Module 3

DC to DC Converters

Lesson 20

Commutation of Thyristor-Based Circuits Part-II

This lesson provides the reader the following:

(i) Practical significance of commutation
(ii) Limitations of line commutation
(iii) Ability to determine commutation interval
(iv) Insight to different methods of commutation
(v) Consequences of the commutating methods on device stresses

20.1 Introduction

The commutation process plays an important role in the operation and control of both naturally commutated (or line commutated) and forced commutated SCR based converters. These converters may be either AC-DC, DC-DC or DC-AC converters. The AC-DC Phase

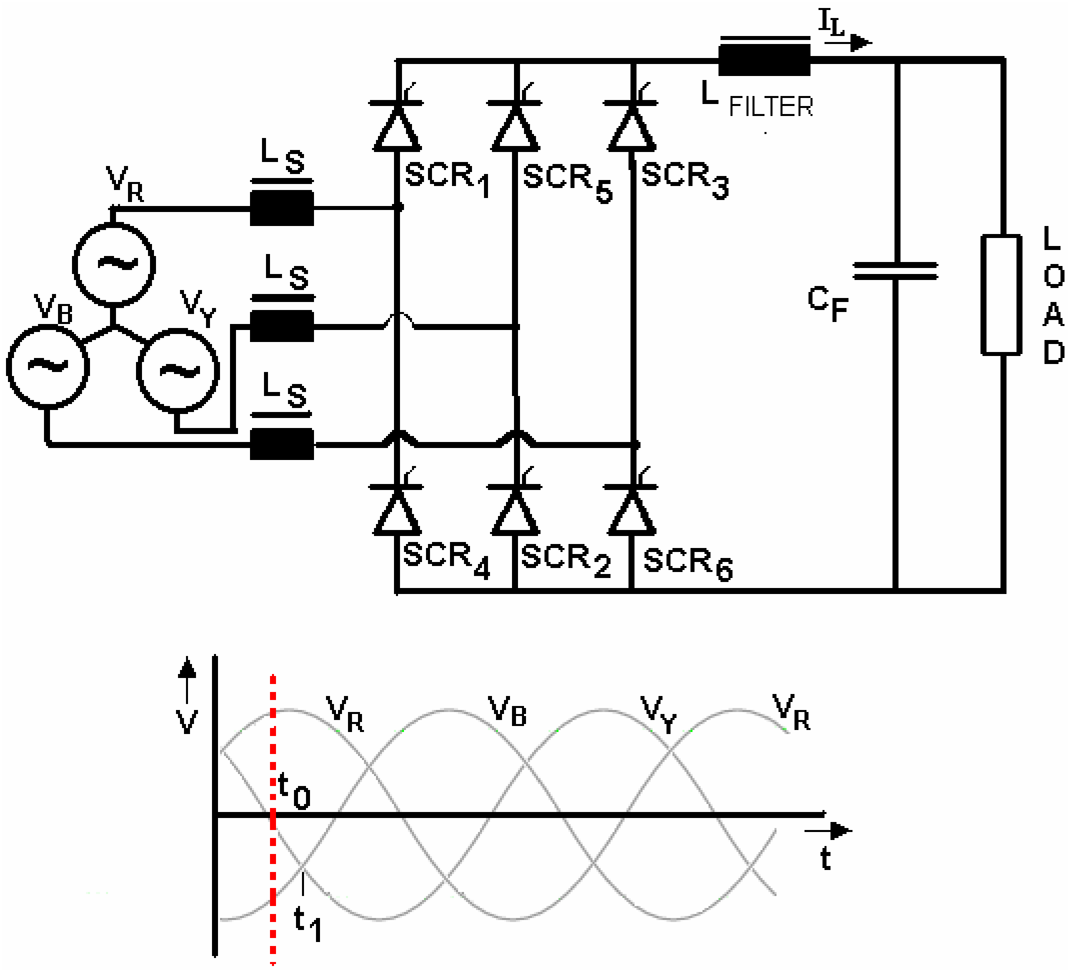

Fig. 20.1 Top: A three-phase Phase Angle Converter; bottom: The input three-phase voltage waveforms

Angle Converter, (PAC) continues to be used in much high power and very high power converters where the application is non-critical or the non-state-of-the-art is preferred for operational advantages. The following section discusses commutation with respect to this application.

