The present status of chopper control technology

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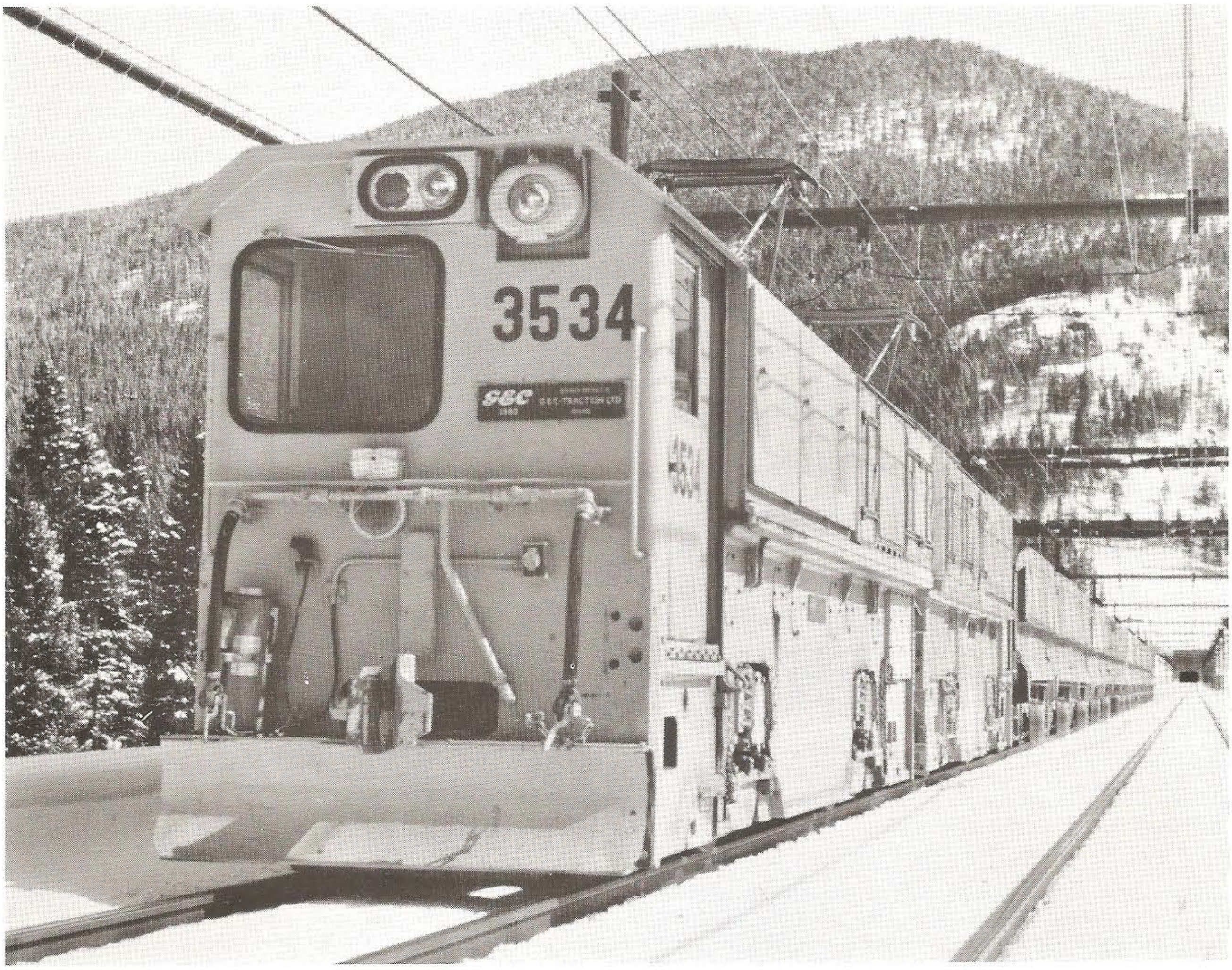


1. INTRODUCTION

In the years since our last Traction Symposium chopper control technology has reached its maturity. It is now the rule rather than the exception for railway administrations to specify chopper control for their new dc stock. The Company has participated to the full in this world-wide emergence of chopper technology, and recent contracts have doubled and re-doubled the number of chopper equipments on order from us.

A particular milestone was the supply of dual-voltage (600/1400V dc) mining locomotives to the Henderson molybdenum mine of the AMAX Corporation in Colorado, USA. These locomotives approach the ideal of the all-solid-state control philosophy. They incorporate many advanced features, such as multiplexed intra-train-communications in place of conventional train-lines, and generation of all auxiliary supplies by a chopper and inverters in place of an MA set. In spite of their narrow gauge (1067mm) and short length (7700mm) these locomotives have a starting-duty rating of 1.25MW.

2. CHOPPERS IN THE RAILWAY ENVIRONMENT

Over the years the emphasis in chopper technology has changed. In the early days there was concern with the detail design of the chopper itself. Now it is taken for granted that the chopper will perform as required, and attention is focused on the external effects of choppers on the entire railway system. A few of these effects will now be discussed.

3. ENERGY SAVING

The lasting impact of the oil crisis of 1973 can be discerned in the specifications for new stock for railway administrations the world over. The rationale in favour of choppers, pre 1973, was often based on their superior reliability and availability compared to conventionally equipped stock, whereas now it is their energy-saving features that have assumed the greater importance. It has become the norm to specify regenerative braking (every one of the chopper orders fulfilled by us since 1975 has had regenerative braking — see Table 1). Two side-effects of regenerative braking will be mentioned.

