VOLTAGE CONTROL OF A PERMANENT-MAGNET GENERATOR

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ABSTRACT

A simple phase-controlled thyristor circuit is described for deriving an adjustable, fixed-voltage dc output from a permanent-magnet alternator. A practical example is described and test results are presented.

INTRODUCTION

The use of permanent magnets for the excitation of small generators brings benefits in terms of reduced weight, size and cost, particularly where the new rare-earth materials are employed. Unfortunately, the use of permanent-magnet excitation precludes excitation control. Consequently, as load is applied, the output voltage falls. The load must be fed via some form of electronic power conditioning if its supply voltage is to be maintained constant.

Where a fixed-voltage dc supply is required, the machine's ac output is rectified to produce dc and voltage may be controlled by phase control of the rectifiers. To reduce the amplitude of the ripple component of the dc output voltage, the generator should produce a high frequency and provide a large number of phases.

This paper describes an eleven-phase system based on the machine "Torus" developed at UMIST. The generator and its operation using an uncontrolled bridge rectifier has been described in earlier papers (1,2,3).

A PRACTICAL EXAMPLE

Generator Arrangement

Torus is an axial-flux machine with a polyphase, slotless, toroidal stator mounted between two rotor discs which carry the permanent magnets. The layout is shown in Fig. 1. The effective airgap is large because of the slotless stator winding so the

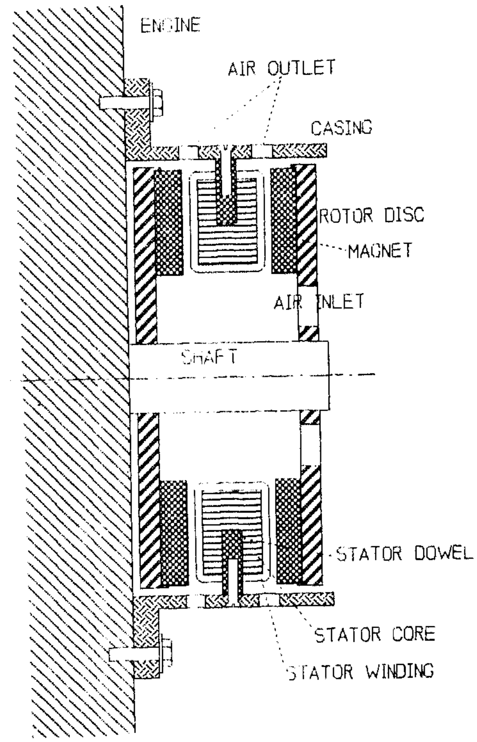

FIGURE 1 GENERAL ARRANGEMENT OF TORUS

low, particularly if the pole number is high. Nevertheless, the machine impedance is significant and the voltage variation with load is unacceptable for most applications. The experimental machine is mounted on a foot/flange induction motor which acts as the prime mover for test purposes. The stator winding comprises 22 coils which pass through the centre of the toroidal core. Any current passing through a single coil would cause a very high flux to pass around the core. Therefore the coils are connected in series pairs to form the 11 phases.

The rotor discs each have six poles and so the basic output frequency is 150 Hz at the nominal speed of 3000 rpm. The ripple frequency at the output of the 11-phase bridge rectifier is 3300 Hz. The high frequency makes it possible to filter the ripple with small passive components. The emf waveform is trapezoidal as shown in Fig. 2. On no-load, the ripple voltage can be very small since the flat sections merge resistive effects generate considerable additional ripple.

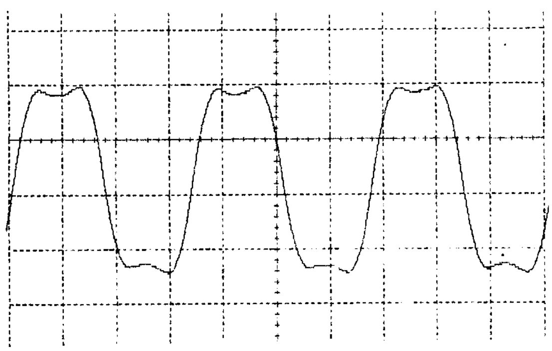

FIGURE 2 WAVEFORM OF EMF

The control circuit

The output dc voltage is controlled using the half-controlled thyristor bridge shown in Fig. 3. The capacitor filters the output ripple voltage and the small permanent resistive load is included to ensure that the thyristors conduct properly under very light load conditions. The main diodes and thyristors are mounted on the machine casing which forms a convenient and well-ventilated heat sink.

