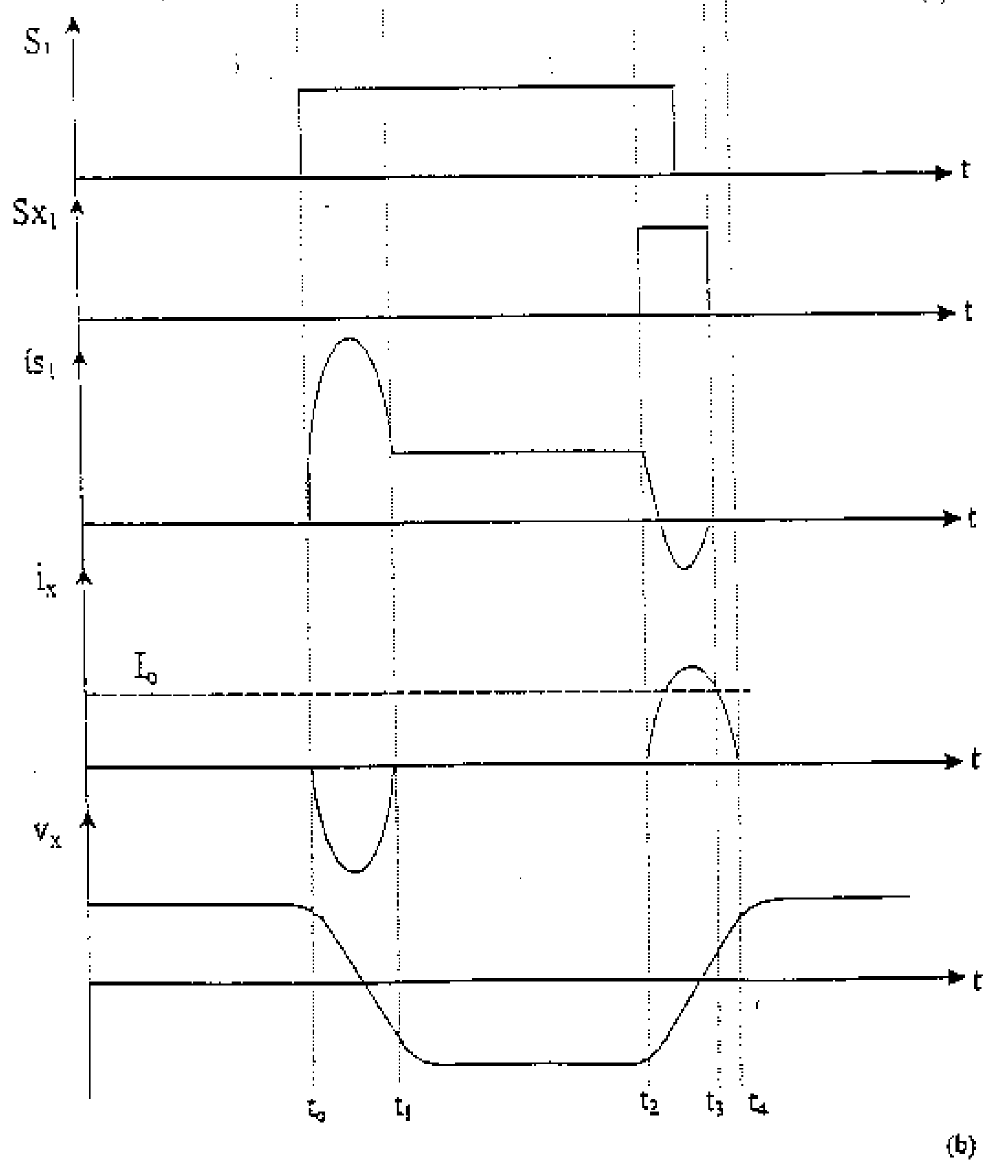
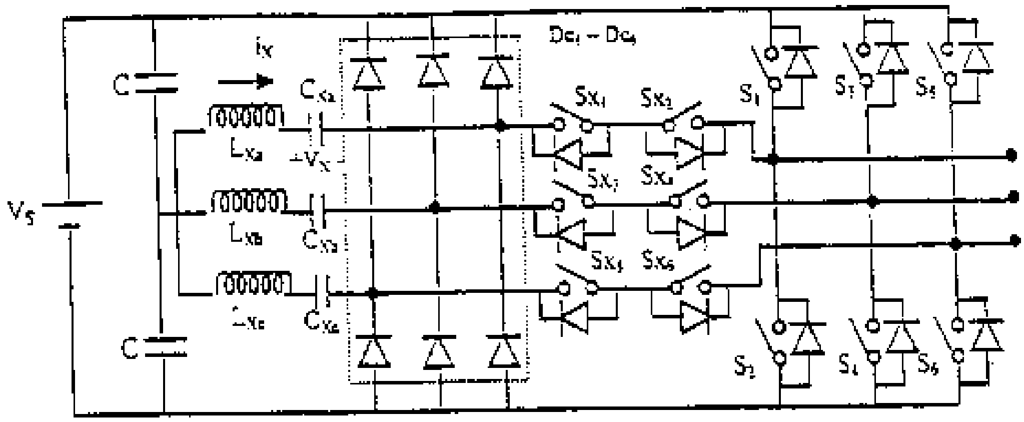


