Induction motors for crane applications

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Abstract: The paper describes a control system for 4-quadrant operation of induction motors with characteristics suitable for crane hoist duty. The control system is based on a combination of stator-voltage control and rotor chopping. A thyristor stator-voltage regulator is used to provide a means of motor-speed closed-loop control. The regulator automatically reverses the phase rotation for plug braking or provides d.c. to the stator for injection braking as determined by load conditions. The rotor chopper operates with a duty cycle that is a predetermined function of rotor speed. Analysis of the chopper action in the rotor is used to determine the optimum function required to develop the maximum possible torque per stator ampere over the operating speed range. Different control functions are found to be necessary for motoring and d.c.-injection modes of operation. Analysis of the system and experimental results are presented showing successful 4-quadrant operation.

List of symbols

α = firing-angle delay
β = turn-off angle
λ = rotor-chopper duty cycle, on time/cycle time
T = cycle time of the rotor chopper
ϕ = phase angle for machine winding
ω = supply frequency, rad/s
L_1 = stator-leakage inductance referred to the rotor
L_2 = rotor-leakage inductance
R = external-rotor resistance
R_1 = stator-winding resistance referred to the rotor
R_2 = rotor-winding resistance
V_{dc} = rotor-chopper d.c. voltage
E = r.m.s. rotor voltage per phase at standstill
I_{dc} = rotor-chopper d.c. current
I_{rms} = rotor-chopper r.m.s. current
Ms = motor torque in synchronous watts
s = slip
n = motor speed, rev/s

1 Introduction

The hoist drive on a crane is difficult to realise as it must operate smoothly over a wide speed range to raise or lower the hook at controlled speeds irrespective of the load. When lifting, the drive must provide motoring torque with a relatively flat speed/torque characteristic to prevent excessive speed change from heavy-load to light-hook conditions. In addition, when lowering, the drive torque can be motoring or braking depending upon whether the load torque exceeds the mechanical friction of the hoist mechanism. A situation can be found when, on releasing the mechanical brake, the motor must provide a motoring torque to exceed friction, but as soon as the load torque exceeds the running friction the motor must change to a braking mode. Thus 4-quadrant operation of the motor is required.

2 Combined stator-rotor control system

A method for controlling a slip-ring induction motor to provide high torque in all four quadrants of operation is shown in Fig. 1. Thyristor controls are applied to both the stator and rotor of the machine.

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A stator-voltage regulator controls the speed of the induction motor to the demanded value by closed-loop control. The regulator thyristors can be selected to provide both forward and reverse rotation of the motor. Braking torque can be developed by either d.c. injection or phase reversal.

The stator-voltage regulator also operates within the limit of full-load rated current of the motor. Although the voltage regulator is capable of controlling the motor at any set speed throughout the speed range the large stator currents and power loss at high slip values would place a severe restriction on the drive.

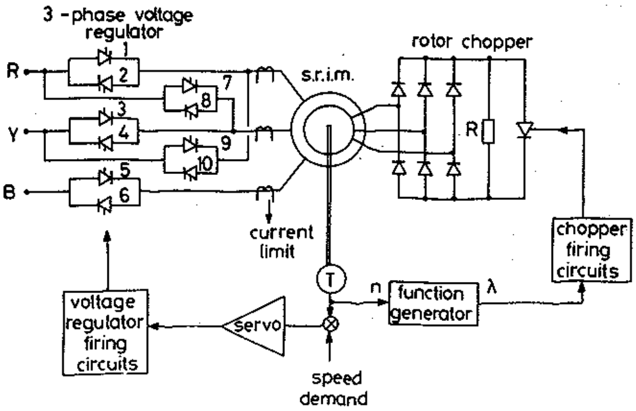

Fig. 1 *Combined stator-rotor control system*

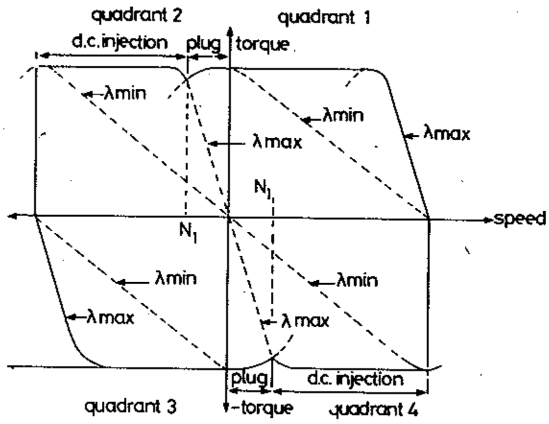

Fig. 2 *Four-quadrant characteristics*

Quadrant 1 – Motoring
Quadrant 2 – Braking
Quadrant 3 – Motoring
Quadrant 4 – Braking

