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A New Wide Range Current Source Converter for AC Motor Drive: Part I-Six-step Inverter

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Abstract

A novel six-step current source inverter (CSI) with DC-side commutation and energy rebound capability is presented with detailed explanation of the circuit operation. The proposed inverter can operate in a very wide range of frequency and load variation by employing DC-side commutation. Also, the energy rebound makes the use of low voltage SCR's possible and increases the inverter efficiency. Motor operation is also possible in four quadrants in this proposed current source inverter. The advantages of the proposed CSI over conventional ones are described and experimental results are given in oscillograms.

1. Introduction

The advantages of the current source inverter (CSI) over the voltage inverter are well known. The most widely used CSI is probably the auto-sequential commutated inverter (ASCI) [1]~[3]. Recently, another type of CSI, namely, third harmonic auxiliary commutated inverter(THACI) was published. Their configurations are shown in Fig. 1 (a) and (b), respectively.

In THACI, which has a simpler configuration than ASCI, stable operation is secured in both the motoring and the generating regions by employing the delayed gating method [4]. However, many factors such as the torque loss, harmonic power and spike voltage are depend on the amount of delay and the capacitance value; also, the optimum control of the delay under various operating conditions seems to be not so simple. In addition, the allowable range of load variation and its operating frequency in THACI are about one-third those of ASCI. In a specific or limited range operation, however, THACI may be a good choice for its simplicity in configuration.

The wide difference in the operating range between THACI and ASCI is caused mainly by the difference of the paths of the DC current flowing through the capacitor during commutation; namely, this current passes through the load in ASCI while it bypasses the load in THACI. Therefore, the operating range becomes narrow in THACI due to the capacitor charging time in addition to the delayed gating. This may be the common problem in all circuit configurations where the current through the commutating capacitor bypasses the load.

In contrast, the current through the commutating capacitor in ASCI delivers power to the load, which occurs smoothly even in the consecutive commutation where a new commutation starts at the end of one. A wide range of oper-

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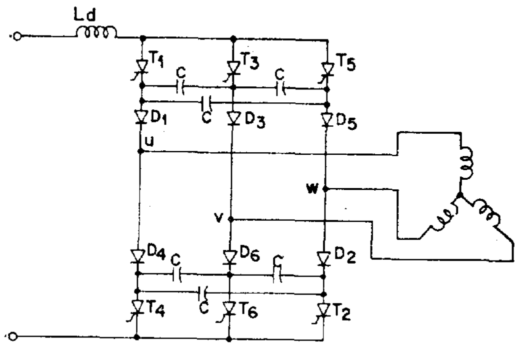
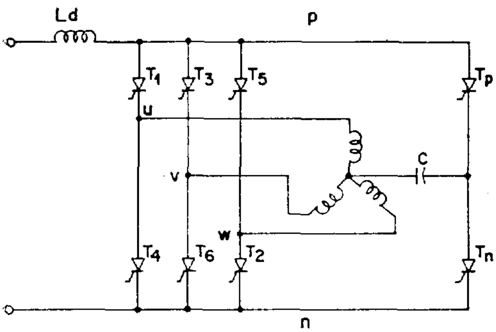


(a)



(b)

Fig. 1. Two typical current source inverters. (a) Autos-equential commutated inverter. (b) Third harmonic auxiliary commutated inverter.

ation is thus possible in ASCI. However, in this case, the operating range as well as the spike voltage are also functions of load and capacitance value since commutation and phase to phase current change occur at the same time while the commutating capacitor(s) are discharged and charged by the DC current. These situations necessiate some compromise, in the choice of the capacitance value, among the various factors involved. Another shortcoming is that it requires a number of commutating capacitors and high power diodes and/or high voltage SCR's.