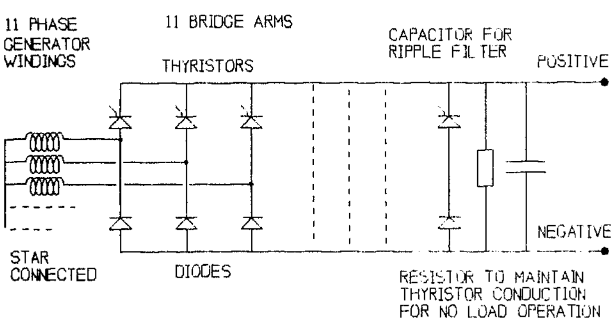

FIGURE 3 THYRISTOR BRIDGE CIRCUIT

Each phase has a separate trigger circuit of the type shown in Fig. 4. Isolation is provided by means of an opto-isolator.

Each trigger circuit is supplied with timing information from the phase being switched and with a control signal common to all the trigger circuits. The control signal is generated by a proportional plus integral (PI) controller from the output of the bridge and so the output voltage is maintained constant. As the load current increases, the controller, sensing the fall, reduces the level sent to the trigger cicuits. This causes the trigger circuits to switch earlier in the cycle and so the conduction period of the thyristors increases to restore the output voltage to the desired value. The PI controller circuit is shown in Fig. 5.

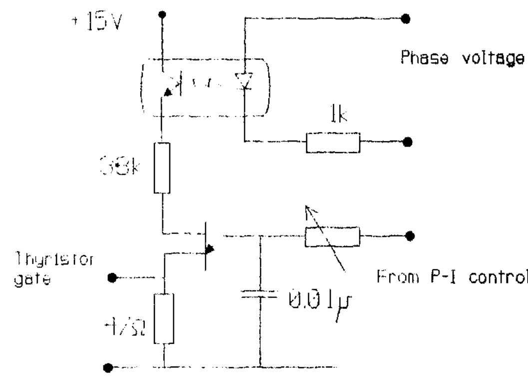

FIGURE 4 THYRISTOR TRIGGER CIRCUIT

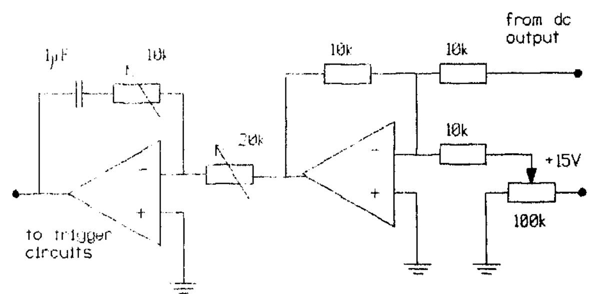

FIGURE 5 P-I VOLTAGE CONTROL CIRCUIT

PERFORMANCE PREDICTION

The rectifier-loaded operation of synchronous machines has been analysed by Bonwick and Jones (Ref. 4). However, the unusual multiple phase arrangement and the permanent-magnet excitation which generates a trapezoidal rather than sinusoidal emf demands a new analysis summarised below and adapted to phase- controlled operation of the rectifiers.

Analytical procedure

The following simple analysis has been developed for design purposes, phase resistances and self inductances are taken into account, but mutual inductances between phases are ignored.

1. Initially, the output voltage from the

2. The difference between the phase induced emf and the output voltage is then applied to the diode and the series resistance and inductance of the phase winding to obtain the phase current.

3. The output current is calculated from the combination of a number of identical components shifted in phase. The mean and ripple components are both obtained. The ripple current so obtained corresponds to the case where the output is loaded by a very large capacitor or a battery presenting a short circuit to ac currents.

4. The ripple voltage appearing across the actual load is calculated using the model shown in Fig. 6. The number of parallel phases is taken to be the average of the number of phases simultaneously conducting into each dc line. The value of the effective ripple emf is determined by the ripple current obtained at stage 3 and the impedance of the parallel phases.

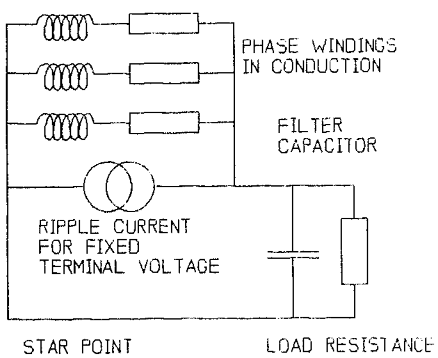

FIGURE 6 MODEL FOR CALCULATING RIPPLE

Phase current

The phase current is assumed to be initially zero. When the phase emf exceeds the terminal voltage, the current begins to rise according to:

