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PERFORMANCE AND ANALYSIS OF A 3-PHASE THYRISTOR COMMUTATOR MOTOR

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Introduction. The ideal adjustable-speed motor would be one which would be directly connected to the a.c. supply and could be designed for any available voltage. The stator-fed a.c. commutator motor is such a machine and insofar as it has any disadvantages, these are associated with the commutator, brushgear and the extra power equipment required for speed control which normally takes the form of a variable-ratio transformer, like the induction regulator. The machine is really an induction motor with a built-in rotating frequency changer which converts mains frequency at the brushes to slip frequency for the rotor coils. By controlling the applied brush voltage, the slip can be altered to any value, positive or negative. This speed-control system is one particular application of secondary-voltage control. Many attempts have already been made to employ thyristor circuits of various kinds for this purpose, using slip-ring induction machines. Erlicki[1], Lavi and Polge[2], Miljanic[3], Shepherd and Stanway[4], Ohno and Akamatsu[5] used various types of static d.c. link inverters in the rotor whereas Yamaguchi et. al.[6], used the 'Graetz' connection frequency-converter in a type of static Scherbius system.

In general terms, the action of a commutator may be considered as providing a frequency-matching link connecting two circuits between which there is to be a power interchange and which in general operate at different frequencies. The action takes place as a result of switching governed by shaft position. The present paper describes the performance and analysis of a machine in which this function is carried out by stationary thyristors connected to the slip rings of an induction motor. The machine system thus becomes analogous to a stator-fed commutator motor, having a static 'commutator' with three segments per pole pair, forming the link between the rotor windings and the variable voltage, constant-frequency mains supply.

System Arrangement. Fig.1 shows the main details of the rotor circuits, a simple position detector consisting of a slotted disc with phototransistors, being used to determine the switching instants. Photopulses generated every 120 electrical degrees are processed through suitable logic circuits to direct firing pulses to the thyristor units in the following sequence:-

$0^\circ - 120^\circ$ T_{1A}, T_{2B}, T_{3C}
$120^\circ - 240^\circ$ T_{1B}, T_{2C}, T_{3A}
$240^\circ - 360^\circ$ T_{1C}, T_{2A}, T_{3B}

Thus, slip rings 1,2 and 3 are connected sequentially to phases ABC, BCA, and CAB in accordance with rotor position. From this viewpoint, the rotor coils are being switched in the same way as would occur with a 3-segment-per pole-pair commutator. However, the circuit behaviour is similar to that of the cycloconverter and the voltage generated, which has a pronounced slip-frequency component, is applied to the slip rings. Assuming ideal, instantaneous commutation, it can be shown by Fourier analysis, that the slip-frequency component is in general, $0.827, (3.\sqrt{3}/2\pi)$ times the amplitude of the supply voltage. The circuit permits reversible power flow naturally, unlike the simple inverter circuit and therefore sub-synchronous and super-synchronous speeds are possible. By moving the position of the phototransistors, phase-control is available as for brushgear rotation with a mechanical commutator.