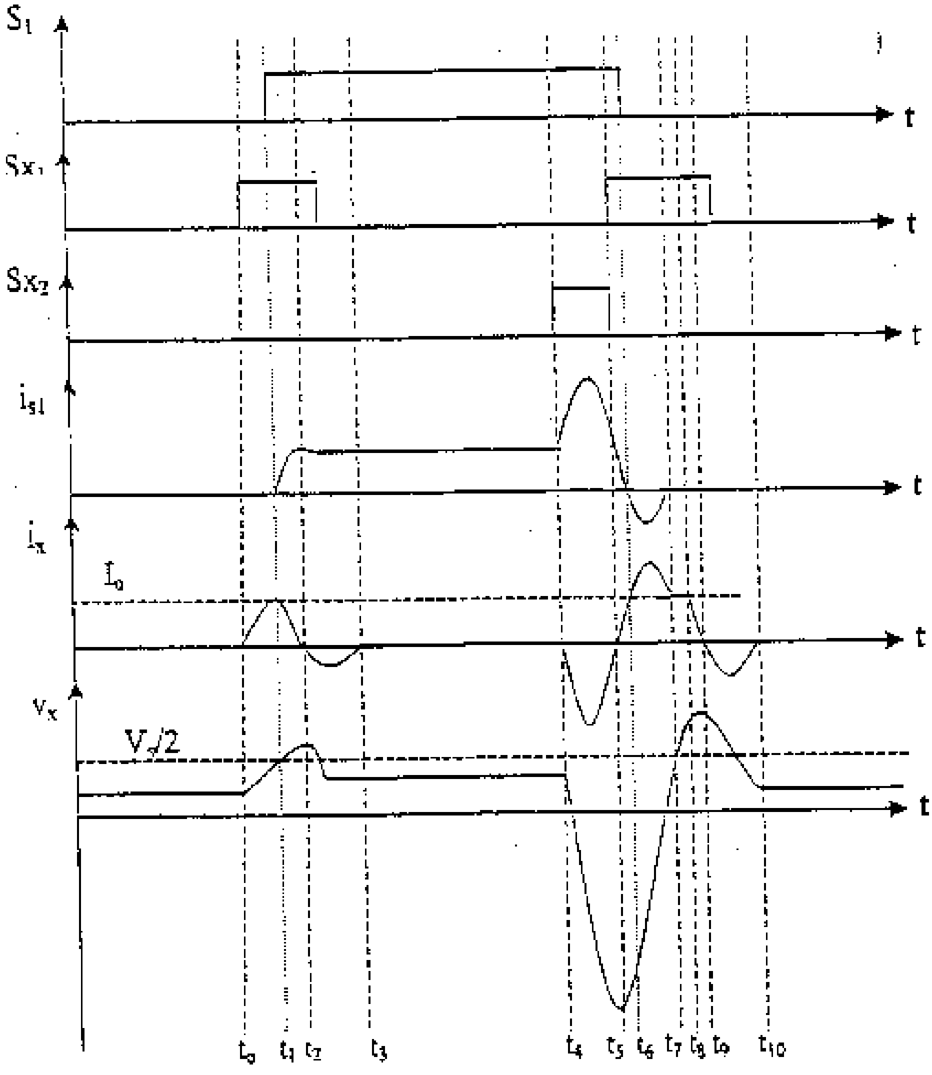
Fig.1 :-Three-phase ZCT PWM inverter.

(a) Topology.

(b) Operational waveforms in one switching cycle of S_1.



(a)



(b)

Fig.2:- New ZCT three – phase inverter.
(a) Topology.
(b) Operational waveforms in one switching cycle of S_1.