In the inverter scheme proposed in this paper, the operating range, which is limited in ASCI and THACI for the reason described above, is extended by employing a different commutation scheme, namely the DC-side commutation (DC-SC) method. In the new DC-SC circuit, not only the polarity of the commutation capacitor reverses at high speed for turning off the main SCR's and eliminating the time of capacitor recharging, but also the regenerative capability of the inverter is preserved. Also is employed in the new inverter a novel energy rebounding method, the main purpose of which is to limit the peak voltage, whereby making possible the use of low voltage SCR's.

Combining the DC-SC and the energy rebound circuits in such a way that their espective functions be kept independently, a novel six-step CSI is obtained, which allows both motoring and regenerating operations.

A prototype of the new current source inverter has been designed, constructed and tested; oscillograms of the experimental results are shown.

2. A New Six-step Current Source Inverter

General

It is not a new idea in commutation circuits to reverse a capacitor voltage at high speed and thereby turn off of associated SCR's; actually this method is employed in the McMurrary inverter, chopper and other circuits. However, several considerations must be made to apply this scheme to CSI's without loss of their advantages. Fig. 2 shows the block-diagram of the new six-step CSI, while Fig. 3 shows its complete circuit diagram. The destinctive features of the new inverter are, as can be seen from these figures, employment of the DC-SC, and addition of the peak voltage limit and ERC. The DC-SC method has relative merits and demerits as compared with the branch commutating method [5]~[6]. In the conventional DC-SC inverters simply a free-wheeling diode is connected back-to-back to each main SCR. This simple connection may fail when appled directly to the CSI, since then regenerative capability, one of its advantages, will be lost. However, the free-wheeling diodes can not be eliminated since they play a crucial role in the commutating transient, during which phase-

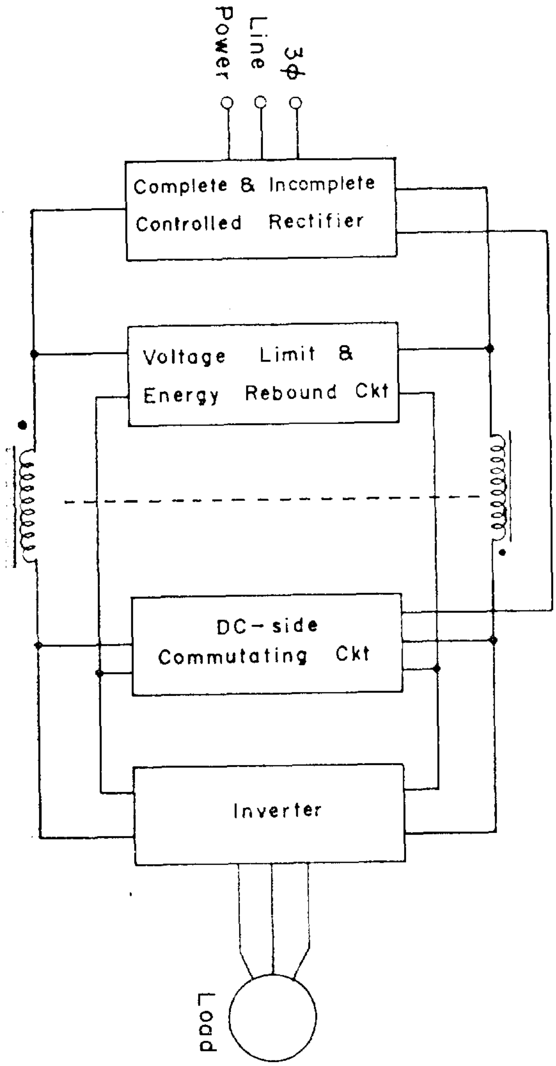


Fig. 2. Block-diagram of the proposed six-step current source inverter.