Date	Description	Quantity	Axle Arrangement	CHOPPERS		MOTORS		No. of Main Thyristors per Chopper	Electric Braking System	Supply Voltage
				No. per Set	Max. Rating (A)	No. per Chopper	Con. Rating (kW)			
1963	Works Delivery Vehicle	1	N/A	1	250	1	7	1	—	72V (battery)
1965	BMC Mini Traveller	1	N/A	1	400	1	7	3	Regenerative	96V (battery)
1965	London Transport Experimental Equipment	1	Bo-2	1	260	2	48	3	—	600V (fourth rail)
1967	Netherlands Railways Postal Coach	1	Bo-Bo	2	220	2	112	12	—	1500V
1968	London Transport 1960 Stock	2 Four-car Trainsets	Bo-Bo + 2-2 + 2-2 + Bo-Bo	4	360	2	48	4 (reduced to 2 in 1972)	—	600V (fourth rail)
1968	Netherlands Railways V6 Stock	2 Two-car Trainsets	2-Bo + Bo-2	2	500	2	142	10	—	1500V
1970	Netherlands Railways Postal Coach	Conversion of 1967 Equipment	Bo-Bo	2	220	2	112	12	Rheostatic	1500V
1971	South African Railways 5M2A Motor Coaches	2	Bo-Bo	2	300	2	220	6	—	3000V (overhead)
1973	Netherlands Railways SGM Stock	2 Two-car Trainsets	Bo-Bo + Bo-Bo	4	320	2	164	4	Rheostatic	1500V
1973	South African Railways 5M2A Motor Coaches	24	Bo-Bo	2	300	2	220	6	—	3000V (overhead)
1974	Netherlands Railways Postal Coach	Conversion of 1870 Equipment	Bo-Bo	2	220	2	112	16	Regenerative/ Rheostatic	1500V
1975	London Transport 'Experimental Tube Train'	1 Three-car Trainset	Bo-Bo + 2-2 + Bo-Bo	4	560	2	60	6	Regenerative/ Rheostatic	600V (fourth rail)
1976	Danish State Railways Regional S-Train	2 Four-car Trainsets	2-2 + Bo-Bo + Bo-Bo + 2-2	2	600	4	163	14	Regenerative/ Rheostatic	1500V
1978	British Rail S'n Region TSO Coach	1	Bo-Bo	2	450	2	153	1	Regenerative/ Rheostatic	750V (third rail)
1978	AMAX Henderson Mine (USA) Locomotives	4	Bo	2	600	1	450	4	Regenerative/ Rheostatic	600/1400V Dual Voltage (overhead)
1980	VicRail (Australia) Multiple Units	4 Three-car Trainsets	Bo-Bo + 2-2 + Bo-Bo	2	730	4	121	4	Regenerative/ Rheostatic	1500V
1980	C.I.E. Dublin Multiple Units	40 Two-car Trainsets	Bo-Bo + 2-2	1	730	4	163	4	Regenerative/ Rheostatic	1500V
1982	SMSC (Seoul) Multiple Units	134 Three-car Trainsets	Bo-Bo + Bo-Bo + 2-2	2	730	4	150	4	Regenerative	1500V

TABLE 1

The first side-effect stems from the fact that during regeneration the motor voltage is necessarily limited to line voltage, which is in turn limited by legal or technical constraints to no more than (typically) 20% above the nominal line voltage. This contrasts with the normal practice in rheostatic (dynamic) braking, in which the motor voltage is permitted to rise to about twice the nominal line voltage.

Now, the specified electric braking effort is usually required to be achieved at a speed which is also about twice the speed corresponding to full-field, maximum armature current, nominal line voltage condition. The rheostatic brake can achieve this performance without any increase in armature current; not so the regenerative brake, which must double the armature current to obtain the same braking effort. The designer is faced with two alternatives: to install a 'higher characteristic' motor which can handle the higher armature current, or to fit a resistance bank in series with the armature. The resistance shall be of such a value that at maximum speed the power loss in the bank equals the excess of the generated motor power, necessary to produce the required braking effort, over the maximum power capable of being returned to the line. The choice therefore is between a larger, costlier traction motor on the one hand and a reduction in regenerated energy on the other. While it is the railway administration which must make this choice, we can help them in their decision-making by providing comprehensive data on energy consumption through the suite of computer programs we have developed to evaluate theoretical train performance.

A second side-effect is that braking effort is contingent upon the line supply. The braking effort is required to be produced dependably and smoothly, but if the line supply system (the overhead wire or third rail) does not have a load able to sink at least as much energy as is being generated by this train, somewhere connected to it, the electric braking effort will cease to be available. (What happens in practice is that the line voltage will begin to rise, in response to which the chopper control electronics reduces the current it is asking the equipment to generate, and thus the braking effort will fall.) The short-fall in braking effort in such circumstances can of course be made up by the train's air brake system, but it is much to be preferred to make the electric brake independent of the line supply, whose characteristics are often beyond our immediate control. Moreover, an extreme case of the 'non-receptivity' of the supply occurs during pantograph bounce. When that happens, the chopper output voltage rises far too quickly for the air brake to respond to any sensible degree before it becomes necessary to switch the electric brake off altogether. The inevitable result is a jerk felt by the passengers. The remedy is to fit a second chopper to the equipment, controlling a resistor bank connected across the line supply. Again, this technique has reached a high state of development by the Company.

4. ELECTROMAGNETIC INTERFERENCE

It is only relatively recently that signalling systems designed from the start to be compatible with choppers have been marketed. In the great majority of applications, it is the chopper which must be designed to work with the existing signalling system, since it would be far too expensive to immunise the fixed installation.

The theory of interference due to conducted emissions is well known and we can make accurate estimates of the line current ripple produced by the chopper using computer Fourier analysis. To keep the line current ripple low, various expedients such as interlacing the chopper pulsing of two motor groups to double the effective ripple frequency are used, but the principal defence against excessive ripple must always remain the line filter inductor or choke. This is a large and heavy component and its good design effects the success of the entire chopper equipment to a greater extent than any other single component.

The other categories of interference are radiated and inductively-coupled emissions. Here, it is the relatively high frequency current found in the chopper's commutation circuit which is one of the main sources, and again choke design is important, but in this context it is the commutation choke which requires close attention. A major recent advance has been the application of toroidal construction to commutation chokes, which improves their 'Q' factor as well as reduces their external field.

A feature of our standard chopper design, which is described in detail in the following section, is that the resonant frequency of the commutation circuit is much lower than that in many competitors' schemes. This is possible because the peak resonant current does not need to be two or three times the motor current, as is required by those schemes. The operation of the GEC circuit only requires that the commutation resonant frequency be somewhat higher than the chopper frequency itself. This feature combines with the toroidal construction of the commutation choke to reduce power losses, noise and the stray magnetic field to low values.

Fig. 2 Toroidal construction — large commutating choke.

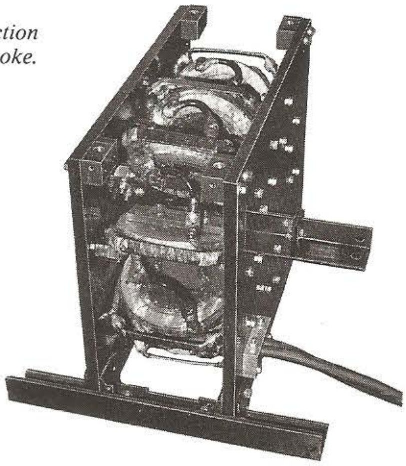


Fig. 3 Toroidal construction — small commutating choke.

5. THE GEC STANDARD CHOPPER

The key factors that make for a good chopper design are enumerated in this section, by reference to the GEC standard chopper, which is shown schematically in Fig. 4.