20.2 Commutation in PAC

A three phase PAC is shown in Fig. 20.1. Nominally balanced three phase voltages V_R, V_Y and V_B are connected to the three legs of the converter via three inductances LS, which can be considered to represent the leakage reactance of the supply transformer. At any instant, two devices are conducting, say SCR_1 and SCR_6 at the time instant indicated by the dashed line in Fig, 20.1, bottom. At that instant, phase voltage V_R is most positive and V_B most negative.

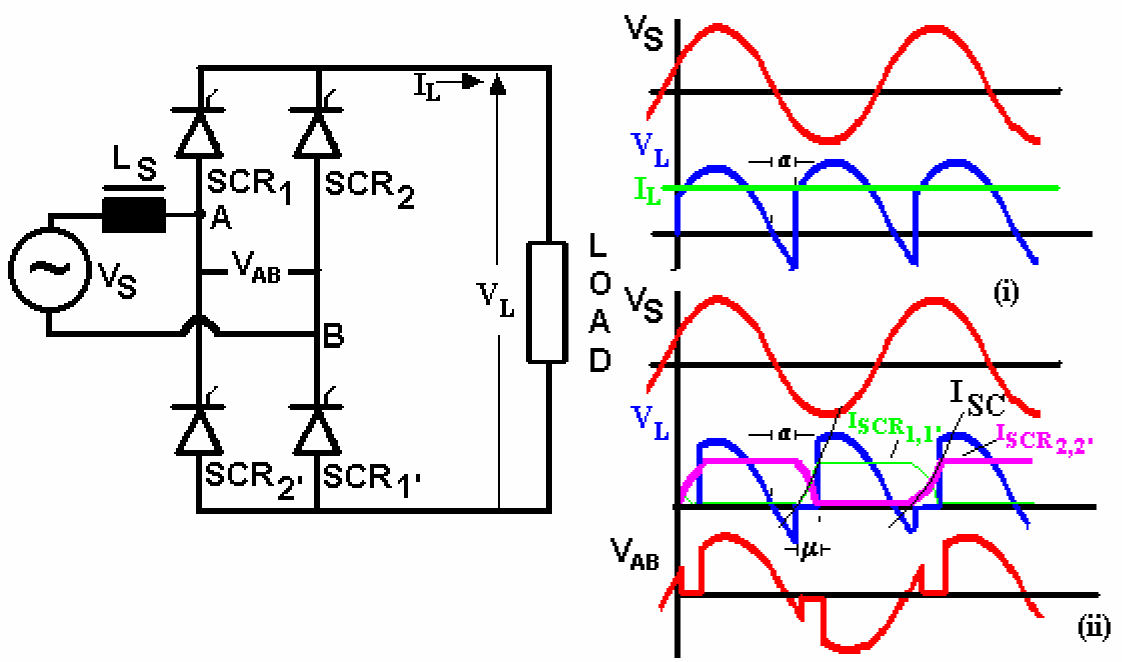

Fig. 20.2 Significant voltage and current waveforms of a single phase converter highlighting the overlap instants and the corresponding converter terminal and output voltages

Subsequently, at the crossover point, V_Y becomes most negative and SCR_2 is more forward biased with respect to SCR_6. The incoming SCR does not take the full load current I_L, nor does the outgoing SCR turn-off immediately. There ensues an 'overlap' period when three SCRs conduct for a transient period. It is evident that with the simultaneous conduction of SCR_2 and SCR_6 there is a short circuit at the converter terminals with the short circuit current I_{SC} being limited by the per-phase series inductances L_S. Line voltage V_{YB} drives this current. With no delay in triggering (as if the SCRs are all replaced by diodes) the SCRs, they would be triggered 60^0 after the zero crossing of the corresponding line voltage. The triggering on this line voltage is delayed by the trigger angle α from this 60^0 point.

There are a few significant effects of the commutation process when three devices conduct. The voltage waveforms at the output and at the converter input terminals reflect the commutation process. All-SCR (fully-controlled) converters, which are capable of operating with trigger angles α between 0^0 to 180^0 ideally, are restricted in the inverter mode to operate within the 'margin-angle'. This angle is of the order of 160^0 and the output voltage is limited.