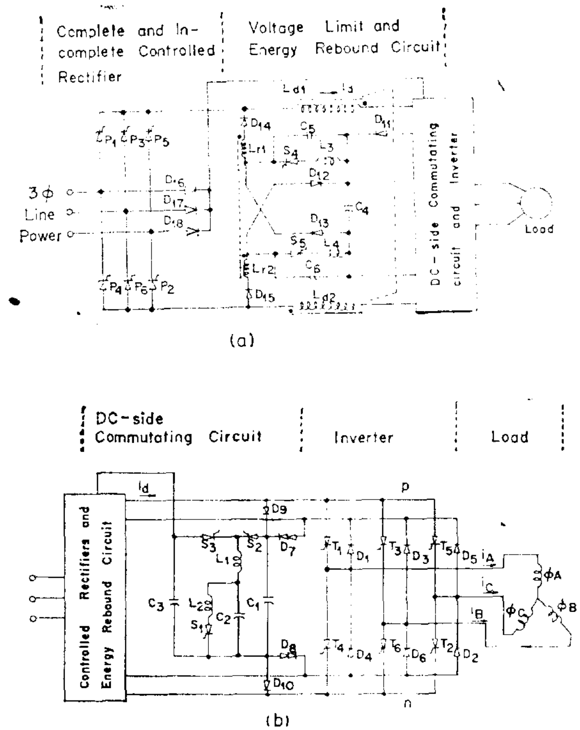
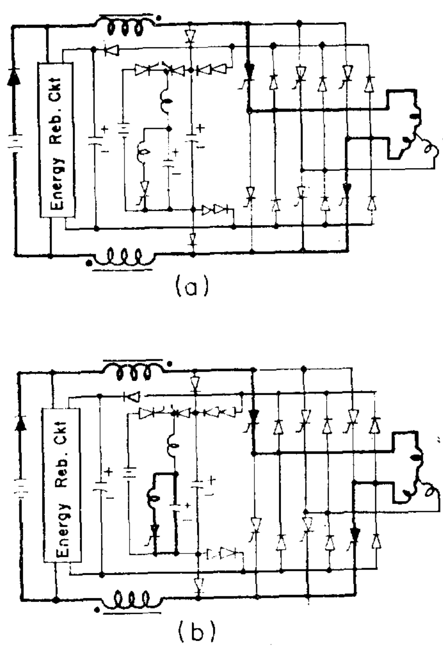
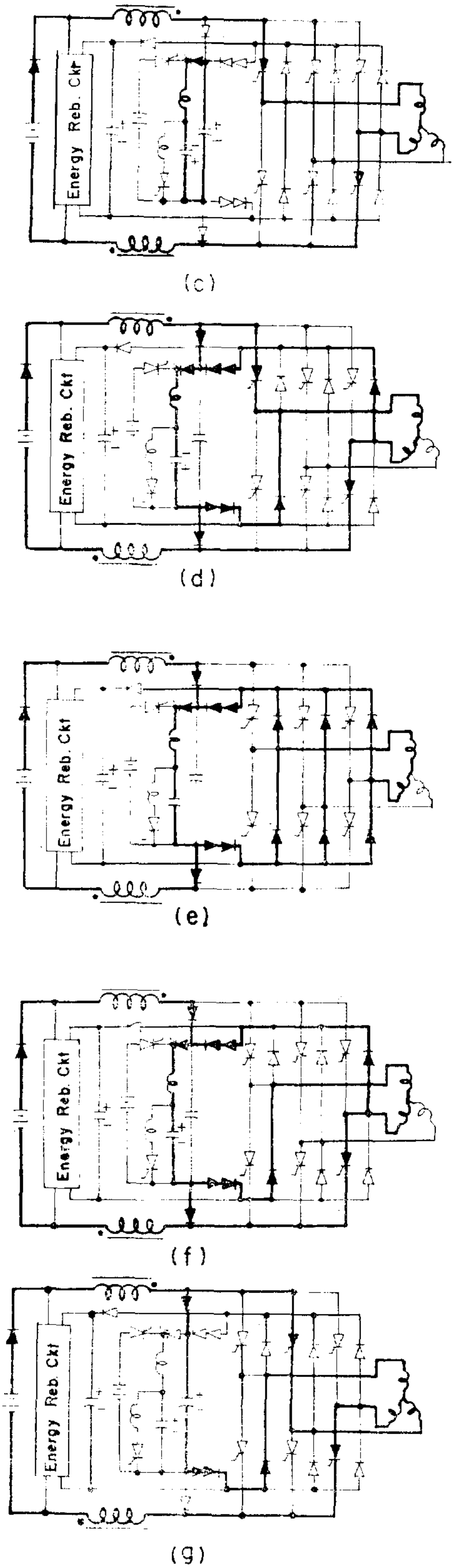