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Table 1: Thyristor operation

Mode	Thyristors operating					
Forward motoring	1	2	3	4	5	6
Reverse motoring	7	8	9	10	5	6
D.C. braking	1	4	6	8	9	–

To achieve a high value of torque at all speeds the rotor resistance must be changed to suit the desired operating speed. This is achieved by controlling the duty cycle λ of the chopper in the rotor circuit as a predetermined function of motor speed; the function being such that maximum possible torque is available at all speeds within the limitation of rated motor current. The resultant 4-quadrant characteristics are shown in Fig. 2. It should be noted that the function relating duty cycle λ to speed is different in the motoring and braking regions. The characteristics show that d.c.-injection braking will not give high braking torque below speed N_1, and so to operate at low speeds with an overhauling load, plug braking, by phase reversal, must be used.

3 Steady-state analysis of the stator-regulator

A simplified diagram of the regulator and delta-wound stator of the induction motor is shown in Fig. 3. To fully describe the operation of the regulator the voltages across the machine windings have to be examined. There are two distinct types of waveform present. Mode-1 operation occurs when the current is discontinuous and only two thyristors conduct at any time. Mode-2 operation occurs when the current is continuous and there are either two or three thryistors conducting.

3.1 Conduction mode 1

The thyristors are fired in pairs with a delay angle α shown in Fig. 4 for thyristors 5 and 2 operating during the half cycle $\sin(\omega t - 4\pi/3)$. With an inductive load, current will continue to flow after reversal of the applied voltage and the thyristors revert to their off state when the current is zero at angle β.

The limit of mode 1 occurs when the waveform is no longer discontinuous, i.e. when $\alpha = \beta - \pi/3$. At this point α is defined as α_1. Note that the line-to-line voltage will appear across winding 1 for conduction of thyristors 5 and 2 during the half cycles of $V\sin(\omega t - 4\pi/3)$, but only

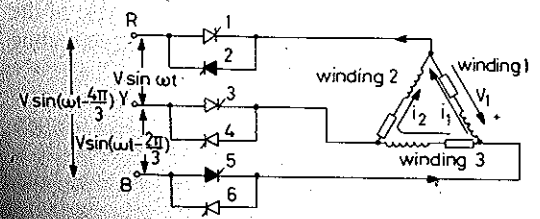

Fig. 3 *Stator-voltage regulator*

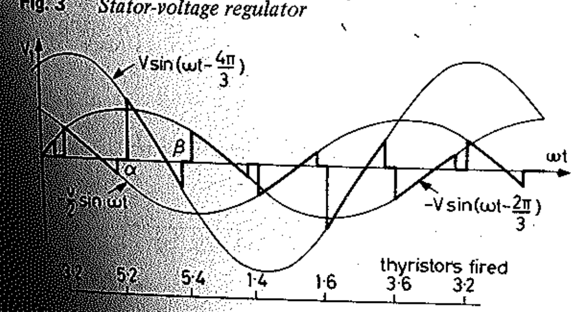

Fig. 4 *Voltage across winding 1: mode 1 operation*

half the line-to-line voltage will appear across winding 1 during half cycles of $V\sin\omega t$ and $V\sin(\omega t - 2\pi/3)$.

To calculate the voltage and current harmonics it is necessary to determine the value of β for specific values of α and phase angle ϕ. An analytic technique was used as described by Shepherd[1] which determines that

$$\sin(\beta - \phi) - \sin(\alpha - \phi)\exp[-\cot\phi(\beta - \alpha)] = 0$$

Where $\phi = \tan^{-1}\omega L/R$ for the machine winding. Angle β can be found by an iterative solution.