20.3 Input voltage waveform distortion

A single-phase converter, Fig 20.2 is considered to illustrate this. A four-SCR fully-controlled converter operates into a load, which draws a constant current. The AC source includes the series (leakage) inductance L_S. Waveforms are shown for (i) no overlap case (when $L_S = 0$) and (ii) for a finite value of L_S causing an overlap. It is evident from waveforms of $I_{SCR\ 1,1'}$, $I_{SCR\ 2,2'}$ that they take a finite time to rise and fall. In the intervening period all four SCRs are ON. The current in the incoming device rises till it equals the load current I_L while that in the out going one falls to zero. All conducting SCRs can be considered to be short circuits and consequently the output voltage and thus also the input voltage is zero during this period. The output voltage is diminished and a 'notch' appears across the input. The input distortion affects other equipment connected to the same bus and protection must be provided against this cross-talk between two converters through this type of line distortion. The input voltage exhibits two notches in a single-phase converter both of which are identical and reach down to zero.

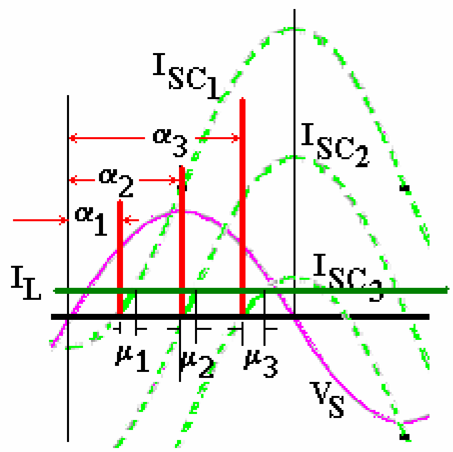

Fig. 20.3 Short circuit currents between incoming and out going SCRs for various trigger angles

Example 20.1

A single-phase converter, Fig. 20.2 operates with an input inductance $L_S = 0.04$ mH. Indicate the current waveforms of the outgoing and incoming phase for trigger angles $\alpha = 45^0$, 90^0, 160^0.Calculate the overlap times for each case and sketch the current waveform in the incoming SCR pair. The input voltage is 230 V, 50 Hz and the level load current is 15 Amps.

Solution 20.1

The commutating voltage for a single phase converter is the supply voltage itself, 230 V. When the incoming SCRs (say 2 and 2') are triggered, the SCR pairs 1, 1' and 2, 2' are all conducting. A short circuit of the supply voltage takes place via the SCRs. A short-circuiting current, I_{SC} flows through the SCRs, in the forward mode in 2, 2' and reverse mode, opposing the load current, I_L in 1, 1'. Current, I_{SC} is initially zero and rises ultimately to load current level when SCRs 1, 1' turn off and the overlap time is complete.

For all trigger angles, current, I_{SC} can be separated into two components – the *steady state* part and the *transient* part. The steady state component is for all cases the current that occurs when the voltage is applied to a pure inductance (L_S).

$$V_S = 230\angle 0^0 \quad Volts$$
$$For\,\alpha = 45^0, 90^0 \; and \; 160^0$$
$$Steady-state \quad component \quad of\, short \quad circuiting \quad current \quad is$$
$$I_{SS} = 230\angle 0^0 / 2.\pi 50.0.01 = 73.21\angle -90^0 \quad Amps$$
$$The \quad transient \quad current \quad is \quad a \quad level \quad current$$
$$= - \quad (the \quad magnitude \quad of \quad I_{SS} \quad at \quad the \quad instant \quad of \quad triggering)$$
(A current flowing in a short-circuited pure inductor does not decay – it is level)

$$For\,\alpha = 45^0,$$
$$Transient \quad component = 73.21\sin(90^0 - 45^0) = 51.77\,Amps$$
$$For\,\alpha = 90^0,$$
$$Transient \quad component = 73.21\sin(90^0 - 90^0) = 0.00\,Amps$$
$$For\,\alpha = 160^0,$$
$$Transient \quad component = 73.21\sin(90^0 - 160^0) = -68.80\,Amps$$