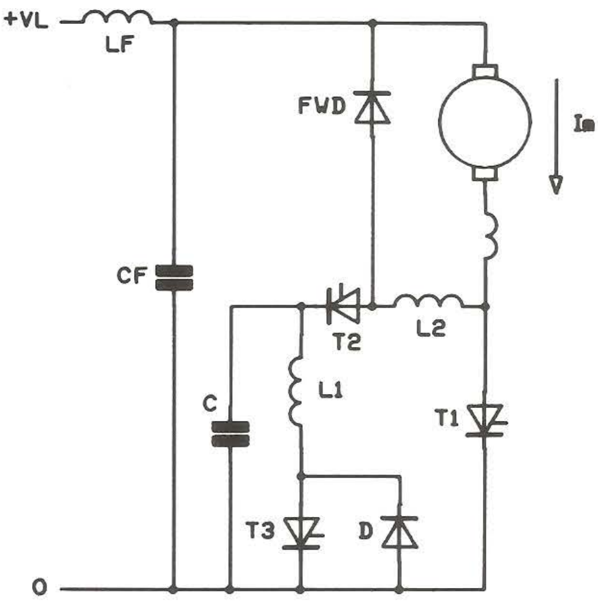


Fig. 4

5.1 Minimum on-time

The output voltage range should be very wide, ie from no more than 1% of the supply voltage up to 100%. For any given minimum on-time (which is determined by the type of chopper circuit adopted), the minimum output voltage could be made arbitrarily low by reducing the chopper operating frequency; however, this is not an acceptable solution because the choice of frequency is constrained by consideration of interference with the signalling system. In practice a single fixed frequency in the region 200 to 400Hz is usually mandatory, and therefore it is essential that the chopper should be capable of a minimum on-time which is very short (15 to 30μs). The GEC standard chopper has two features which enable it to achieve a minimum on-time this short.

The first feature is that the circuit for the resonant reversal of the charge on the commutating capacitor C (which in less sophisticated designs is via the main thyristor T1) is provided by a separate path through the extra thyristor T3. Thus the main thyristor does not need to be conducting during the time it takes for the capacitor charge to be reversed and the chopper, seen from the point of view of the load, is "off" during this time. The resonant current in C circulates via L1 and T3 quite independently of the load circuit. This contrasts with the working of lower-performance, two-thyristor choppers which must be "on" (applying line voltage to the load) during the resonant reversal time. (Reversal of the charge on the commutating capacitor is a precondition for turning off the main thyristor by firing thyristor T2, and this charge reversal is invariably accomplished in traction choppers by a resonant circuit.)

The second feature which enables the GEC chopper to achieve low on-times is the inclusion of diode D. Normally in each chopper cycle T1 is fired before T2, and the output voltage of the chopper is varied by varying the timing of the T1 firing pulse with respect to the T2 pulse. Without diode D the minimum output obtainable (which would be achieved by not firing T1 at all) would be due to the energy stored in C (after its resonant reversal has been completed) being discharged into the load when T2 is fired. This is shown in Fig. 5a.

With diode D, the energy stored in C need not be discharged entirely into the load. The chopper output can be further reduced by delaying the firing of T2 (T2 is normally fired exactly one half-cycle of the resonant period of L1 and C after T3, ie when the energy stored in the capacitor is at its peak). When T2 firing is delayed, the oscillation of C with L1 will proceed into a second half-cycle, with the resonant current now flowing through D rather than T3, and the potential of the top plate of C rising back towards line voltage as shown in Fig. 5b. The longer the delay, the less the energy that is fed into the load when T2 is eventually fired. (Note: When the firing of T2 is being delayed in this way, the charge remaining on C when T2 is fired would be insufficient to provide the reverse bias time required to turn off T1, but of course T1 is never in any case fired when the chopper is being worked in this low-output mode.) If the firing of T2 is delayed until one whole cycle of oscillation of C with L1 has been completed, the top plate of C will have returned almost to line potential as shown in Fig. 5c, and the energy fed into the load is only that necessary to make up the energy lost in the resonant circuit during the cycle. This small energy loss sets the lower limit to the output of the chopper. The higher the "Q" factor of the L1-C circuit, the lower the chopper's minimum output. Hence the importance of toroidal, high-Q construction of L1 mentioned above.

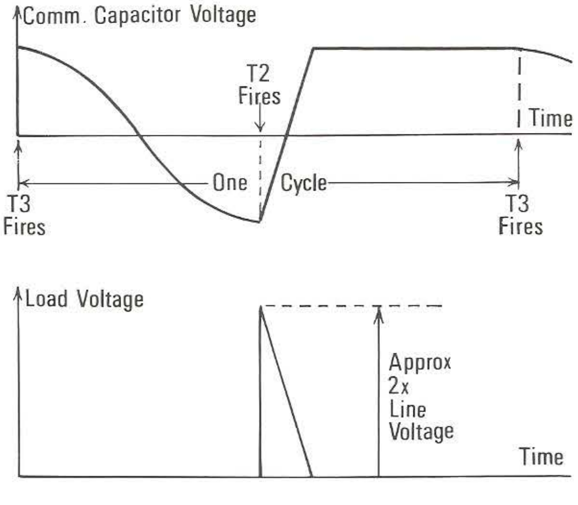


Fig. 5a Chopper waveforms when T2 firing is not delayed.

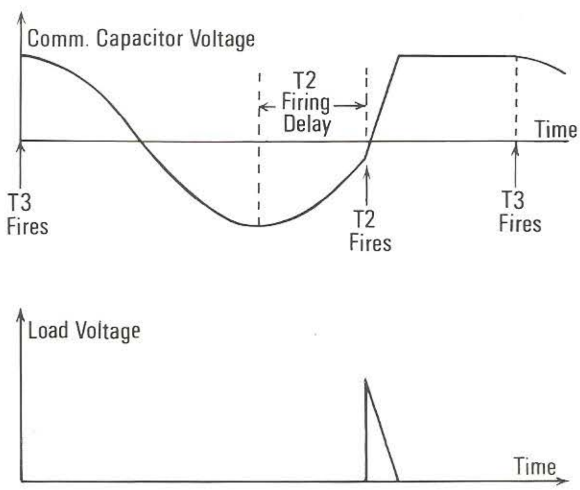


Fig. 5b Reduced load voltage with T2 firing delayed.

