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DEVELOPMENT OF A IGBT INVERTER DRIVEN AXIAL-FLUX PM SYNCHRONOUS MOTOR DRIVE

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Abstract. Available high-field permanent magnets have opened opportunities for axial-flux PM machines, which can find their advantageous application in low-speed high-torque electrical drives. Applications of axial-flux PM motor drives prompt new solutions in designing both the machine and the power converter. In particular, this the paper discusses innovative design criteria which lead to a machine of high efficiency and reduced costs by maximizing the torque/weight ratio. Furthermore, a novel power converter topology is illustrated, considering machine supply requirements which allow an improvement in the drive performance. Finally, the paper presents the characteristics of a low-speed high-torque motor drive, which has been constructed using an IGBT power converter together with a 1.3 kW axial-flux machine having Ne-Fe-B permanent magnets and slotless stator winding wound in a toroidal fashion.

Keywords. IGBT Inverter, Axial-flux PM motor drives.

INTRODUCTION

Today's available high-field permanent magnets, such as Ne-Fe-B, can produce reasonably high flux densities even with quite large air-gaps, and this fact has opened up opportunities for axial-flux PM synchronous machines. Besides low copper losses due to the lack of rotor current, such a kind of machine allows the arrangement of a slotless-designed stator winding, which has the advantage of a relatively short end-winding resulting in a further reduction of losses and thereby increased efficiency [1,2]. Hence, the compactness of the overall mechanical arrangement together with significant improvements of the electrical performaces suggest that axial-flux PM machines can find their advantageous application in electrical drives having requirements of low speed and relatively high torque, such as in the case of systems driving the wheels of electrical vehicles or gearless wind power plants.

Using axial-flux PM motors in electrical drives prompts a number of problems which concern the design of both the machine and the power converter required for supplying the machine. For low-speed high-torque applications the motor is characterized by a high number of poles, and designing the machine with a torque/weight ratio as high as possible is mandatory in order to increase the machine power density, as well as to reduce the costs. Furthermore, the machine structure involves, at any given time instant, conductors of all the phases under the action of one permanent magnet. Hence, the overall drive performance can be improved greatly if the same value of current is allowed to flow simultaneously into each phase, which fact results in supplying the machine by a three-phase system of square-wave current waveforms. However, such an approach involves a large 3rd harmonic current in the neutral, so that taking out an increased and ripple-free torque from the machine requires a suitable configuration of the power converter.

In the development of axial-flux motor drives of high performances and reduced cost this paper is concerned with the problems outlined above. The machine design is investigated in depth, and criteria are given in order to maximize both torque/weight ratio and efficiency. Furthermore, requirements of the machine supply are discussed, and a new converter topology is illustrated. Finally, the paper presents the design characteristics of a prototype, which has been built up using a IGBT power converter together with a 1.3 kW axial-flux machine having Ne-Fe-B permanent magnets and slotless stator core supporting a three-phase toroidal winding.

MACHINE CONFIGURATION

Axial-flux machines differ substantially from conventional electrical machines because of the direction of the flux into the air-gap, which is in this case along the machine mechanical axis. Due to the high flux density exhibited by Nd-Fe-B permanent magnets, the machine stator structure can be realized simply by means of a slotless tape-wound toroidal core which carries coils connected in a three-phase winding fashion [1,2]. Figure 1 shows the basic configuration of the axial-flux PM machine considered throughout this paper. The stator structure compounds a tape-wound magnetic core carrying a toroidal three-phase winding, whereas the two rotors are realized by means of discs of steel rigidly connected to the mechanical shaft. The stator core is positioned between the two rotors, and each rotor disc carries axially-magnetised Nd-Fe-B permanent magnets which are mounted radially on the surfaces facing the stator structure.

Since the two rotating discs act naturally as fans, the rotor structure can be designed suitably in order to remove the machine heating due to copper and iron stator losses. Hence, this machine configuration permits an exploitation of active materials higher than in conventional machines. The task related to heat removal can be achieved by means of holes positioned near the mechanical shaft, so that a flow of air is sustained radially through the machine air-gap and cooling is provided thereby.

The flux path into the machine can be represented as indicated schematically in Figure 2a, where only two poles of the machine are considered. As is shown, the magnets drive flux from the rotors across the two resulting annular air-gaps into the stator; the flux then travels circumferentially along the stator core, back across the air-gaps and PMs, and then through the back iron. Figure 2b shows computer traces resulting from a F.E.M. analysis carried out on an axial-flux machine having the configuration described above. Because of the machine geometrical symmetry only a machine pole is represented. As it appears, the air-gap flux density can be assumed as a constant value along the PM width and equal to zero in the zone between the two contiguous PMs. Hence, the open-circuit terminal voltage can be derived easily from standard methods, and the result is shown in Figure 2c.

Since the stator winding is wound in a toroidal fashion and two working surfaces of the core are used, this machine configuration allows a higher percentage of copper that produces torque compared with conventional machines having winding placed in slots. The current flowing through each coil interacts with the flux generated by the magnets producing a force tangential to the machine axis. As a consequence, the average electromagnetic torque resulting from the overall contribution of all the forces which act on the two working surfaces of the toroidal core can be expressed

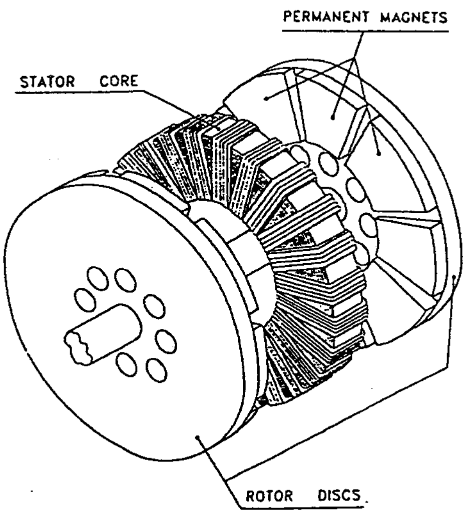


Figure 1. Axial-Flux PM Machine basic configuration.