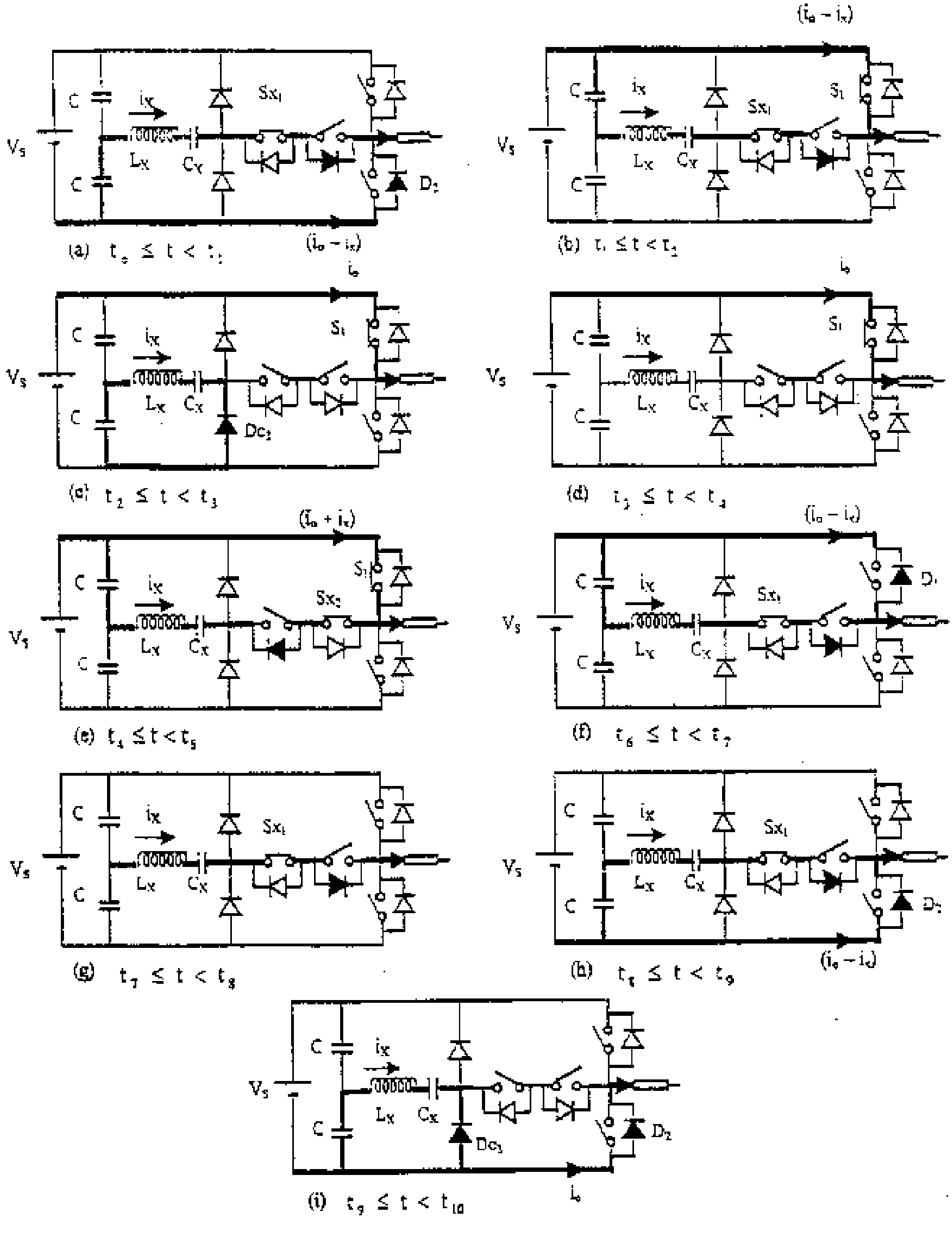


Fig.3 : - Operating stages in the soft – switching commutation.