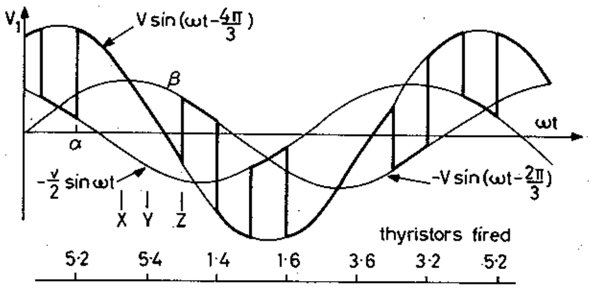

Fig. 5 *Voltage across winding 1: mode 2 operation*

3.2 Conduction mode 2

The voltage across winding 1 for this mode of operation is shown in Fig. 5. At some arbitrary instant X current flows through thyristor 5 to the combination of winding 1, in parallel with the series connection of windings 3 and 2, and returns to the supply via thyristor 2. At instant Y thyristor 4 is fired and, as three thyristors are conducting, full line-to-line voltage appears across all windings. As the voltage at the cathode of thyristor 4 is more negative than that at the cathode of thyristor 2, the current through winding 2 reduces and then increases in a reverse sense until it is equal to the current in winding 1. The current through thyristor 2 will then be zero and it will turn off at point Z. Thus, thyristor 5 conducts over the range α to β and, provided β can be found for given values of α, then the waveform across each winding can be fully specified.

The technique used to determine β was to assume a value for β which then permits the voltage waveform across windings 1 and 2 to be represented by regular piecewise functions.[2] A numerical integration technique[3] was then used to calculate the harmonic coefficients in the Fourier series representing the voltage across windings 1 and 2. Using a single-phase equivalent circuit model for the induction motor the effective impedence of each winding was found and used to calculate the currents in windings 1 and 2 using a current harmonic summation method.[4] If the two currents sum to zero then the current to thyristor 2 would

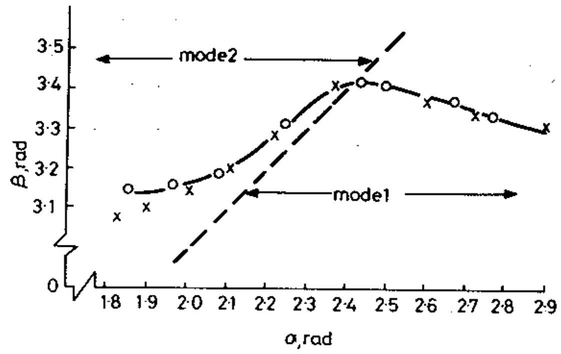

Fig. 6 *Relationship between firing angle α and turn-off angle β*

o Experimental locked rotor
x Calculated locked rotor

be zero corresponding to turn off showing that the assumed value for β at the turn-off point was correct. If the currents do not sum to zero the procedure is repeated for different values of β until a zero is achieved. Fig. 6 shows the comparison of calculated and experimentally observed results for β as a function of α for a locked-rotor condition.

3.3 *Torque/speed characteristics*

The voltage analysis gave information on the harmonic content of the applied voltage to the machine windings. As the contribution to motor torque decreased significantly as the order of harmonic increased, only the fundamental component was considered for prediction of motor torque.

The motor operates under speed control by regulating the stator voltage but with an overriding control limiting the stator current to a prescribed maximum value. To calculate the maximum torque available at a given slip, the appropriate winding parameters in the model are used to determine the α/β relationship, thus allowing calculation of the fundamental total r.m.s. voltage ratio. The total r.m.s. stator current can then be calculated and a value of α found that just maintains the current at the rated maximum value. The fundamental component of voltage for this value of α is then used to determine the motor torque from the single-phase model. In this way torque/speed characteristics can be predicted allowing for harmonics and the current limiting action of the control system.

4 Control of the induction motor by rotor-current chopping

It is evident that the desired torque-speed characteristics, providing essentially constant torque at all speeds, cannot be realised by the stator voltage regulator alone. The peak of the torque-speed characteristic can be moved to the desired operating speed by changing the rotor resistance. This can be accomplished by connecting the rotor to a 3-phase bridge rectifier with resistance load and thyristor chopper, as shown in Fig. 7. A d.c. equivalent circuit is shown in Fig. 8.