Fig. 3. The new six-step current source inverter circuit.(a) Controlled rectifiers and energy rebound circuit. (b) DC-side commutating circuit and inverter.



to-phase change of the motor current occurs right after the main SCR's are blocked by the operation of the commutating circuit. And, the associated high spike voltage is inevitable. This necessiates some means to limit the spike voltage when the DC-SC method is applied to CSI's. In order to limit the spike voltage and at the same time to increase the inverter efficiency the spike energy must be fed back to the source. This and the connection of free-wheeling diodes have to be done without affecting the regenerative mode operating of the motor. For this purpose a novel ERC has been devised. With this circuit and a



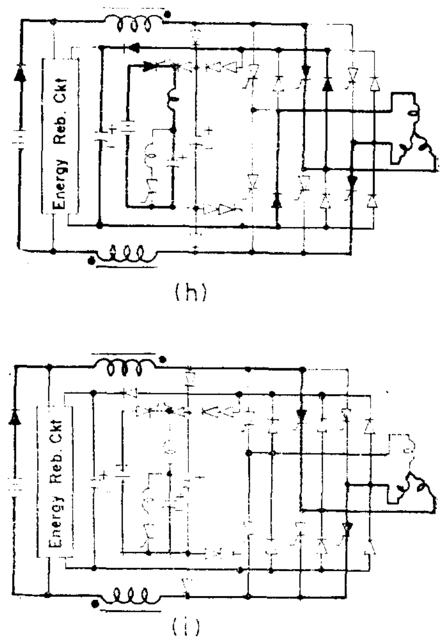


Fig. 4. Sequence of topology modes of the six-step CSI.

simple control, it is possible to increase the inverter efficiency using low voltage SCR's.

Operation

Fig. 4 shows the sequence of topology modes starting with a state where SCR's T_1 and T_2 are conducting. Typical waveforms of voltages across capacitors C_1, C_2, and C_4 as well as currents through C_2, diode D_{11} and phase currents are shown in Fig. 5, in which the various intervals correspond to respective topology modes. (The operation of the ERC, which is included in Fig. 4 as a block, will be described later in connection with Fig. 8).

The initial state with T_1 and T_2 conducting is shown as interval A. Interval B starts with S_1 turned on and the voltage across C_2 reverses ploarity and S_1 turns off before the end of interval B. S_2 is turned on at the start of interval C, which places C_1 and C_2 in series with L_1 and S_2. When voltage across C_1 becomes zero, interval D begins. The new conducting paths from the main and commutating buses are now formed with diodes D_4, D_5, $D_7 \sim D_{10}$ turned on.