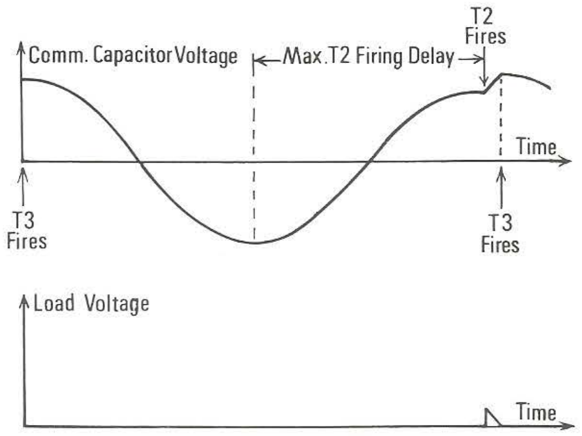


Fig. 5c Reduced load voltage with T2 firing delayed.

5.2 Avoidance of fast, expensive thyristors

Many chopper schemes have a minimum on-time which is directly proportional to the main thyristor's turn-off time. In such schemes it is therefore necessary to use "fast" main thyristors (in this context, thyristors with turn-off times of 25μs or less), which are not only expensive in their unit cost, but which are also available only in voltage grades up to about 1200V, rather than the 1800V or more available in "slow" (turn-off times 40μs or more) thyristors. It follows that more thyristors per "string" must be connected in series to handle the rated supply voltage.

The GEC standard chopper, on the other hand, has a minimum on-time which is almost independent of the turn-off time of the main thyristor, and so the "slow" type of thyristor can be used. This means that fewer thyristors are needed in series. At present, the thyristors used have silicon wafers of 50mm diameter, and it is sometimes necessary to use two strings of thyristors in parallel to handle the traction motor current. We will therefore be able to use with advantage the 75mm and 100mm thyristors which are now becoming available, to reduce the main thyristor to a single string.

These large thyristors will only be available with relatively long turn-off times (about 50μs), and the ability of our standard chopper to accommodate long turn-off times without compromising minimum output is thus one of its more important features. A comparison of the minimum on-times of some chopper circuits, including the GEC circuit, in which minimum on-time is expressed as a fraction of the turn-off time of the main thyristor, is given in a later section of this paper, and illustrates this point quantitatively.

5.3 Soft commutation

Soft commutation is another feature of the design of the GEC standard chopper which reduces main thyristor costs. The term "soft commutation" is applied to chopper circuits which use an inductor (which during main thyristor commutation is effectively in series with the commutation capacitor) to limit the rate of fall of current: the lower the rate of fall, the shorter the turn-off time of a given thyristor. Therefore for a given size of commutation capacitor, a soft commutation scheme allows a slower (and less expensive) main thyristor to be used than a hard commutation scheme does.

The soft commutation feature is provided in the GEC scheme by the extra inductor L2. This inductor has to be rated to carry the motor current only at low chopper outputs and is not a large component because it has a relatively small inductance: its only purpose is for limiting the rate of change of current in T1 and T2 (whereas in many schemes the same inductor is used both for giving the soft commutation feature and as the commutating inductor, and so a bigger component is required). Furthermore, by using a separate inductor for each function, the need (common to many soft commutation schemes) to have a peak resonant-reversal current of two or three times the maximum motor current is avoided, and by placing L2 at this point in the circuit one also avoids the overcharging of the commutation capacitor resulting from the soft commutation mechanism and the consequent need for damping resistors (also frequently encountered in competitor's schemes).

5.4 Avoidance of resonant currents through T1

The resonant currents referred to are due to the circuitry which reverses the polarity of the commutation capacitor every chopper cycle. Such currents increase the power dissipation in the main thyristor and so may necessitate the use of either a more expensive thyristor or a more elaborate heatsink. There are secondary reasons also for avoiding resonant currents in T1: if the resonance starts when T1 is triggered, it is possible for T1 to be turned off spuriously if the motor current is low and the resonant current high; or if the resonance ends when T1 is commutated, the transiently elevated thyristor temperature causes the thyristor's turn-off time to be increased. In the GEC standard chopper, the resonant currents are confined to the T3-D circuit and do not flow in T1.

5.5 High efficiency of operation

In many chopper schemes the resonant current mentioned above must have a high frequency (ie the capacitor polarity must be reversed in a short time). This may be either because the scheme's minimum on-time is proportional to the resonant-reversal time, or because (as with many soft-commutation schemes) the peak resonant current must be several times the motor current. In the GEC standard chopper the circuit arrangement is such that a long resonant-reversal time is possible without compromising either the minimum-on or the soft-commutation capabilities. It may be noted here that in the standard chopper, the minimum on-time is independent of the resonant-reversal time but is dependent on the efficiency of the reversal, and the peak resonant current does not need to be greater than the motor current. This is desirable because power losses, noise and stray magnetic fields are all thereby reduced. In the standard chopper the minimum output power is equal to the power loss in the resonant-reversal process. With a resonant-reversal time almost as long as the chopper's cycle time, the GEC scheme achieves a minimum power of only about 1200W at a line voltage of 1500V.

5.6 Full-on capability

Another design feature which increases the efficiency of the chopper is the ability to go "full-on" when the traction motor full-voltage characteristic is reached. In this condition the resonant-reversal process is stopped altogether and the main thyristor is left continuously on. The losses inevitably associated with switching the main thyristor on and off are thereby avoided.

5.7 Low component count

This aspect of chopper design may be considered under two heads:

(a) **Avoidance of series diodes**

These diodes are expensive devices since they have to conduct line supply current. They are required in two cases. First, a series diode is required in series with the chopper in schemes where the main thyristor is a reverse-conducting thyristor or where it has a diode connected in anti-parallel. The series diode prevents uncontrolled regenerative currents flowing when the motor's back-emf overhauls the supply voltage, as may often occur during line gaps. Second, a series diode is required in those soft-commutation schemes which produce some over-charging of the commutating capacitor after T1 turns off and where a discharge path then exists from the commutating to the filter capacitor. (This path may be provided, for example, by the commutating diode.) The series diode prevents this discharge, which would result in the commutation capacitor ending up as much under-charged as it was initially over-charged, from taking place. In the GEC standard chopper, series diodes are not needed.

(b) **"Double voltage" strings**

By the term "double voltage" is meant that the semiconductor string is subjected to twice the line supply voltage during the normal course of chopper operation. The free-wheel diodes form such a string in all schemes except those which employ a reverse-conducting main thyristor (which as we have noted have their own disadvantages). "Double voltage" strings also appear to be an unavoidable adjunct of schemes which provide very low minimum on-times. No such scheme can be found in the literature on choppers which does not employ a "double voltage" thyristor string. However, in the case of the GEC standard chopper, the "double voltage" string is the T2 thyristor string, where relatively cheap thyristors can be used and mounted on minimal heatsinks since their current duty cycle is very low, and so the impact of the increased number of thyristor capsules in this string on the overall cost of the chopper is small.