From conventional theory the value for V_{dc}, allowing for overlap is

$$V_{dc} = sE_0 - \frac{3s\omega}{\pi}(L_1 + L_2)I_{dc} \tag{1}$$

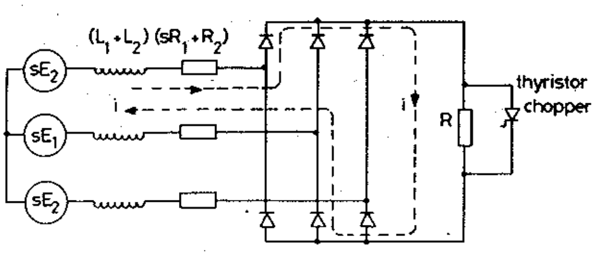

Fig. 7 *Rotor-chopper circuit*

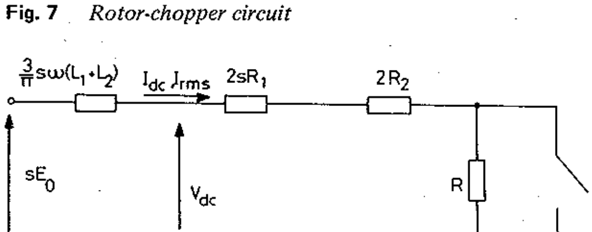

Fig. 8 *D.C.-equivalent circuit*

where

$$E_0 = \frac{3\sqrt{6}}{\pi}E_2$$

The output torque, in synchronous watts, is given by

$$Ms = \frac{\text{rotor-circuit copper loss}}{s} \tag{2}$$

$$= \frac{V_{dc}I_{dc} - 2sR_1I_{rms}^2}{s}$$

$$= \left[E_0 - \frac{3\omega}{\pi}(L_1 + L_2)\right]I_{dc} - 2R_1I_{rms}^2 \tag{3}$$

The chopper current consists of an exponential rise and fall corresponding to the 'on' and 'off' states of the chopper (see Appendix 9). Detailed analysis of the rotor-chopper circuit[5-7] can then be used to determine I_{dc} and I_{rms} for each value of slip and substituted into eqn. 3 to give the predicted torque. Theoretical and experimental results for the torque-speed characteristic were taken and gave good agreement.

4.1 *External rotor resistance, R*

The value of the external rotor resistance controls the shape of the complete operating envelope of the motor. The duty cycle of the chopper will have operating limits λ_1 and λ_2 which will be a function of the chopper design. The chopper used had a minimum value λ_1 of 0·2, i.e. the chopper was on for a minimum of 20% of the operating cycle time of 2·5 mS. Torque is a function of slip, external rotor resistance R, and duty cycle λ with all other parameters held constant. The developed torque and motor current can be determined from eqns. 11 and 3 for a range of values of R with $\lambda = \lambda_1$ and $s = 1$. Thus a value for R was determined to give the maximum possible standstill torque within the rated value of motor current. Ideally the chopper should have maximum value λ_2 of 1·0, i.e. effectively short circuiting the rotor terminals for operations near synchronous speed. The chopper used had a value λ_2 of 0·8 which limited high speed performance.

4.2 *Function generator*

The function generator is used to produce a relationship between the speed of the motor and the duty cycle of the chopper such that the machine can, within its current-rating

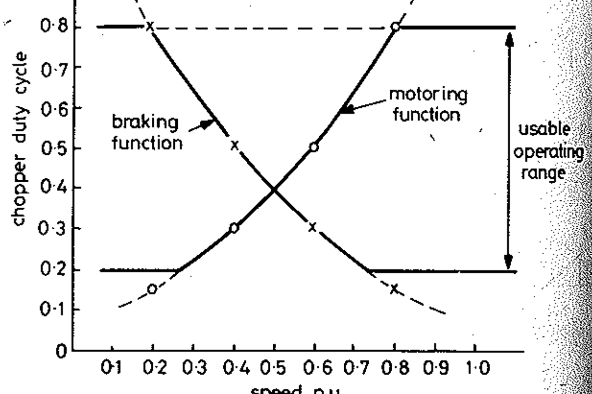

Fig. 9 *Rotor-chopper control function*

limits, produce maximum possible torque at that speed. Using the previously determined external rotor resistance, values for the duty cycle λ were calculated which just gave rated motor current at each of a range of operating speeds. The function relating duty cycle to speed is shown in Fig. 9. During d.c.-injection braking, a low value of rotor resistance is required near standstill, but a high value of resistance is needed at low slip speeds. The duty-cycle function during braking operation is, approximately, the motoring function inverted with respect to speed.

The functions were linearised and electronically generated to control the duty cycle with the appropriate function being automatically selected for motoring or braking operation.