The forward drops of diodes D_7 and D_8 determine the cut-off of T_1 and T_2 which is the start of interval E when all diodes D_1 to D_6 conduct through commutating bus and D_7 and D_8. The current flowing through L_1 in interval E consists of the DC current from the main bus and the current, from the commutating bus which conains the load current. Therefore, the commutating circuit must be capable of handling twice the DC current. The voltage accross C_2 becomes positive again by the inductive current through L_1, which, then, decreases with the commutating bus current. As the bus current decreases to the load current, T_2 turns on again and interval F starts. In interval F, the current through the commutating bus continues to decrease. Just after it becomes zero, the current through L_1 and C_2 also becomes zero so that S_2 turns off, when interval G starts. In interval G, T_3 is turned on and C_1 begins charging at a rate of $\frac{dv}{dt}=\frac{Id}{C_1}$ through D_9, D_8, and D_4. This value can be large as long as it does not exceed the dv/dt rating of the main SCR's at full load. Actually, C_1 can be much smaller than C_2 and in some cases interval D or G can be skipped depending on the size of C_1. When the voltage on C_1 equals the voltage on C_4, D_8 and D_9 stop conducting, then D_3 and D_{11} start conducting and charging capacitor C_4, in interval H. Specifically, the phase-to-phase current, which has kept almost constant until the end of interval G, starts changing as it charges capacitor C_4. Thus, the capacitor voltage continues to rise very slowly, if C_4 is sufficiently large, until the phase A current becomes zero and the phase B current reaches I_d. After the end of the transition state, T_3 maintains a constant conduction current as T_2 does; this state continues until the next commutation begins.

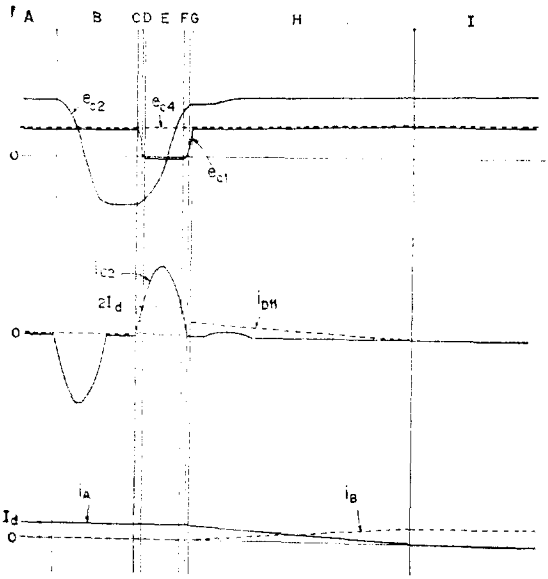


Fig. 5. Voltage andcurrent waveforms for each mode. Intervals A, B, ..., I corresponds to modes (a), (b), ..., (i) in Fig. 4.

For convenience S_3 is turned on during interval H to supply any energy loss(from the DC source consisting of D_{16}, D_{17}, D_{18}, and C_3) to capacitor C_2 in order to insure stable and continuous operation. The control sequence for the above cycle is S_1 turned on(interval B); S_2 turned on(interval C); T_2 turned on again (interval F); T_3 turned on (interval G); S_3 turned on in any interval G to I.

Fig. 6 and Fig. 7 show, respectively, the sketches and oscillograms of the voltage and current waveforms during the complete cycle of operation for the six-step inverter. As is seen from Fig. 7, the voltage spikes are limited but still relatively high because the experiment was done at low voltage. This fact will further be examined later in connection with the ERC operation.

Distinctive Features of the DC-SC Circuit

The DC-SC circuit as described in the above has several advantages over the conventional ones. First, a wide range of operating frequency is possible due to the fact that the commutating interval is determined mainly by the SCR turn-off time and is almost independent of the load current, since the voltage on C_2 reverses at high speed and a small capacitance suffices for C_1.

Second, a very wide range of load variation is allowed. This can be explained as follows. The voltage on C_2 which is necessary for commutation is determined by the voltage on C_3 due to the