5.8 Avoidance of large and expensive reactive components

Some soft-commutation chopper schemes overcome the problem of commutating capacitor over-charging (which is a by-product of many such schemes) by placing the commutating inductor in series with the main thyristors. Since the inductor then has to carry the line supply current in addition to the resonant-reversal current, its rating is greatly increased. The alternatives are (1) to dissipate the energy represented by the over-charge on the commutating capacitor in resistances elsewhere in the chopper circuit; (2) to place the inductor in series with the free-wheel diodes. In this latter case the overall rating of the inductor may be modest, since the effective current which it carries falls as the chopper on-time increases, and is zero when the motor's full-voltage characteristic is reached. It is this solution which has been adopted for the GEC standard chopper, with the additional feature that since the "softening" inductor does not have to perform as the commutating inductor as well, its inductance is comparatively small. Another reactive component is the filter capacitor; in at least one published chopper scheme the resonant-reversal current path includes the filter capacitor, increasing its rating and so its size and cost.

6. COMPARISON OF SOME CHOPPER CIRCUITS

Although most present day choppers have a basic similarity, various manufacturers have adopted different compromises in the face of conflicting requirements of cost and performance. The resulting differences in circuit detail are sufficient to cause a wide variation in effectiveness.

The salient features of some published chopper schemes are summarised in the section that follows. It is not our intention to belittle particular schemes, but rather to clarify by examples the many sometimes conflicting criteria that the designer must attempt to reconcile.

An important feature of any chopper circuit is its minimum on-time, since the lowest output voltage, expressed as a fraction of the supply voltage, that the chopper is capable of is its minimum on-time multipled by its operating frequency. The minimum on-time of a chopper is obtained when the turn-off thyristor is fired as soon as possible after the main thyristor, a certain minimum interval between the two trigger pulses being necessary in many circuits to allow for resonant reversal of the commutating capacitor charge. In many circuits the minimum on-time effectively continues after the main thyristor has been turned off because the remaining energy in the commutating capacitor may have to be discharged into the load.

Formulae for the minimum on-time of the various choppers have been derived by circuit analysis and approximate expressions, valid when the load current is small, are given for each example. The exact formulae contain such terms as arcsin k and $\sqrt{(1-k^2)}$, where k is the ratio of the load current Im to the peak of the resonant reversal current $V_L\sqrt{(C/L)}$. (Here V_L is the supply voltage, C is the commutating capacitance and L is the commutating inductance.) In the approximations these terms are replaced by k and $(1-\frac{1}{2}k^2)$ respectively, since k is assumed to be small.

Typically the exact formulae then reduce to terms in $\pi\sqrt{LC}$ and V_LC/Im. In addition, 'soft commutation' circuits usually have a term in ImL/V_L. Taking these terms as the standard, the effectiveness of various means of reducing minimum on-time may be judged. A simple chopper with one each main thyristor, auxiliary thyristor and commutating diode strings will, it seems, always have a minimum on-time of at least approximately $\pi\sqrt{LC} + 2V_LC/Im$. To remove the $\pi\sqrt{LC}$ term requires the commutating diodes to be replaced by thyristors (and one thyristor string needs to be rated for twice line voltage), and to remove the $2V_LC/Im$ term as well requires an extra diode or thyristor in the circuit. Several 'half-way' schemes are known, for example a chopper which uses three thyristors but no diode and achieves $\frac{1}{2}\pi\sqrt{LC} + 2V_LC/Im$ without stressing any thyristor string to more than line voltage; but in general it seems that three thyristors and a diode is the minimum complement of a very low on-time chopper. The $2V_LC/Im$ term may be made less than inversely proportional to current by providing another, resonant, path for the commutation capacitor energy besides the path through the motor. When that is done, the term $2V_LC/Im$ is typically replaced by $2\sqrt{LC}$ arctan (k/Im) which tends to $\pi\sqrt{LC}$ as Im tends to zero.

At high motor currents, most of the capacitor energy goes to the motor and the motor on-time is only slightly less than in the case of the simpler circuit (arctan x tends to x at small angles), but as the motor current falls, a larger proportion of the capacitor energy is re-circulated via the resonant path and the motor on-time tends to the limiting value ($\pi\sqrt{LC}$) whereas with the simpler chopper the motor on-time can extend to the complete cycle time. One way of providing the additional resonant path is by means of an inductor and diode in anti-parallel to the main thyristor but other ways are possible, for example by means of a separate resonant path directly in parallel with the commutating capacitor.

The minimum on-time of any chopper is a function of the main thyristor turn-off time tq. From the circuit analysis, the reverse bias time tr of the main thyristor can be obtained as a function of the product LC. At the rated minimum supply voltage and the rated maximum load, current tr will be (say) twice tq by design. Hence LC may be expressed as a function of tq and of the ratios a and b, where

$$a = \frac{\text{rated minimum supply voltage}}{\text{actual supply voltage}}$$

and

$$b = \frac{\text{rated maximum load current}}{\text{actual load current}}$$

Also, assuming that by design the ratio k at the rated maximum load current is (say) ½, the ratio C/L may also be expressed as a function of tq, a and b. Hence the entire expression for the minimum on-time can be reduced to

$$t_{min} = tq.g\,(a,b)$$

where g (a,b) is a function of a and b only. The actual values of C, L, load current and supply voltage are not involved. Therefore, by substituting 'faster' thyristors in any given circuit an arbitrarily short minimum on-time may be obtained, but only at a cost.

The function g (a,b) is:—

$$g(a,b) = M(\pi P_1 + P_2\sin^{-1}(a/2b) + P_3b/a + P_4a/b + P_5)$$

where the terms are given for the various circuits in the following table. By comparing the values of the g(a,b) of the various circuits an indication of their cost-effectiveness in respect of minimum on-time is obtained.

Circuit H in the following table is the GEC standard chopper. The low values of g(a, b) obtained with this circuit show its superior performance in respect of minimum on-time.

							g (a,b)	
Circuit	**M**	**P_1**	**P_2**	**P_3**	**P_4**	**P_5**	**a/b = 1**	**a/b = 0.1**
A	.955	1	—½	½r_1	0	0	2.8	3.0
B	.955	1	—½	½r_1	¼	0	3.0	3.0
C	.577	1	1	r_2	½	0	4.4	25
D	.577	1	1	r_2	0	0	4.1	25
E_1	.577	1	1	r_2	0	0	4.1	25
E_2	.8	1	1	r_1	0	r_4	4.9	5.5
F	.5	½	0	4	0	0	2.8	21
G	1	0	0	r_3	0	0	0.4	2.8
H	1	0	0	r_3	0	0	0.4	2.8

In the above table,

$r_1 = (1-\sqrt{(1-(a/2b)^2)})^2$

$r_2 = (1+\sqrt{(1-(a/2b)^2)})^2$

$r_3 = 2(1-n^2)/n \tan^{-1}(2b/a)$

where n = efficiency of resonant reversal

$= .422/\tan^{-1}(2b/a)$ with n = 0.9 (typical).