In each case the transient current adds up with the steady-state component to give the net current. Since the *transients* are all level currents, the steady state component can be considered to just being shifted up or down by an amount equal to the transient component. Thus for $\alpha = 45^0$, the shift is by +51.77, there is no transient for $\alpha = 90^0$, and for $\alpha = 160^0$ the shift is by –68.80. Note the shape of the relevant portions of the current waveform lying between 0 to I_L in each case. The expressions for each delay angle α is:

$$I_{SC_1} = 73.21\sin(2.\pi.50 - 90) + 51.77$$
$$I_{SC_2} = 73.21\sin(2.\pi.50 - 90)$$
$$I_{SC_3} = 73.21\sin(2.\pi.50 - 90) - 68.80$$

The overlap angle is the period over which the current in each case builds up from zero to the load current I_L level. So equating each current expression to 15 Amps,

$$\mu_1 = -\cos^{-1}(-36.77/73.21) + \cos^{-1}(-51.77/73.21)$$
$$= 14.85^0$$
$$\mu_2 = -\cos^{-1}(15/73.21) + 90^0$$
$$= 11.82^0$$
$$\mu_3 = -\cos^{-1}(-83.80/73.21) + \cos^{-1}(68.80/73.21)$$
$$so \quad commutation \quad is \quad not \quad possible\, for \quad \alpha \quad = \quad 160^0$$

It may be noted that the overlap time decreases and comes to a minimum when the trigger angle reaches 90^0, but again increases when the delay angle goes beyond 90^0. Two other overlap angles are also of interest. First the overlap angle for $\alpha = 0^0$ and when the delay angle just permits the overlap to be over before the commutating voltage reaches 180^0. The peak of I_{SC} occurs at this instant. This angle plus the time period required by the SCRs to complete their turn-off process (refer: turn-off dynamics of SCR) is called the *Margin Angle*. Assuming zero turn-off time,

$$\mu_{margin-angle} = -\cos^{-1}(-58.21/73.21) + 180^0$$
$$= 37.33^0$$

$$I_{SC_{0^0}} = 73.21\sin(2.\pi.50 - 90) + 73.21$$
$$\mu_{0^0} = \cos^{-1}(58.21/73.21) + \cos^{-1}(-73.21/73.21)$$
$$= 37.33^0$$

The two angles are numerically equal as is evident from Fig. Example 20.1.

20.4 Three-phase converters

In a three phase six-pulse converter, the notches in the line voltage waveform are as shown in Fig 20.4. The triggering angle is $\alpha = 0^0$ for the case illustrated. There are six notches per cycle. While two of the notches reach down to zero volts, the four other have different magnitudes.

The three-phase converter, Fig. 20.1, has three inductances L_S, each in series with each of the three phases. They are the leakage inductances of the transformer, which may supply other equipment of the plant too.