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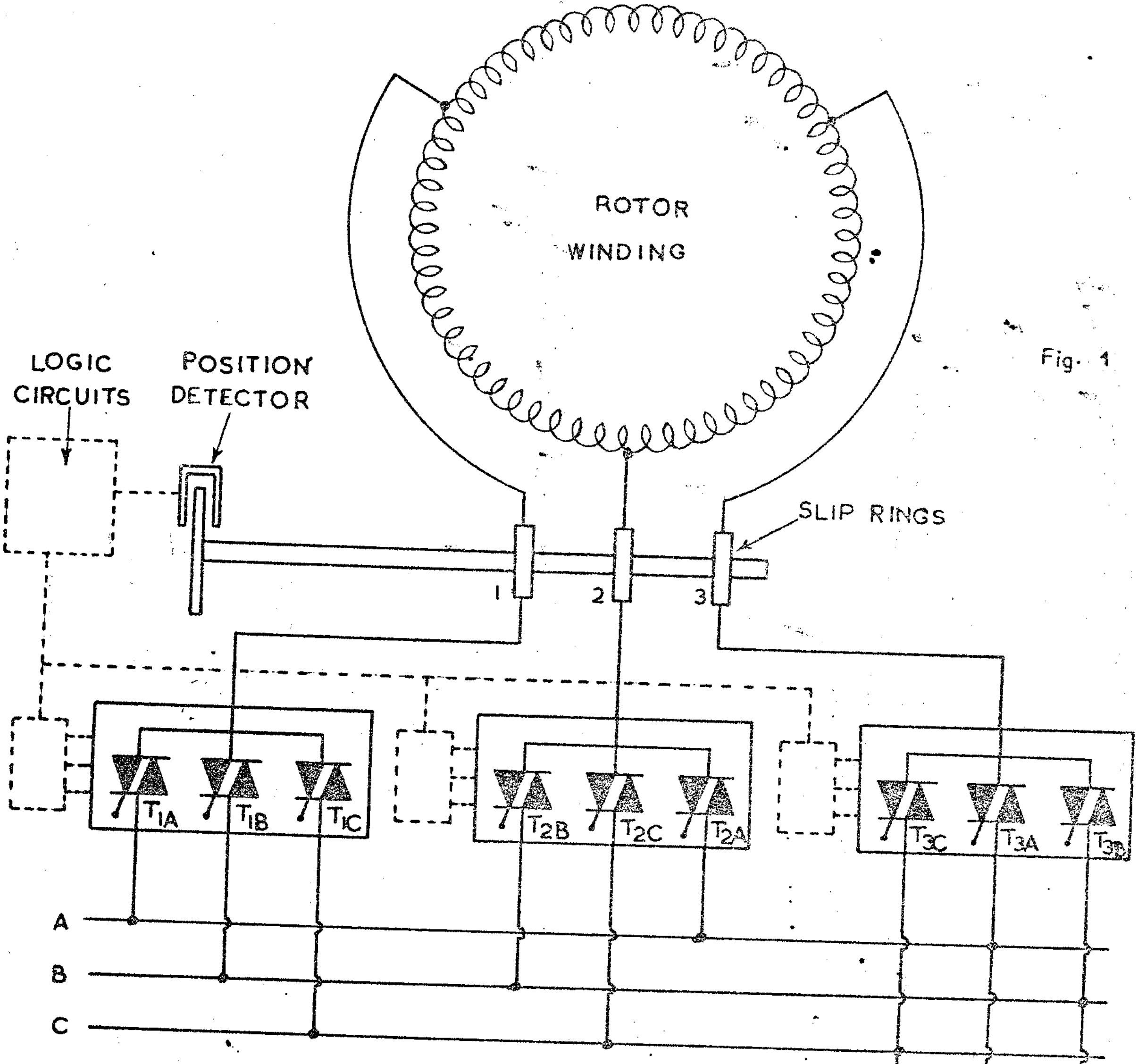
ROTOR
WINDING
LOGIC
CIRCUITS
POSITION
DETECTOR
SLIP RINGS
1
2
3
T_{1A}
T_{1B}
T_{1C}
T_{2B}
T_{2C}
T_{2A}
T_{3C}
T_{3A}
T_{3B}
A
B
C
TRANSFORMER
C
A
B

Fig. 1

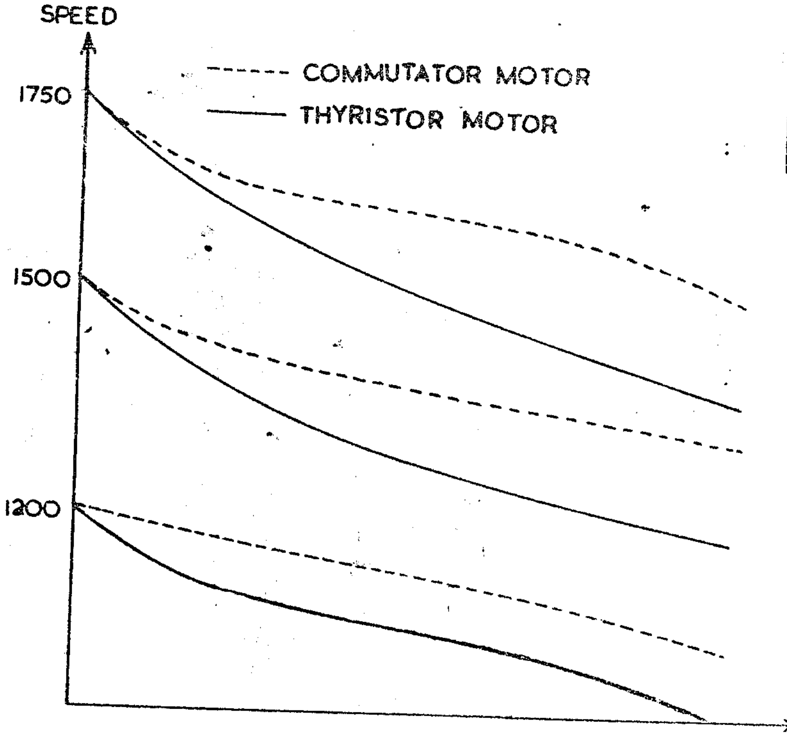
SPEED
1750
1500
1200
COMMUTATOR MOTOR
THYRISTOR MOTOR
TORQUE