$r_4 = \sqrt{6} \tan^{-1}(2b\sqrt{2}/a\sqrt{3})$

The effect of introducing an additional (resonant) path for the commutating capacitor energy besides the path through the motor is strongly seen by comparing the figures for a/b = 0.1 and a/b = 1. Where there is no additional path, the on-time is markedly longer at the lower value of a/b. It has been assumed that the inductor in the additional path has half the inductance of the commutating inductor.

The following notes apply to all the examples.

i All circuits have been drawn with one plate of the commutation capacitor at either live or return potential, in order to bring out the differences between schemes more clearly. It is sometimes possible to re-configure the circuit so that one plate of the capacitor is connected to the main thyristor anode instead, and several of the quoted schemes have employed this alternative configuration.

This re-arrangement, while not changing the normal working of the chopper, makes a difference to re-starting the chopper from full-on; the commutation capacitor voltage has to be resonantly reversed before the main thyristor can be turned off, or re-starting may not be possible at all. Full-on bleed resistors have been omitted from the sketches for clarity.

ii The re-arrangement may also make it more difficult to arrange for damping of commutation capacitor over-charge in some circuits; but damping networks have been omitted for clarity.

iii Di/dt limiting chokes have been omitted for clarity, although many circuits use them. Those circuits where di/dt limiting for the main thyristor is not provided by the commutation inductance, and where some extra saturating (or other) choke would be needed in practice, are marked S on the sketches.

iv Thyristors with inverse parallel diodes have been drawn as separate devices although reverse conducting thyristors are often used.

v Diodes marked with a circle are thought to be necessary (either to prevent resonant discharge of the commutation capacitor via the filter capacitor, or to prevent inadvertent regeneration in the event of motor back-emf overhauling line voltage) although the literature does not specifically refer to them.

vi All circuits have been drawn in a motoring (powering) configuration with the motors indicated diagrammatically. Special arrangements for starting or field weakening have been omitted.

vii Only choppers using resonant reversal of the commutation capacitor charge via an auxiliary circuit have been included, ie 'H' choppers, choppers using the motor itself as resonating inductance, and choppers using transformers or auto-transformers ('energy recovery' circuits) have all been excluded.

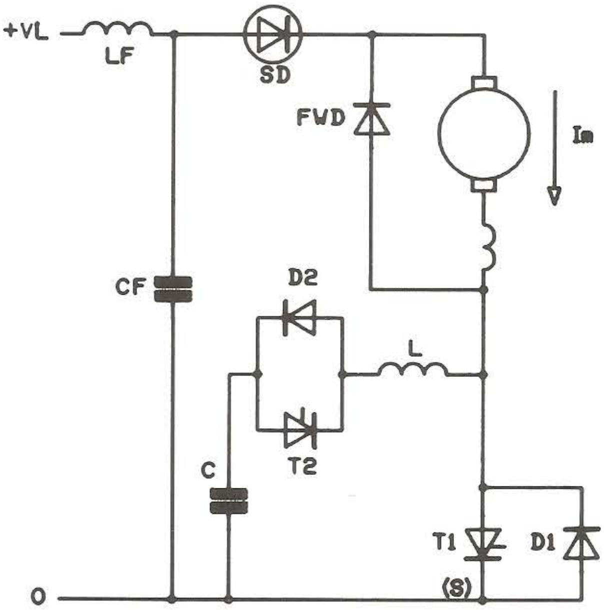
CIRCUIT A

Advantages

- ★ Soft commutation.
- ★ Capable of full-on operation.
- ★ Very low component count, although SD may be necessary and at high powers the RCTs are expensive.
- ★ No large reactive components or 'double voltage' strings.

Disadvantages

- ★ Moderately long minimum on-time, approximately $2\pi\sqrt{LC} - ImL/2V_L$.
- ★ T1 carries the resonant-reversal current.
- ★ The resonant-reversal time must be short, and the peak resonant-reversal current must be 2-3 times the maximum motor current.
- ★ A damping resistor (not shown) is needed to dissipate the energy in the over-charge of the commutating capacitor C resulting from the use of inductor L to perform the soft commutation function.



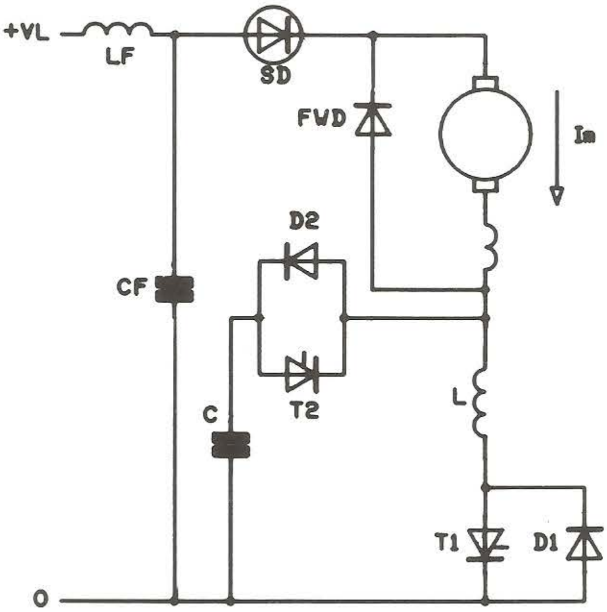
CIRCUIT B

Advantages

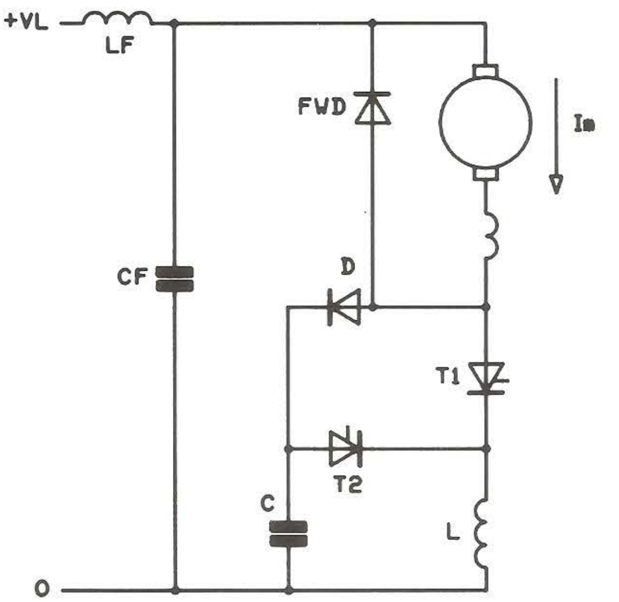
- ★ Soft commutation.
- ★ Capable of full-on operation.
- ★ Very low component count if reverse-conducting thyristors are used, but the unit cost of these is high and series diode SD is probably necessary.