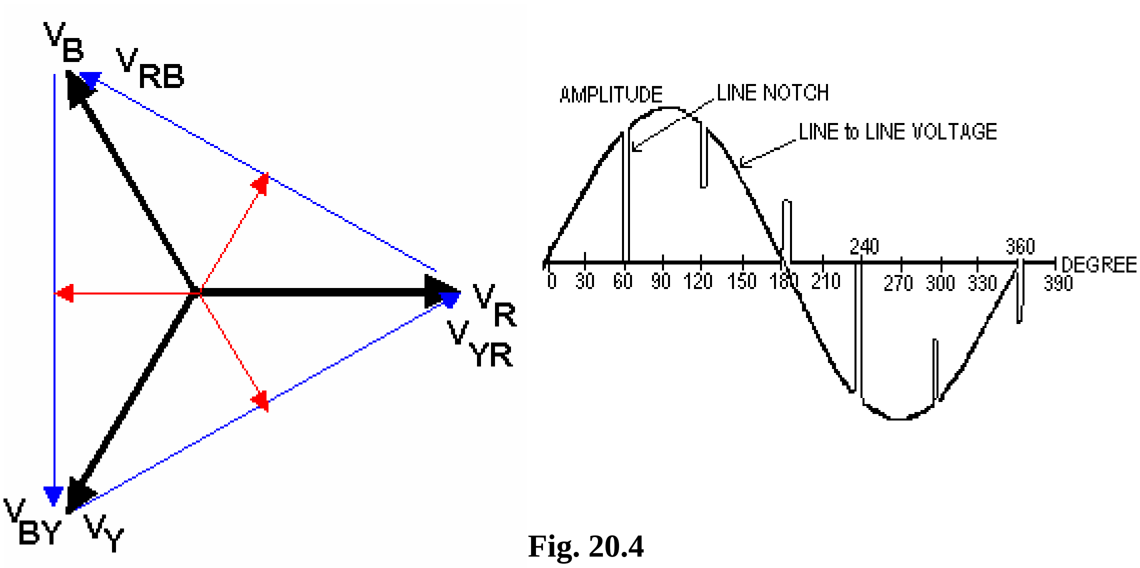

Fig. 20.4

The overlap time is dependent on the load current existing during the commutation period and also the voltage behind the short circuit current. This commutating voltage magnitude is dictated by the trigger angle. Thus for $\alpha = 0^0$ this voltage is minimum. At $\alpha = 180^0$ too it would have been very low if successful commutation had been possible. However, without any allowance for an overlap time, the SCR current would just start to fall before it rises again. Note at $\alpha = 180^0$ the converter operates in the 'inverter' mode and if the out going SCR fails to turn off it is effectively triggered at $\alpha = 0^0$ which pushes the converter from peak inversion to peak rectification mode. The resulting 'commutation failure' can cause severe short circuits. Thus the trigger angle must be restricted to values, which permit successful commutation of the SCRs.

20.5 Commutation in DC-DC Choppers

DC-DC Choppers have also been categorised on the basis of their commutation process. Three types of commutation are identified: i) Voltage commutation, ii) Current commutation and iii) Load commutation.

20.5.1 Voltage Commutation

In a voltage commutated thyristor circuit a voltage source is impressed across the SCR to be turned off, mostly by an auxiliary SCR. This voltage is comparable in magnitude to the operating voltages. The current in the conducting SCR is immediately quenched, however the reverse-biasing voltage must be maintained for a period greater than that required for the device to turn-off. With a large reverse voltage turning it off, the device offers the fastest turn-off time obtainable from that particular device. It is an exposition of 'hard' turn-off where the reverse biasing stress is maximum.

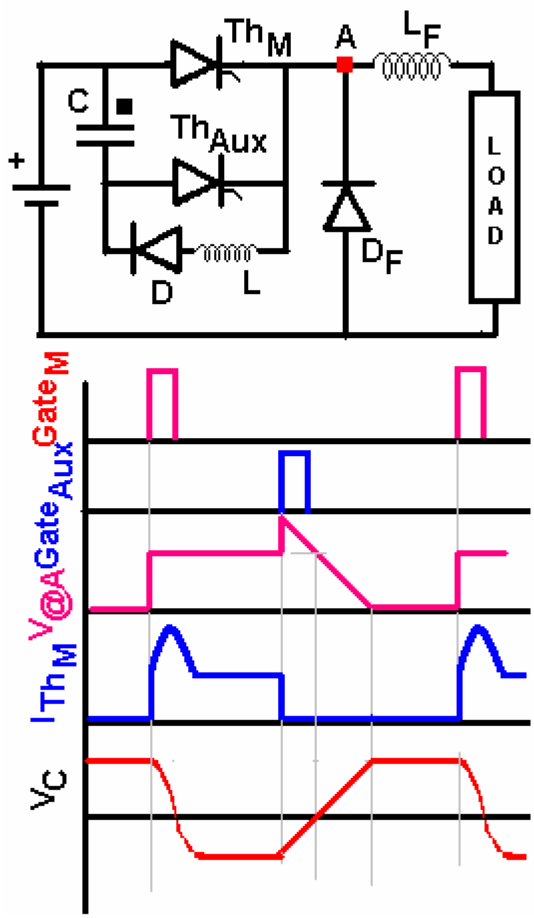

Fig. 20.5 A voltage commutated DC-DC Chopper and most significant waveforms

Fig. 20.5 illustrates voltage commutation. Th_M is the main SCR and Th_{Aux} is the Auxiliary. As a consequence of the previous cycle, Capacitor C is charged with the dot as positive. When the Main SCR is triggered, it carries the load current, which is held practically level by the large filter inductance, L_F and the Free-wheeling diode. Additionally, the charged Capacitor swings half a cycle through Th_M, L and D ending with a negative at the dot. The reverse voltage may be less than its positive value as some energy is lost in the various components in the path. The half cycle capacitor current adds to the load current and is taken by the Main SCR.