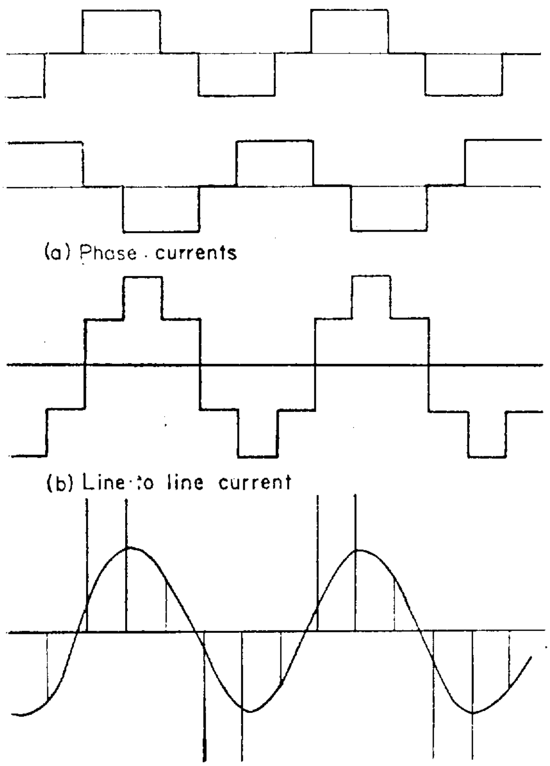


Fig. 6. Current and voltage waveform sketches for the new six-step inverter.

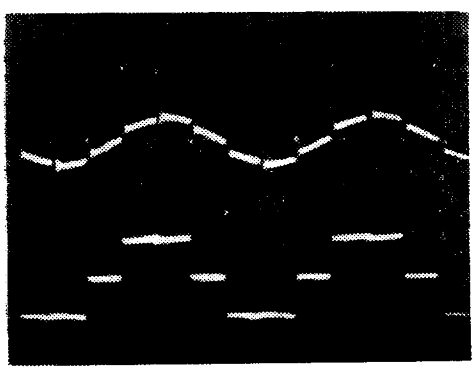


Fig. 7. Oscillograms of the line-to-line voltage (top) and phase current(bottom). Vertical: 50V/div. (bottom). Horizontal: 10msec/div.

role of S_3. Now, the voltage on C_3 is maintained almost always at a maximum level, with a slight variation depending on the converter output voltage, since it is supplied by the incomplete bridge rectifier consisting of diodes $D_{16} \sim D_{18}$ and SCR's P_2, P_4, and P_6. Thus, for simplicity C_3 is replaced by a *DC* source in Fig. 4. As a result, stable operation is secured even at low voltage and high current such as in the motor starting. Even in the extreme load conditions, open or shorted load, the commutating circuit operates independently, and temporary failure such as caused by noise turn on of the main SCR's can be immediately recovered.

The third distinctive feature of the proposed DC-SC circuit is that it does not affect the regenerative operation of the inverter. Specifically, the commutating circuit is isolated from the rest part of the system when the motor operates as a generator, since then the voltage polarity of the p side in Fig. 3 becomes minus while that of the n side becomes plus and hence diodes D_9 and D_{10} are turned off. In other words, by the presence of D_9 and D_{10} both motoring and generating operations are possible; at commutating operation they are conducted to turn off the main SCR's and at regererative operation they are blocked to isolate the commutating circuit from the rest part of the system.

3. Voltage Limit and Energy Rebound Circuit

Operation

In the proposed system, the phase currents do not change appreciably until interval *G;* they change only after the turn-off of the main SCR's. A desirable situation in this case is that the line to line voltage reaches a high value in as short a time as possible and at the same time the peak voltage be limited to an appropriate value in relation to the input voltage, in order to make a rapid and safe phase-to-phase current change. The purpose of the ERC is to store temporarily and then feed back to the source, the excess energy resulting from the peak voltage limiting action at each commutation. This feedback loop is initiated by an excess voltage level, therefore the circuit provides voltage limiting as well as energy feedback.