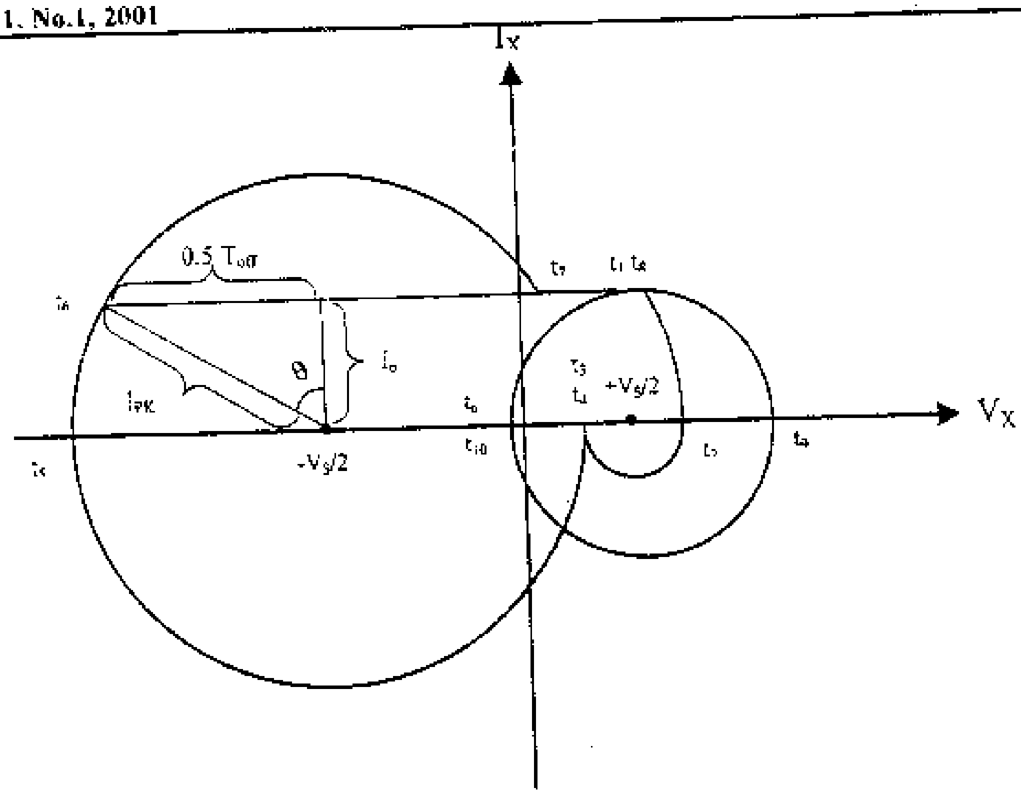


Fig.4 :- State plane trajectory

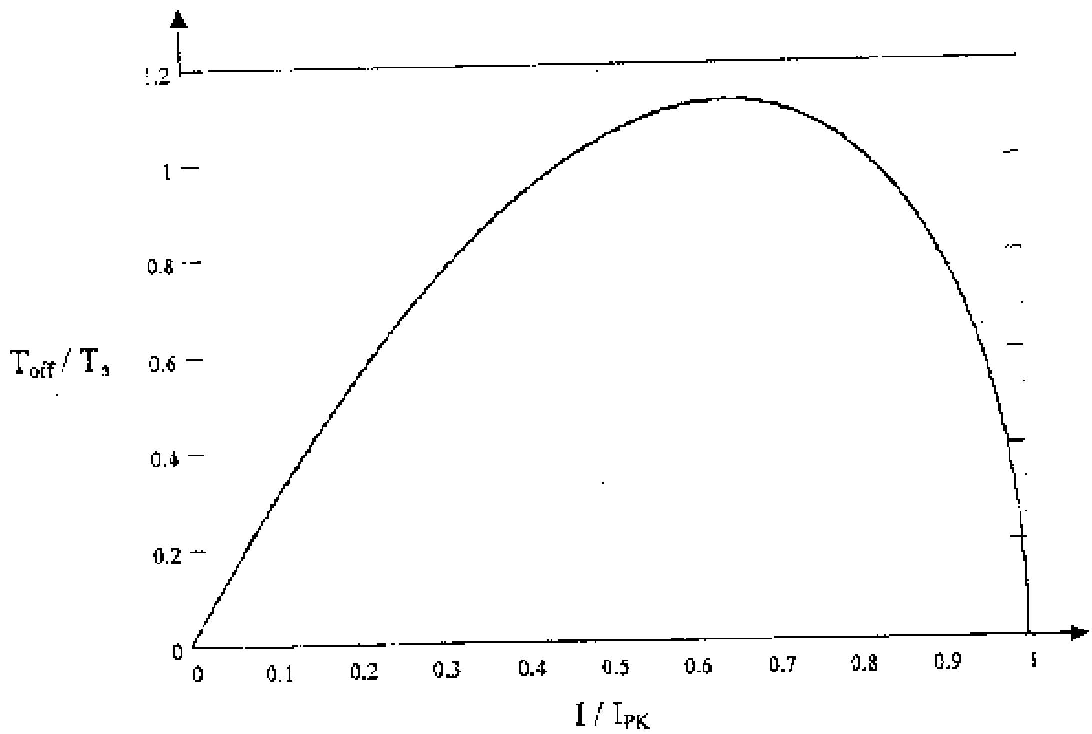


Fig.5 :- Turn off time in basic circuit as a function of current ratio parameter m.