Disadvantages

- ★ Moderately long minimum on-time, approximately $2\pi\sqrt{LC} + ImL/2V_L$.
- ★ T1 carries the resonant-reversal current, the peak of which must be 2-3 times the maximum motor current.
- ★ The resonant-reversal time $\pi\sqrt{LC}$ must be short.
- ★ The commutating inductor L has to carry the supply current as well as the resonant-reversal current.
- ★ Note that because of the position of L, the FWD must withstand 'double voltage' even though T1 is an RCT, but there is no over-charging of the commutation capacitor C resulting from soft commutation.



CIRCUIT C



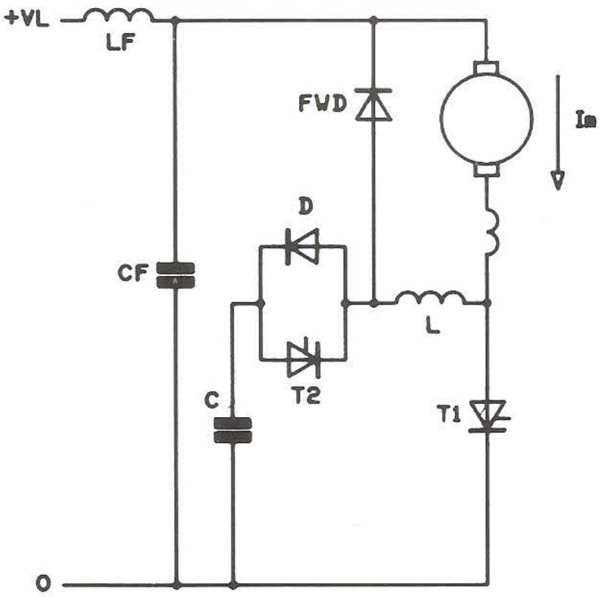
Advantages

- ★ Soft commutation.
- ★ T1 does not carry the resonant-reversal current.
- ★ Capable of full-on operation.
- ★ Low component count.

Disadvantages

- ★ Very long minimum on-time, approximately $\pi\sqrt{LC} + ImL/2V_L + 2V_LC/Im$.
- ★ T1 must be 'fast' to keep the minimum on-time short; the resonant reversal time $\pi\sqrt{LC}$ must be short too, and the peak resonant-reversal current must be 2-3 times the maximum motor current.
- ★ The commutation inductor L has to carry the supply current as well as the resonant-reversal current, but note that because of this there is no over-charging of the commutation capacitor C resulting from soft commutation.

CIRCUIT D



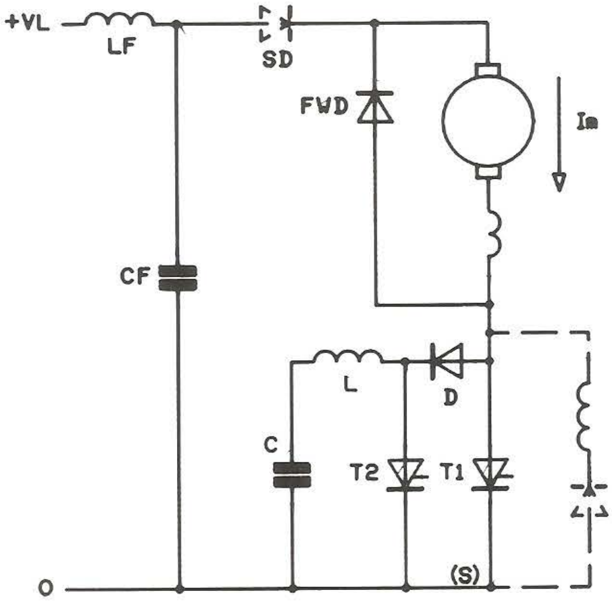
Advantages

- ★ Soft commutation.
- ★ Capable of full-on operation.
- ★ Low component count.

Disadvantages

- ★ Very long minimum on-time, approximately $\pi\sqrt{LC} + ImL/2V_L + 2V_LC/Im$.
- ★ 'Fast' T1 needed.
- ★ T1 carries the resonant-reversal current.
- ★ The resonant-reversal time must be short, and the peak resonant-reversal current must be 2-3 times the maximum motor current.
- ★ The inductor L has to carry motor current at low on-time; on the other hand this arrangement of L avoids the capacitor over-charging usually associated with soft commutation.

CIRCUITS E1 and E2



Note:

Circuit E2, published at a later date, has the components shown in dotted line.

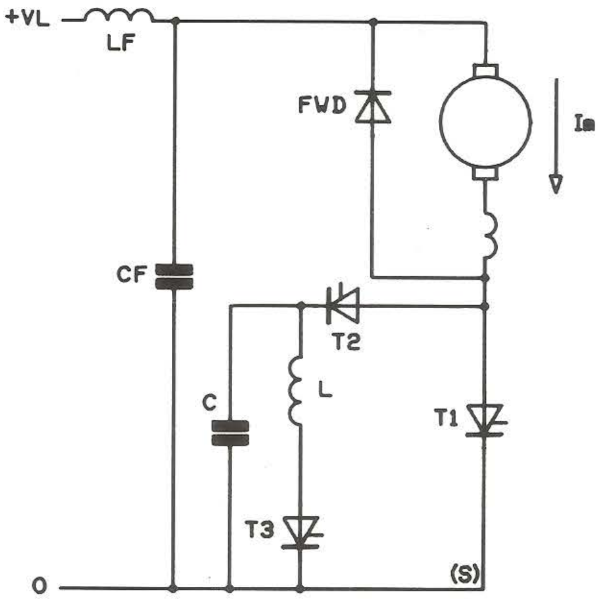
Advantages

- ★ Soft commutation.
- ★ T1 does not carry the resonant-reversal current.
- ★ Capable of full-on operation.
- ★ Low component count (in the earlier version).
- ★ No large reactive components.