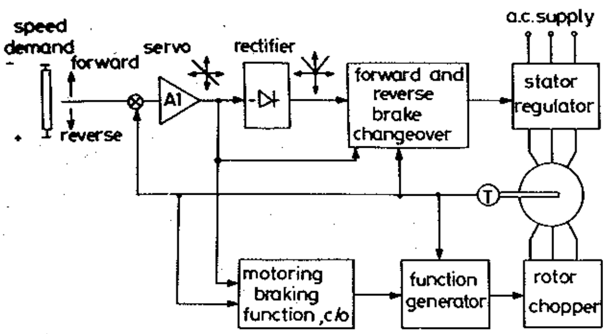

Fig. 10 *Block diagram of control system*

5 Control system operation

A block diagram of the electronic controls required to provide 4-quadrant operation of the system is shown in Fig. 10. The pulse circuits to the stator regulator reduce the firing-delay angle as the positive input to them increases.

When the system is operating in the forward (hoisting) mode, i.e. quadrant 1, the negative speed reference will be greater than the positive feedback from the tachogenerator and the output of $A1$ will be positive. A positive voltage at $A1$ selects the motoring function for the rotor chopper and the forward motoring thyristors in the stator regulator.

If the negative reference is reduced slowly towards zero, the motor will slow down with the output from $A1$ still being positive, but of a smaller value. If, however, the demand signal is quickly reduced towards zero the output of $A1$ will change polarity. A negative voltage at $A1$ selects the braking function for the rotor chopper and the d.c. braking thyristors in the stator regulator. The drive will then be operating in quadrant 4. The electronic rectifier ensures that the pulse circuits still see a positive input giving a phase advance and therefore increasing d.c. injection for increasing speed error.

Consider the hoist drive lifting a load at a speed very close to standstill. If the demanded speed is reduced, the motoring torque will eventually become insufficient to hold the load which will start falling. The change in tachogenerator polarity will increase the output of $A1$ positively and the system will be operating in the plug-braking mode, i.e. in quadrant 2. If the demand is further reduced and reversed the load will fall at an increasing, but controlled, speed. At a predetermined lowering speed, when plug braking becomes less effective, a detector changes the a.c. regulator to the d.c.-braking mode and selects the braking function for the rotor chopper. Thus the drive is lowering with a braking torque in quadrant 2.

If it is required to lower a lightly loaded hook that cannot overhaul the drive then the speed demand must be reversed causing amplifier $A1$ to change polarity. The negative polarity of $A1$ together with a reverse-speed demand is detected, and changes the a.c. regulator to the reverse-motoring mode. The electronic rectifier ensures an increasing phase advance for increased speed demand and the load is driven down in quadrant 3.

6 Experimental results

Laboratory tests were carried out with the drive system operating in all four quadrants. The torque-speed characteristics obtained are shown in Fig. 11. The curves show maximum possible torque up to the limit of rated motor current. The limited range of duty cycle of the chopper can be seen particularly as a loss of performance near synchronous speed in quadrants 1 and 3. The changeover from plug braking to d.c.-injection braking in quadrants 2 and 4 was optimised at speeds greater than anticipated because the superior plug-braking performance caused by the high stray-load losses of the test machine. Predicted performance of the system agreed well with experimental results except in the regions where the stray load losses had a noticeable effect.

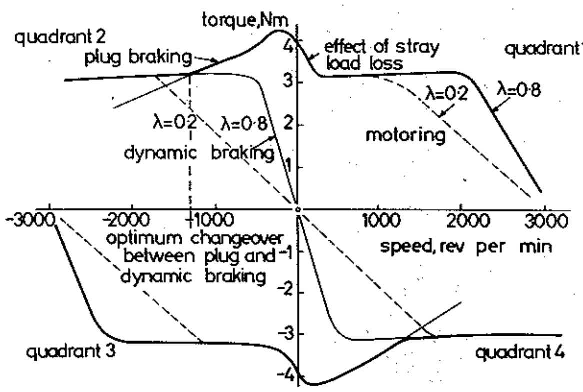

Fig. 11 *Speed/torque characteristics of the 4-quadrant controller*

The characteristics of the 4-quadrant controller are suitable for a hoist drive and are close to the operating requirements, although the speed range at which full-load torque is available is limited by the design of the rotor chopper.

A linearised model of the controller and motor was used to predict the dynamic behaviour of the system to small perturbations in speed demand. The predictions compared very favourably with experimental results but a more detailed analysis would be necessary to include discontinuities and nonlinearities for operation through the four quadrants.

7 Conclusions

A system for combining the control of a stator-voltage regulator and a rotor chopper for an induction motor has been analysed and experimental results show that stable 4-quadrant operation suitable for hoist applications is possible. The speed range of the practical system was restricted by the limited range of the rotor chopper used in the tests. The speed range could be extended by improving the chopper design. Plug braking torques on the test equipment were high due to stray losses; however, the technique of automatic changeover to d.c.-injection braking was implemented and found effective. The disadvantages of the system are the complexity of stator/rotor control and the energy losses dissipated in the machine and in the external rotor resistance.