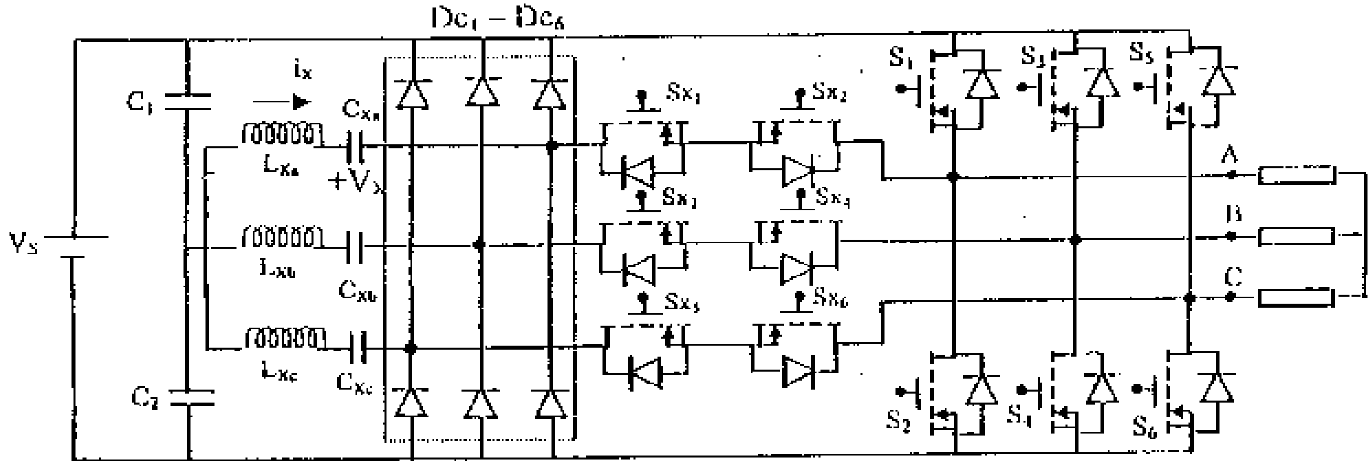


Fig.6 :- Three - phase ZCT inverter.

The implement:

V_S=50V $L_{Xa}= L_{Xb}= L_{Xc}$= 0.1297mH (Ferrite core)

I_0=2A $C_{Xa}= C_{Xb}=C_{Xc}$=1.9526μF (Ceramic capacitance)

$C_1=C_2$=100 μF

all diodes of the type BYX 71

all transistor of the type VN 4000A power MOSFET

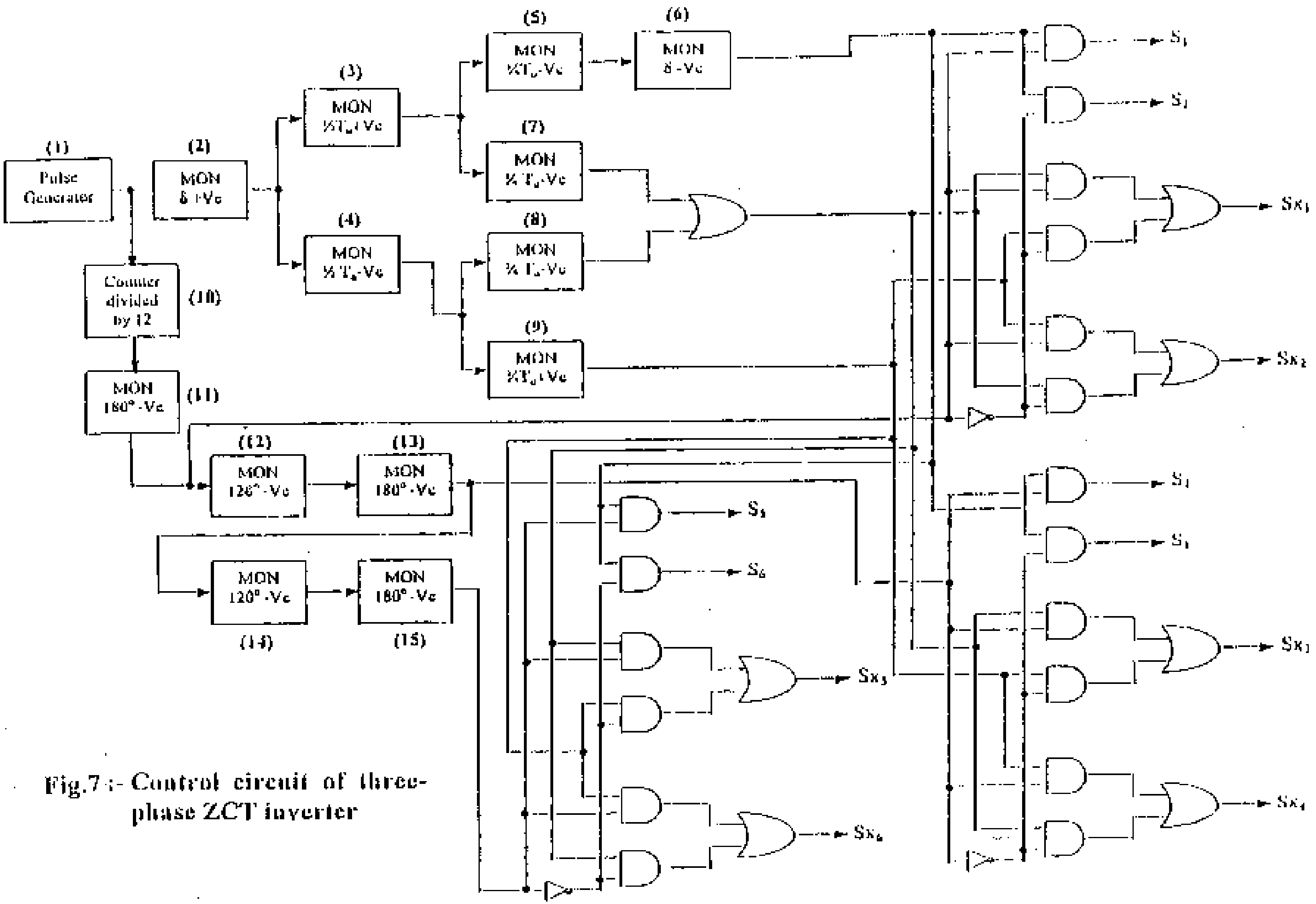
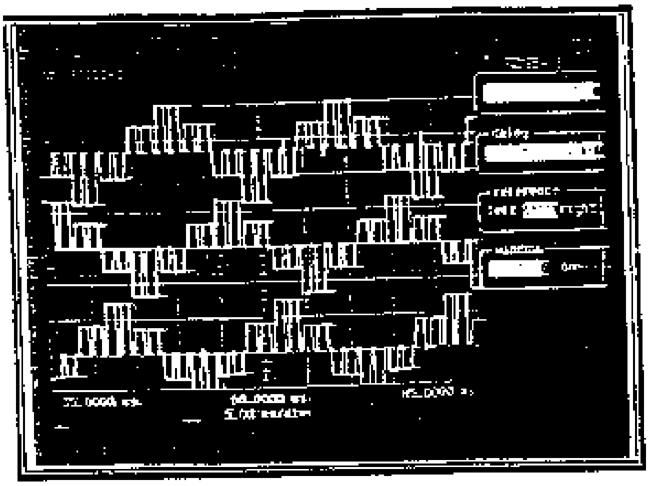