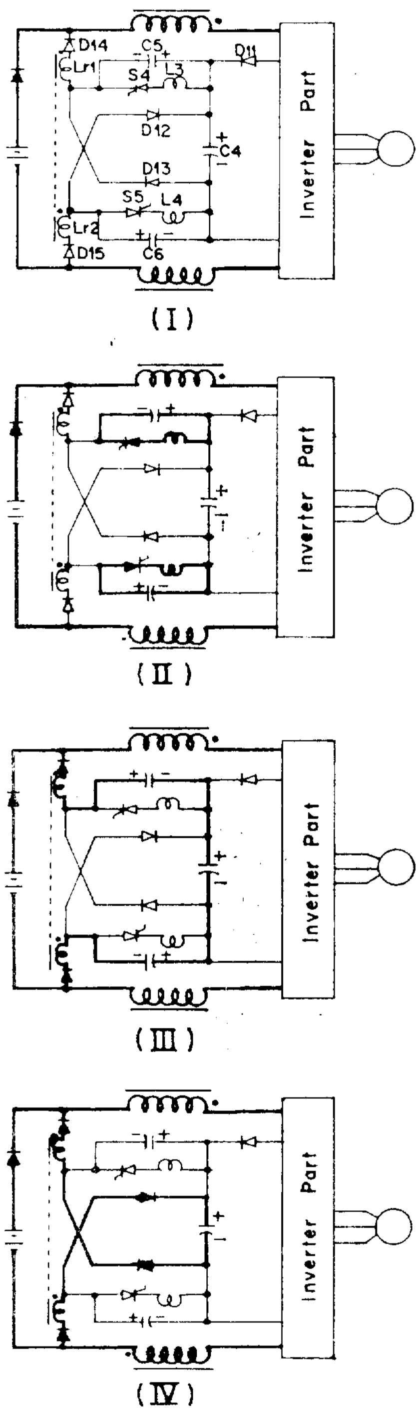


Fig. 8. Sequence of topology modes of the energy rebound circuit. Each Figure corresponds to a distintive interval of operation.

Fig. 8 shows the sequence of topology modes of operations for ERC. A large capacitor C_4 is used for temporary storage of the excess energy, which is connected to the commutating system through D_{11}. The behavior of C_4 is described previously in connection with interval H of Fig. 4. In the following we will examine the operation of the ERC in more detail referring to the topology modes.

In interval I, the capacitors are charged with the polarities shown. When the voltage on C_4 becomes sufficiently high, S_4 and S_5 are turned on simultaneously, which reverves the voltages on C_5 and C_6 very rapidly through L_3 and L_4, respectively (interval II). As the sum of the voltages on C_4, C_5 and C_6 exceeds the source voltage, interval III begins conducting through D_{14} and D_{15}, feeding back the excess energy to the source while discharging C_4. Turn-off time of S_4 and S_5 is made sufficiently long by using an inductance L_r $(=L_{r1}+L_{r2})$ much larger than L_3 $(=L_4)$. When C_5 and C_6 are charged in the same direction as in interval I and each of their voltages reaches that of C_4, the magnetic energy stored in inductor L_r, which has not been discharged fully, recharges C_4 through D_{12} and D_{13}; in this way rebounding continues (interval IV). After all the stored energy in L_r has been discharged, the cycle is in state of interval I and the process repeats. Again in interval I, D_{14} and D_{15} are blocked, preventing the discharge of C_5 and C_6 for continuation of stable operation of the next cycle. Faster energy rebounding can be carried out, if necessary, by turning on S_4 and S_5 before the current through L_r becomes zero in interval IV, in which case, however, turned-off of the SCR's must be taken into consideration.

Energy rebounding occurs discretely and the voltage drop of C_4 per pumping depends on its voltage and the size of C_5 and C_6. A possible control reference voltage V_{ref} to limit the spikes is shown in Fig. 9, where V_{ref} changes linearly from V_1 to V_2 ($V_1 < V_m < V_2$; V_m=maximum source voltage) in the full range of the source voltage V_s. For a given Source voltage V_{s1}, if the instan-

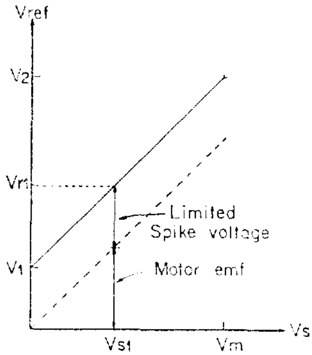


Fig. 9. One scheme of the capacitor (C_4) voltage reference with respect to the source voltage for limiting the voltage spikes effectively.