Before such a system could be implemented industrially, detailed consideration would be required into the safety implications of equipment failure. Application of brakes and removal of power would have to be automatically initiated by monitoring appropriate parameters, i.e. speed error. The system, however, does provide a solution to the 4-quadrant operation of induction motors for crane-hoist drives.

8 References

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9 Appendix: Analysis of the rotor chopper

At the relatively high chopping rate, the analysis can be based upon a typical instantaneous current path as shown in Fig. 7 in which, neglecting ripple, the ins voltage may be assumed to be sE_0. The current at the rectifier output of the rotor chopper is Fig. 12. The current consists of two exponential c

During the rise period

$$i_1 = \frac{sE_0}{R_3} - \left(\frac{sE_0}{R_3} - I_1\right) \exp\,[-T_1 t]$$

where

$$R_3 = 2(sR_1 + R_2) \quad \text{and} \quad T_1 = \frac{R_3}{2(L_1 + L_2)}$$

When $t = \lambda T, i(t) = I_2$ hence

$$I_2 = \frac{sE_0}{R_3} - \left(\frac{sE_0}{R_3} - I_1\right) \exp\,[-T_1 \lambda T]$$

During the fall period

$$i_2 = \frac{sE_0}{R_4} - \left(\frac{sE_0}{R_4} - I_2\right) \exp\,[-T_2(t - t_1)]$$

where

$$R_4 = R_3 + R \quad \text{and} \quad T_2 = \frac{R_4}{2(L_1 + L_2)}$$

When $(t - t_1) = (1 - \lambda)\,T, i(t) = I_1$, so

$$I_1 = \frac{sE_0}{R_4} - \left(\frac{sE_0}{R_4} - I_2\right) \exp\,[-T_2(1 - \lambda)\,T]$$

Substitution gives

$$I_1 = \frac{sE_0}{1 - \exp\,[-T_1\lambda T - T_2(1 - \lambda)]}\left\{\frac{1 - \exp\,[-T_2(1 - \lambda)\,T]}{R_4} + \frac{[1 - \exp\,(-T_1 \lambda T)]\,\exp\,[-T_2(1 - \lambda)\,T]}{R_3}\right\}$$

and

$$I_2 \; \frac{sE_0}{1 - \exp\,[-T_1\lambda T - T_2(1 - \lambda)\,T]}\left\{\frac{1 - \exp\,[-T_1\lambda T]}{R_3} + \frac{1 - \exp\,[-T_2(1 - \lambda)\,T]\,\exp\,[-T_1 \lambda T]}{R_4}\right\}$$

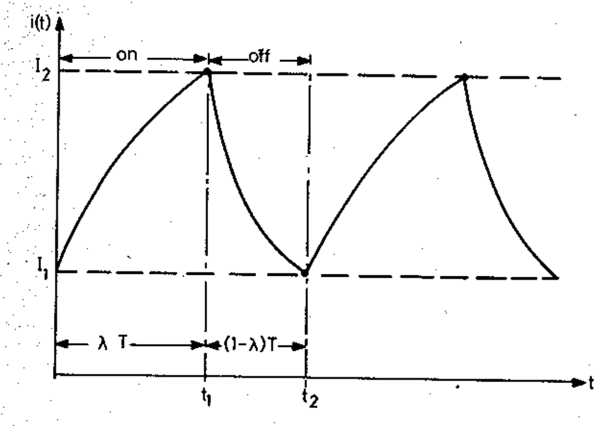

Fig. 12 *Rectified current waveform*

The mean value I_{dc} and the r.m.s. value I_{rms} can be obtained from

$$I_{dc} = \frac{1}{T}\int_0^{\lambda T} i_1\,dt + \frac{1}{T}\int_{\lambda T}^{(1-\lambda)T} i_2\,dt \tag{10}$$

and

$$I_{rms} = \left(\frac{1}{T}\int_0^{\lambda T} i_1^2\,dt + \frac{1}{T}\int_{\lambda T}^{(1-\lambda)T} i_2^2\,dt\right)^{1/2} \tag{11}$$

The values of I_{dc} and I_{rms} can then be used in eqn. 3 to calculate the output torque for which the motor r.m.s. current will be given from eqn. 11.