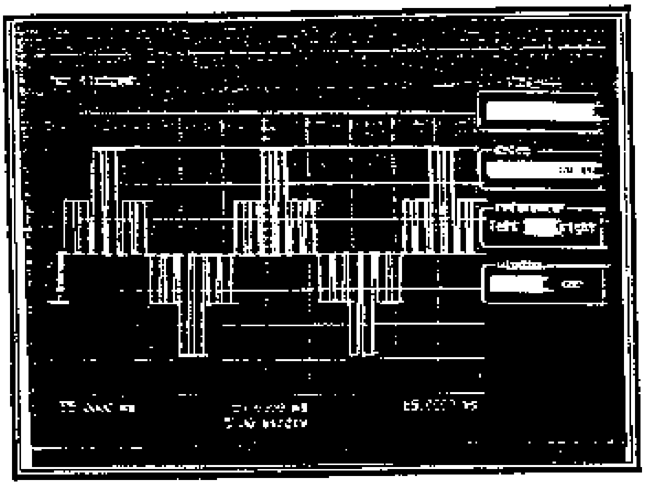
Fig.7 :- Control circuit of three-phase ZCT inverter

Fig.9 :-



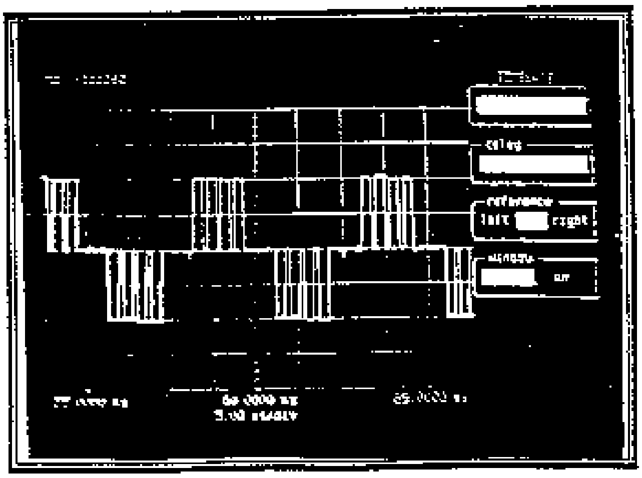
25 V/div
5 msec/div

a- output three-phase line-to-neutral voltages V_{an}, V_{bn}, and V_{cn} at resistive load only.