Fig. 2

Performance of the Experimental Motor[7] No provision was made for forced commutation and since switching could occur at any instant in the cycle, short periods of rotor-transformer line-to-line short circuit could take place. Nevertheless, operation in both sub-synchronous and super-synchronous regions has been proved to be possible. A 2-kVA Generalised Laboratory Machine was used so that a direct comparison of performance with both a static and with a rotating commutator could be made. The speed/torque curves of Fig.2 show the speed regulation to be rather greater with the staticcommutator, a feature due primarily to the additional rotor impedance required to limit the short-circuit current. This deficiency in the commutating arrangements was also responsible probably for a low-frequency oscillation which developed at about 2/3 of synchronous speed. The no-load speed was readily varied over a range of 25% to 130% of synchronous speed by varying the magnitude of the transformer voltage. It was possible to run smoothly through synchronous speed and in general, the performance was better in the super-synchronous region because of the higher switching frequency.

Simulation and Analysis. Having proved the practical feasibility of the motor, the next step was to consider improvements to the logic and control circuits. To make an appraisal of the various possible alternatives, analogue and digital computer simulations of the machine/thyristor system have been undertaken. The analogue computer has the advantage that the effect of various parameter changes can quickly be examined and recorded. Further, in implementing the logic for controlling the system in a different manner, this becomes available for application to the practical system itself. The digital simulation is more precise, within the limits of parameter accuracy. It also provides a cross-checking facility and in most instances it is much easier to modify, to accommodate any system changes.

The simulations are based on the method of solving the set of generalised performance equations for a symmetrical induction machine as given by Krause and Thomas[8], under the constraints imposed by the static commutator. The equations were written in per-unit form and of the three common choices of reference frame, the one attached to the rotor was chosen since the switching operations were conducted in this circuit. The analogue model was controlled in the rotor circuit using the parallel-logic facilities of a modern analogue computer. For the digital model, the same equations are solved by the Runge-Kutta method, the control conditions being imposed by simple logical statements. A complete investigation of steady-state and transient performance is possible using either simulation.

Progressing from the simplest theoretical system, comparison of the following alternative schemes forms the objective of the investigation:

(1) Stator-fed motor with sinusoidal injected secondary voltage. This corresponds to the well-tried method of slip-power control using rotating frequency changers. Any new scheme, even with its advantage of using static equipment, must have a performance similar to this motor if it is to be commercially viable.

(2) Stator-fed motor with thyristor circuits as in Fig.1, using ideal switching, i.e. assuming perfect, forced commutation and zero source-impedance. Such a scheme can be approached with improvements in the ratings of gate-controlled switches and power transistors, or with thyristors, having auxiliary forced-commutation circuits.

(3) Circuit as for Fig.1, using natural commutation, but including inhibiting logic to prevent thyristor firing until the possibility of line-to-line short circuit is cleared. This is the simplest practical modification to the present motor which would remove the short-circuit loss.

(4) As for (3) but without the thyristor inhibit circuit; i.e. as in the experimental motor, to verify the simulations against the actual measured performance.
(5) Further modifications to replace the existing variable-ratio transformer with a static voltage control scheme and hence make a self-contained adjustable-speed machine.

Results and Comments. A full comparison has been made between (1), which is the general standard of reference, and the arrangement detailed under (2). In spite of the relatively coarse switching, corresponding to 3 segments per pole pair, the loss of performance for (2) is not considerable. The speed regulation with load and the speed variation with injected voltage (based on the slip-frequency component of the switched-voltage waveform for (2)), are virtually the same. An interesting feature here is the necessity for phase shifting the ideal switching instants by 60° from those corresponding to in-phase relationships between supply and injected voltages. This confirms the Fourier analysis of the switched waveform, which, whatever the value of slip, always gives a displacement of 60° between the voltage applied to the static commutator and the slip-frequency component of the output.

With regard to speed pulsation, this was negligible, though the high-frequency torque pulsations increased with slip value; being within ± 10% at full load, up to slips of about ± 1/3; (2/1 speed range). The corresponding increase in copper loss is 11% for the rotor circuit and 6% for the stator winding, the current harmonics being considerably attenuated by the machine reactance. It should be pointed out here, that all thyristor controlled motors exhibit these additional losses and pulsations with varying orders of magnitude. The digital simulation permitted a simple modification to investigate a 6-phase, (6 segment-per-pole-pair) switching arrangement and this showed a reduction to ± 3% for the torque pulsation and a correspondingly lower copper loss.

The motor power factor is slightly worse for (2), though this can be controlled by phase shifting of the switching instants. There is no significant difference in the transient run-up time or in the peak currents during this time nor in the transients following sudden load changes.

Although the results are not yet complete for the arrangements specified under (3) and (4), investigations are proceeding. These will include the source impedances on the rotor side and the actual functional behaviour of the thyristors in controlled and unrestrained commutation conditions.

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