Disadvantages

- ★ Very long minimum on-time, approximately $\pi\sqrt{LC} + ImL/2V_L + 2V_LC/Im$.
- ★ In the later version, the minimum on-time is somewhat reduced but more components are needed.
- ★ T1 must be 'fast' to keep the minimum on-time short; the resonant-reversal time must be short and the peak resonant-reversal current must be 2-3 times the maximum motor current.
- ★ A damping resistor (not shown) is needed for the same reason as in circuit A, *q.v.*

CIRCUIT F



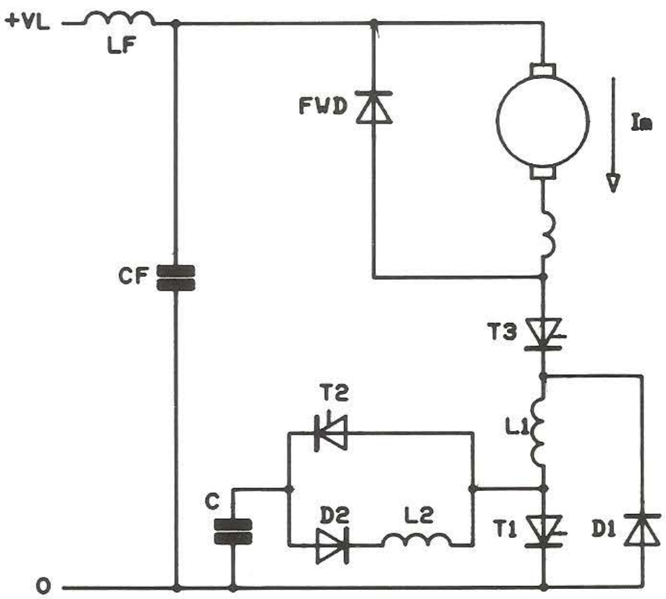
Advantages

- ★ T1 does not conduct the resonant-reversal current.
- ★ Capable of full-on operation.
- ★ Low component count: no 'double voltage' strings except FWD.
- ★ No large reactive components; one published scheme uses a saturating inductor for L, which reduces the size of L and reduces the minimum on-time while keeping T3 current duty reasonable..

Disadvantages

- ★ Minimum on-time is very long, approximately $\pi\sqrt{LC} + 2V_LC/Im$.
- ★ The minimum on-time may be reduced by firing T3 before T1, but may not be made less than $\frac{1}{2}\pi\sqrt{LC} + 2V_LC/Im$ without incurring the penalty of a 'double voltage' T2 string.
- ★ T1 must be 'fast' to keep the minimum on-time short; the resonant-reversal time must be short too.
- ★ Hard commutation.

CIRCUIT G



Advantages

- ★ Very short minimum on-time.
- ★ No 'fast' thyristors are needed.
- ★ The resonant-reversal time may be long.

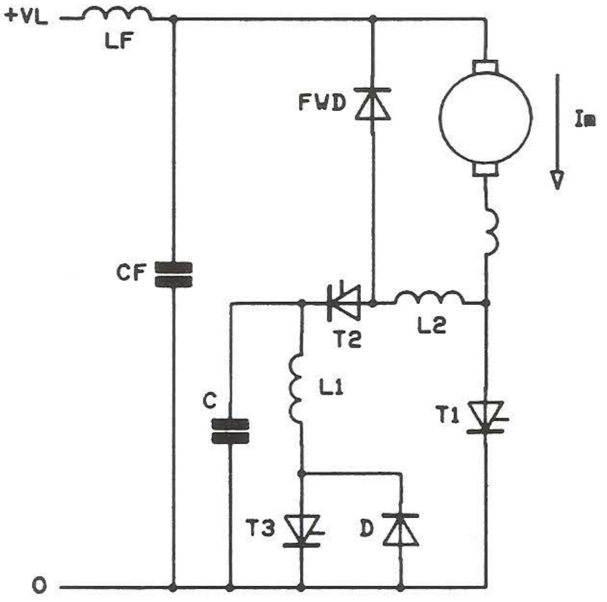
Disadvantages

- ★ Hard commutation.
- ★ T1 carries the resonant-reversal current.
- ★ Not capable of full-on operation.
- ★ High component count: T3 must withstand 'double voltage' and must be rated to carry the supply current, and a 'holding resistor' (not shown) must be connected in parallel with T3 to provide T1 with holding current in the minimum-on condition.
- ★ Inductor L1 must be rated to carry the supply current.

Note:

This was the earliest published scheme which provided very short minimum on-time.

CIRCUIT H
GEC standard chopper



Advantages

- ★ Very short minimum on-time.
- ★ T1 can be 'slow'.
- ★ Soft commutation.
- ★ T1 does not conduct the resonant-reversal current.
- ★ The resonant reversal time can be long and the peak resonant-reversal current need not be related to the maximum motor current.
- ★ Capable of full-on operation.

Disadvantages

- ★ High component count (although note that the scheme does not use series or blocking diodes), and T2 is a 'double voltage' string.

Note:

By using separate inductors for giving the soft commutation feature and for the resonant reversal function, the need (common to many soft commutation schemes) to have a peak resonant-reversal current of two or three times the maximum motor current is avoided, and by placing L2 at this point in the circuit one also avoids the over-charging of the commutating

(continued overleaf)

capacitor resulting from the soft commutation mechanism and the consequent need for a damping resistor (also frequently encountered in competitors' schemes). L2 is not a large component because it has a relatively small inductance and the proportion of the chopper cycle for which L2 is conducting is reduced as the chopper output voltage rises.

If a low chopper output is required, T1 need not be fired and most of the energy in C can be re-circulated via D prior to firing T2. The longer the delay in the firing of T2, the less the energy subsequently fed into the motor. If T2 is fired without a delay, ie $\pi\sqrt{LC}$ after T3, the minimum on-time is $2CV_L/Im$; if the delay is $\pi\sqrt{LC}$ (ie T2 is fired $2\pi\sqrt{LC}$ after T3) the minimum on-time is in principle almost nil; and at intermediate delays, intermediate on-times are obtained.

CONCLUSION

The pace of chopper developments shows no indication of slackening. The application of phase-change cooling (described in Mr W.W. Reid's paper) to choppers will make it possible to utilise silicon wafers of 75mm and 100mm diameter when these become commercially available as 'inverter grade' thyristors. Rapid progress is also being made in gate-turn-off devices, and these also offer exciting possibilities for chopper application. The Company is actively participating in both these developments and will continue to occupy a position in the vanguard of the practical application of chopper technology.

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