10 V/div
5 msec/div

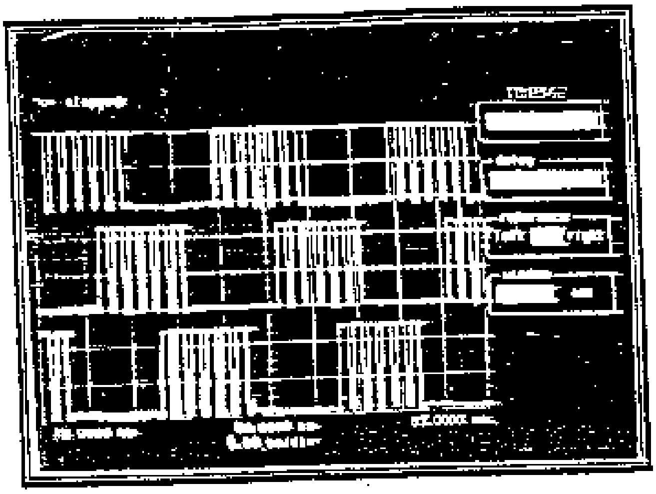
b- output line-to-neutral voltages V_{an} at resistive load only.



25 V/div
5 msec/div

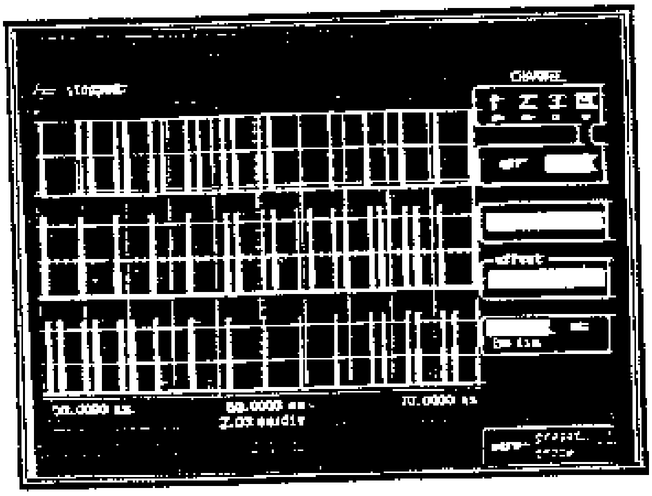
c- output line-to-line voltages V_{ab} at resistive load only.

Fig.8 :-



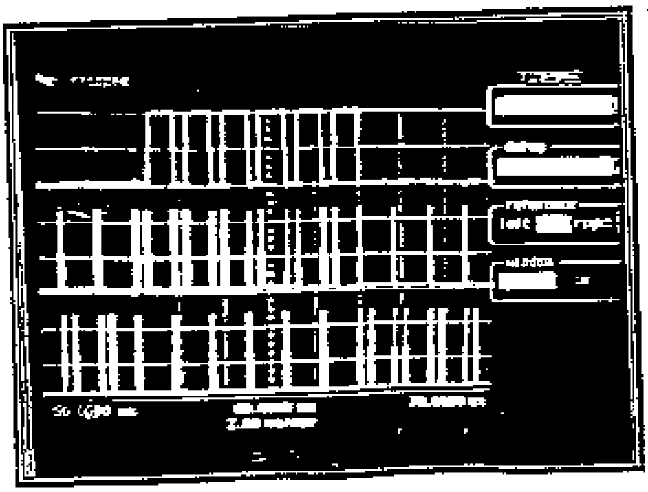
2 V/div
5 msec/div

a- synchronized control pulse for S_1, S_3, and S_5



2 V/div
2msec/div

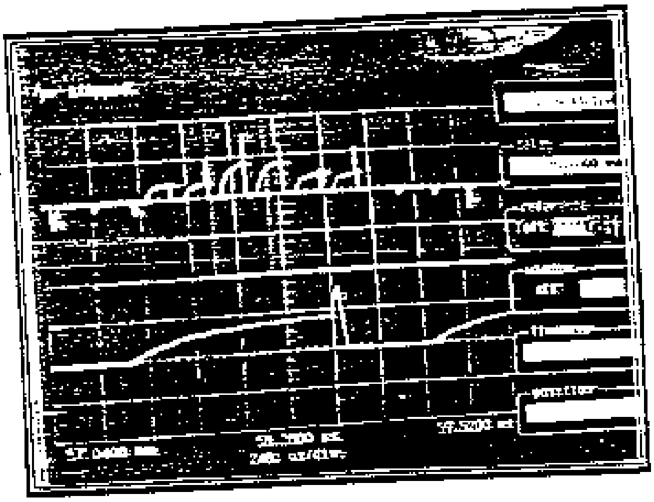
b- synchronized control pulse for S_{x1}, S_{x3}, and S_{x5}