With the negative at the dot C-Th_{Aux} is enabled to commutate Th_M. When Th_{Aux} is triggered the negative charge of the capacitor is impressed onto Th_M and it immediately turns off. The SCR does take the reverse recovery current in the process. Thereafter, the level load current charges the capacitor linearly to the supply voltage with the dot again as positive.

The Load voltage peaks by the addition of the capacitor voltage to the supply when Th_{Aux} is triggered. The voltage falls as the capacitor discharges both changes being linear because of the level load current. When the Capacitor voltage returns to zero, the load voltage equals supply voltage. The turn-off time offered by the commutation circuit to the SCR lasts till this stage starting from the triggering of Th_{Aux}. Now the capacitor is progressively positively charged and the load voltage is equally diminished from the supply voltage. Th_{Aux} is naturally commutated when the capacitor is fully charged and a small excess voltage switches on the free wheeling diode. With the positive at the dot the capacitor is again ready for the next cycle. Here Th_{Aux} must be switched before Th_M to charge C to desired polarity.

Voltage commutation may be chosen for comparatively fast switching and it can be identified from the steep fall of the SCR current. There is no overlapping operation between the incoming and the outgoing devices and both currents fall and rise sharply. Stresses on all the three semiconductors can be expected to be high here.

20.5.2 Current commutation

The circuit of Fig. 20.6 can be converted into a current commuted one just by interchanging the positions of the diode and the capacitor. Here the Capacitor is automatically charged through D-L-L_F-Load with the dot as positive. Any of the SCRs can thus be switched on first.

If Th_M is triggered first, it immediately takes the load current turning off D_F. When ThAux is triggered, it takes a half cycle of the ringing current in the L-C circuit and the polarity of the charge across the capacitor reverses. As it swings back, Th_{Aux} is turned off and the path through D-C-L shares the load current which may again be considered to be reasonably level. The Current-share of TH_M is thus reduced in a sinusoidal (damped) manner. Turn-off process is consequently accompanied by an overlap between Th_M and the diode D in the D-C-L path. Once the main SCR is turned off, the capacitor current becomes level and the voltage decreases

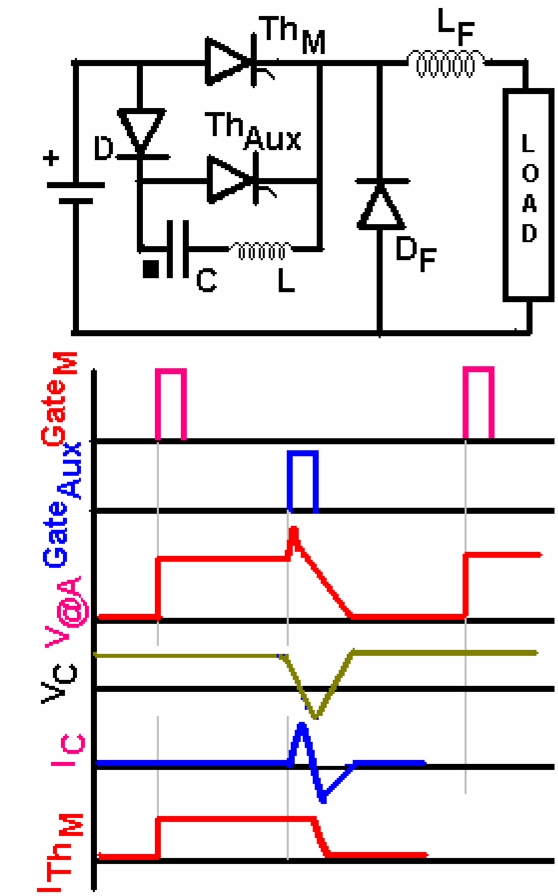

Fig. 20.7 A current commutated DC-DC Chopper and most significant waveforms

linearly. A voltage spike appears across the load when the voltage across the commutating inductance collapses and the capacitance voltage adds to the supply voltage.

The free-wheeling diode also turns on through a overlap with D when the capacitor voltage just exceeds the supply voltage and this extra voltage drives the commutating current through the path D-Supply-D_F-L. Thus there is soft switching of all devices during this period.