$$E - V = I.R + L.\ dI/dt \qquad (1)$$

Now, since the emf has a trapezoidal waveform with maximum value E_{max}, the phase current rises on an exponential curve towards a value, $I_1 = (E_{max}-V)/R$. After t sec, the phase current reaches

$$I = I_1.\ \{ 1 - \exp(-tR/L) \} \quad (2)$$

emf, the emf falls linearly and the current falls to zero. If, as in the present case, the inductance dominates, the phase current rises along an approximately linear ramp to a maximum value

$$I_{max} = t\ .\ (E_{max}-V)/L \quad (3)$$

and returns to zero along a parabola as seen in Fig. 7 which shows the phase current in the experimental machine operating with a simple diode bridge and therefore conducting for the maximum possible period. The additional minor dips and rises are caused by mutual coupling with the other phases.

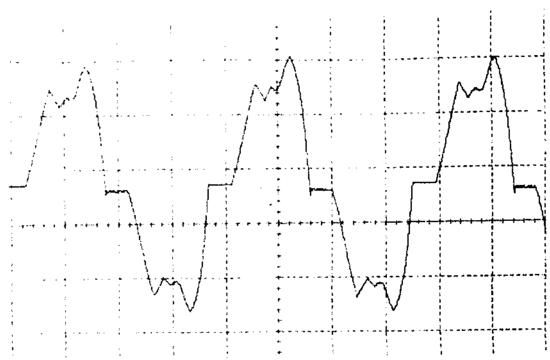

FIGURE 7 EXPERIMENTAL MACHINE PHASE CURRENT

The mean current supplied by each phase is approximately

$$I_{mean} = I_{max}\ t/T \qquad (4)$$

where T is the duration of a half cycle. Since I_{max} is determined by the conduction period t, it follows that the phase contributes to the output a current which varies as the square of the conduction period, and if all m phases conduct equally, the output current is given approximately by

Additional ripple is caused by the inevitable differences between poles between phases and in particular between the trigger circuits. These components of the ripple are at lower frequency and are more difficult to remove by filtering.

$$I_{out} = m\ (E_{max}-V)/L\ .\ t^2/T \quad (4)$$

If V is indeed fixed as when charging a battery for example, then variation of the conduction period by means of delaying the current to be controlled.

Alternatively, with a resistive load, the terminal mean voltage will be determined by the load resistance, R_L, and the output current. Substituting into equation 4 yeilds

$$V = E_{max} . t^2/\{t^2+LT/mR_L\} \quad (5)$$

This is an increasing function of t, therefore the conduction period may be used to control output voltage.

TEST RESULTS

With a simple uncontrolled 11-phase bridge rectifier, the variation of output voltage with load is from 32.4 V on no-load down to 22.5 V at the nominal full-load current of 90 A. With the controlled rectifier installed, the variation becomes barely detectable for load current up to a maximum value determined by the demanded voltage. For example, with a demanded output of 24 V, the maximum available current would be around 75 A, at which point the conduction period is equal to the duration of the flat top of the trapezoidal wave. Any increase beyond this value would cause the voltage to fall below the demanded value.

In practice the maximum current available is rather less than this ideal value because the thyristor can be switched off by induced emf from other phases. Also, the forward voltage drop of a thyristor is greater than that of a simple rectifier. For 24 V output, the maximum current is found to be approximately 45 A.

The ripple voltage superimposed on the dc voltage depends on the capacitor value employed and the operating condition. The 3300 Hz ripple voltage is determined by the firing angle of the thyristors. As the load current increases, the conduction period increases and the ripple voltage reduces. The following values corresponding to 24 V dc operation illustrate the effect of load current.

Load Current (A)	Pk-Pk Ripple (V)
25	2.4
30	2.0
35	1.8
40	1.2
45	1.0

Figure 8 shows a typical ripple voltage waveform for moderate load conditions.

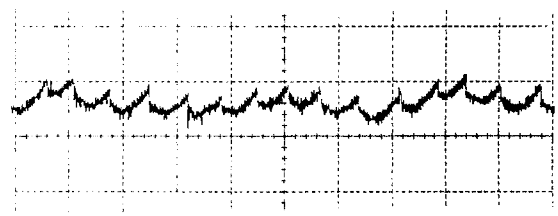

FIGURE 8 OUTPUT VOLTAGE WAVEFORM

CONCLUSION

The use of a multi-phase thyristor bridge with phase angle control for the voltage regulation of a permanent-magnet generator has been demonstrated. A simple P-I controller allows the voltage to be held within narrow limits as load varies. Current waveforms are generally as expected from simple analysis, however a model including mutual inductances is required to account for all the details of the wave.

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