2 V/div
2 msec/div

c- synchronized control pulse for S_1, S_{x1}, and S_{x2}

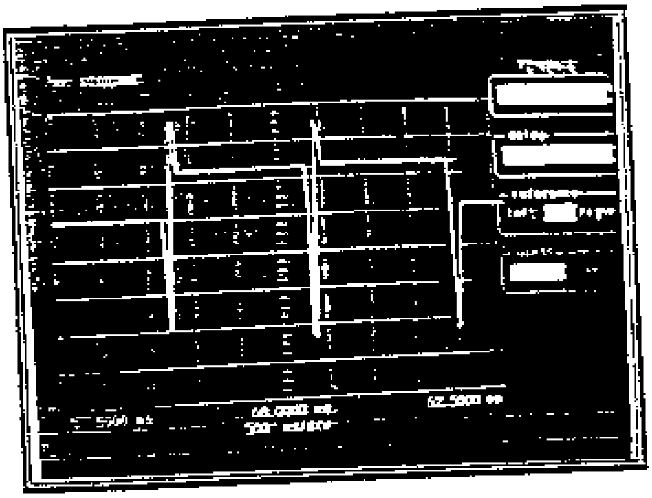
Fig.10 :-



Upper
2 A/div
2 msec/div

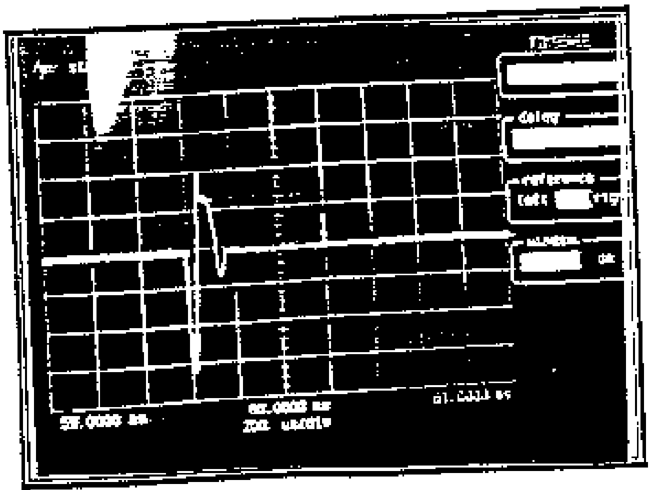
Lower
2 A/div
248 μsec/div

a- i_{s1} current of switch S_1.



20 V/div
500 μsec/div

b- Resonant capacitor voltage V_{cr}.



2 A/div
200 μsec/div

c- Resonant inductor current i_{Lr}.

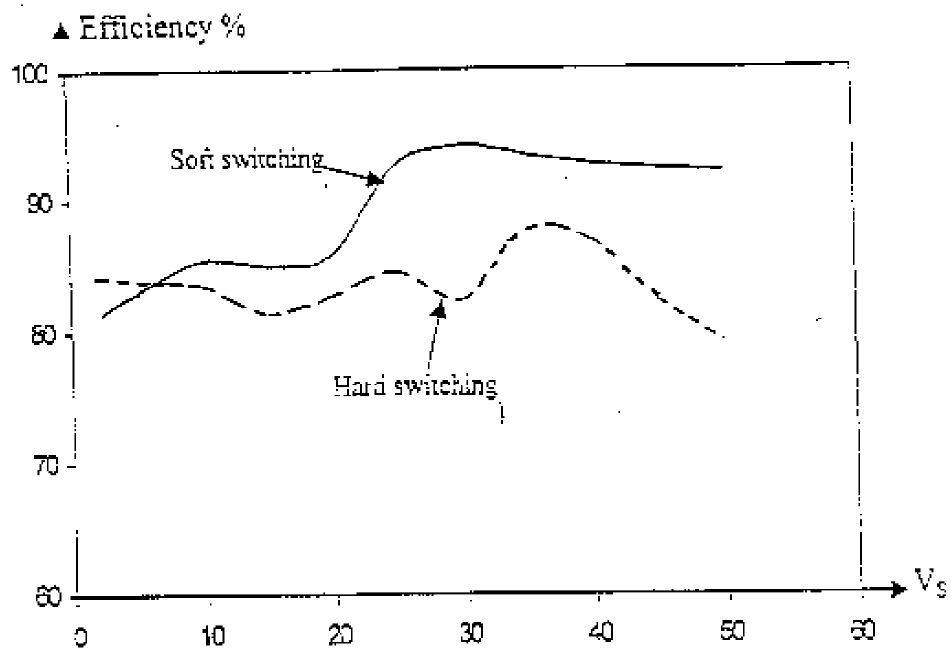


Fig.11 :- The change of the measured efficiency with input voltages at inductive load only for soft switching and hard switching three-phase inverter.