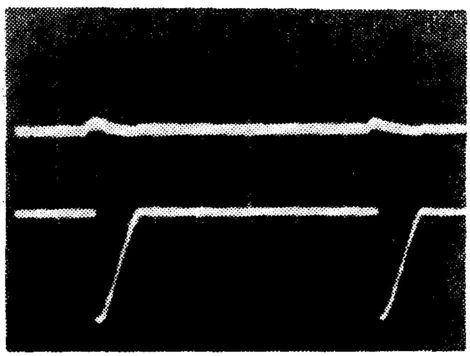


Fig. 10. Oscillograms of the voltage on C_4 (top) and C_6 (bottom). Vertical: 20V/div. (top), 50V/div.(bottom). Horizontal: 0.5msec/div.

taneous voltage on C_4 exceeds V_{r1}, S_5 and S_6 are fired; otherwise, not. V_1, the reference voltage for $V_s=0$, should be high enough, say above 50 volt, in order to get sharp rise and fall in the load current waveform during the commutation transient at low source voltage. This results in a relative amplitude of the spike voltages being high at low source voltage. In this simple control there is no need of taking into consideration the motor operating condition. Fig. 10 shows the oscillogram of the experimental ERC. We see that the start of energy rebounging and rapid inversion of the voltage on C_6 (and C_5) occur simultaneously as soon as the voltage on C_4 exceeds a reference voltage due to the entering of the load current at each commutation instant. We also aware that the voltage on C_4 discharges through the source without accompanying any current spikes.

Distinctive Features

As mentioned earlier, the ERC is essential in the proposed system in order to obtain a wide range of operation by having commutation and phase-to-phase change of the load current occur in different intervals. The addition of the ERC, however, does not increase the overall system cost; it may actually reduce the cost. First, the main SCR's, which are perhaps the most expensive components of the system, can have low voltage ratings since the peak voltages across them are always limited to a predetermined level irrespective of the load condition, full load or noload. Second, the ERC can be built with low-power components since the power to be handled in this circuit is estimated to be less than 10% of the total input power of the system. Specifically, a sm all size inductor suffices for L_r since the current flowing through it is small; also S_4, S_5 andall diodes in this circuit may have very small ratings compared with the main SCR's. C_4 is the only exception; it should have a relatively large capacitance. However, an electrolytic capacitor, which is relatively of small size and low cost, can be used for C_4 since large pulse currents do not flow through it and also it is charged always in the same polarity. Finally, gating control of the SCR's in the energy rebound circuit is achieved in a simple manner as stated earlier. All this accounts for the overall economy of the proposed system.

The regenerative mode of operation is made possible by merely interrupting the firing of S_4 and S_5, in which case C_5 and C_6 play an excellent role as the snubbers with a stable blocking condition of SCR's being secured. The mode change between motoring ard regenerating operations occurs very rapidly and smoothly.

4. Conclusion

A novel six-step current source inverter with DC-side commutation and energy rebound features is designed, constructed and tested in the laboratory with expected results obtained. The proposed inverter has improved reliability and capability of very wide range operation in terms of load variation and operating frequency, and it can be implemented with low voltage SCR's and hence at a lower overall system cost. And also the inverter is capable of regenerative operation.

On the other hand, there are some minor disadvantages of the new CSI. Due to the presence of DC-side commutation and energy rebound circuits, firing control is rather complicate compared with ASCI, but comparable to other inverters. Some redundent commutating loss occurs in the proposed inverter at light load since the commutating circuit is designed considering the full load condition.

In conclusion, due to its many advantages described above, the new current source inverter may be an excellent candidate for many AC adjustable speed drives. detailed quantitive analyses and extensive experimental results will be published elsewhere in the near future.

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