Further an additional diode may be connected across the main SCR. It ensures 'soft' turn-off by conducting the excess current in the ringing L-C circuit. The low forward voltage appearing across the SCR causes it to turn-off slowly. Consequently switching frequencies have to be low. *Note that such a diode cannot be connected across the Main SCR in the voltage-commutated circuit.*

20.5.3 Load Commutation

The circuit in Fig 20.7 is called a load-commutated chopper. Conduction paths are alternately through the diagonal SCR pairs. Conduction patterns of these two groups are symmetrical. Each pair of SCRs conduct with the capacitor in series. The current thus automatically is extinguished when the capacitor achieves supply voltage level and the free-wheeling diode is turned on. Any value of capacitor will suffice for commutation. In fact it is chosen to satisfy the load current requirement. This commutation method permits fastest switching of the SCRs. Currents through

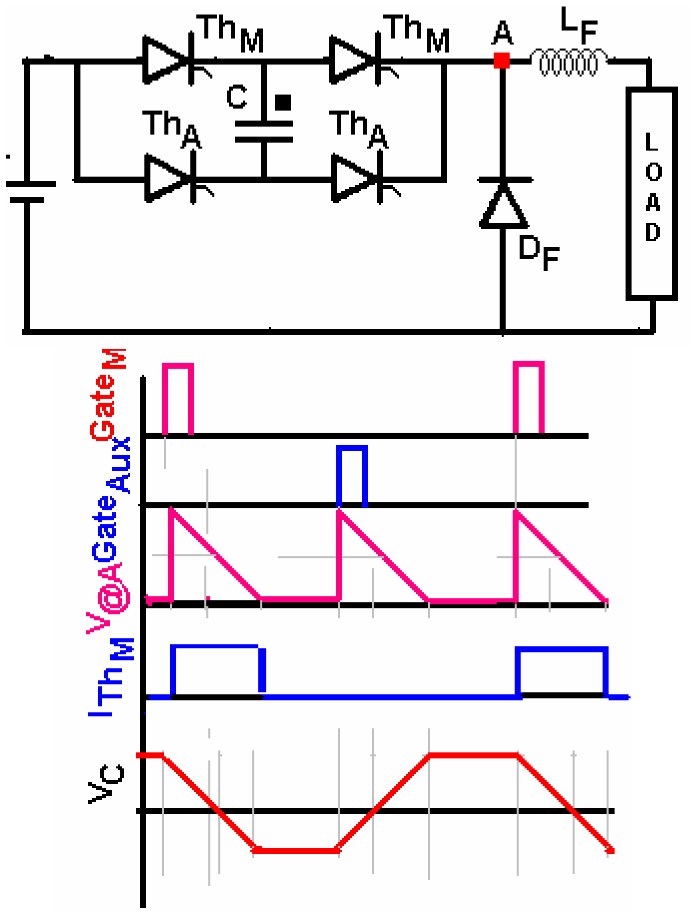

Fig. 20.7 A load-commutated DC-DC Chopper and most significant waveforms

the SCRs rise and fall sharply without any inductance regulating it. The free wheeling diode current also behaves similarly and all devices are stressed by sharp di/dt. The load voltage is of triangular shape with a peak equal to double the supply voltage (average equal to supply voltage for the conduction interval). The capacitor has a symmetric trapezoidal voltage across itself.

20.7 Practice Problems with Answers and Questions

Q1 SCRs having turn-off times of 8 μsecs is connected in a load-commutated chopper. The load current is 10 amperes, level. What is the minimum value of commutating capacitor necessary for successful commutation and what is the corresponding switching frequency? Supply voltage is 20 V DC.

A1 The capacitor charges linearly, and the forward biasing ends when the capacitor discharges to zero. This time should be a greater than or equal to the rated turn-off time of the SCR

$$C\frac{dv_c}{dt} = 10$$

$$dt = (C/10).200$$

$$= 8.10^{-6} \sec s$$

Therefore

$$C = 0.4\mu F$$

Each time the capacitor conducts a current it requires 2*8 μsecs to reverse charge. Switching period is thus 4*8 = 32 μsecs. The corresponding frequency is 31 KHz. The apparent frequency is 62 as the conduction of the SCR pairs is symmetrical.

Q2 For the current commutated circuit with a diode connected anti-parallel to the Main SCR estimate the turn-off time permitted as a function of the commutating capacitor and inductor. Sketch important waveforms specially the current through the Main SCR and its ant-parallel diode.