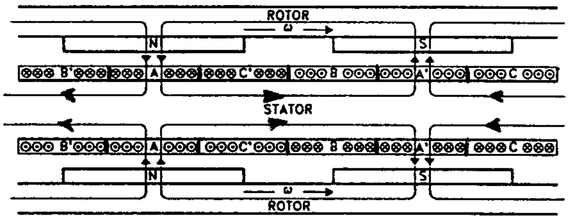


Figure 2a. Flux path into an Axial-Flux Machine.

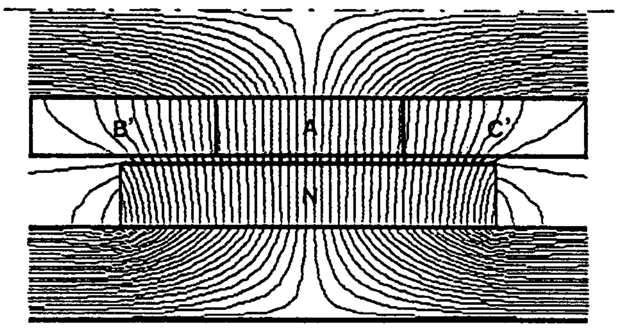


Figure 2b. F.E.M. analysis results.

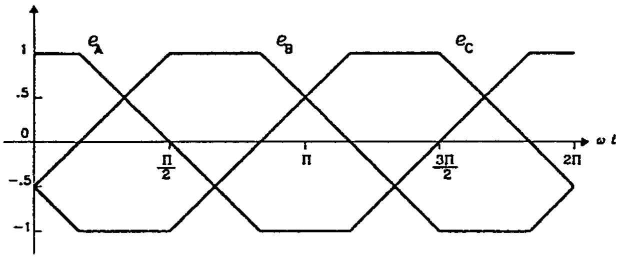


Figure 2c. Back E.M.F. waveform.

as:

$$T = 2\pi K_p B J R_i (R_o^2 - R_i^2) \qquad (1)$$

where B is the average value of the flux density in the air-gap, R_i and R_o are the stator core inner and outer radius respectively, K_p is the percentage of the pole pitch occupied by permanent magnets, and J is the current linear density of the stator winding.

MACHINE DESIGN CRITERIA

Considering the machine geometrical parameters as variables, the machine fundamental equations can be handled in order to investigate the machine design and issue criteria which are related to optimizing the machine characteristics. Equation (1) written above gives the average output torque as a function of both the current linear density J and the geometrical characteristics. However, considering the thermal balance related to an overtemperature ΔT of the stator winding with respect to the environment temperature yields an expression of the current linear density which is a function of the machine geometrical characteristics. As a result, the machine torque can be expressed only as a function of the design variables R_o and R_i [3].

Above result indicates that several pairs of R_o and R_i values satisfy equation (1) for a given value of the electromagnetic torque. Hence, it is possible to define a criterion which involves a constraint between the inner and outer radii in order to optimize the machine design. For a fixed value of the outer radius R_o the machine design characteristics can be evaluated by introducing the variable $K_r = R_i/R_o$. As a consequence, the machine design optimization can be carried out considering K_r ranging from 0 to 1, whereas the machine outer radius value is considered as the linear dimension which characterizes the machine power rating. In the following, for analysis purposes, an unitary value of R_o is assumed (i.e. $R_o = 1$ m). Such a fact leads to absolute values of the machine characteristics which are related closely to this particular value of the machine outer radius. However, apart from the numerical values resulting from such a specific machine design, the overall approach yields general purpose results, since it can be demonstrated that the assumption of a particular value for R_o does not affect the analysis results in terms of optimum value of K_r.

Significant machine characteristics can be evaluated thereby as a function of the ratio K_r. As an example, analysis results show that the output torque can be according with the machine pair of poles [3]. Considering the weight of the machine active materials (iron and copper) as a function of the ratio K_r permits to evaluate the specific torque T_{sp} which is given by the ratio between the output torque and the overall machine weight. Such a parameter is a particularly relevant concern for the machine design, since it allows to reduce the machine costs for a given value of the machine torque. Figure 3 reports curves of the specific torque T_{sp} as a function of the ratio K_r, considering machines having a different number p of pair of poles. It can be noted that the value of K_r which maximizes the specific torque is quite different from the K_r value indicated above for the maximum torque. As a consequence, maximizing either the torque or the specific torque will result in a different machine design, so that the more suitable design criterium should be chosen considering the application the machine is designed for.

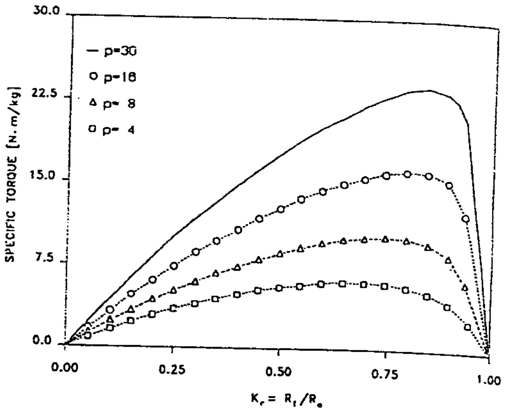


Figure 3. Specific torque vs. K_r characteristics (p: machine pair of poles).

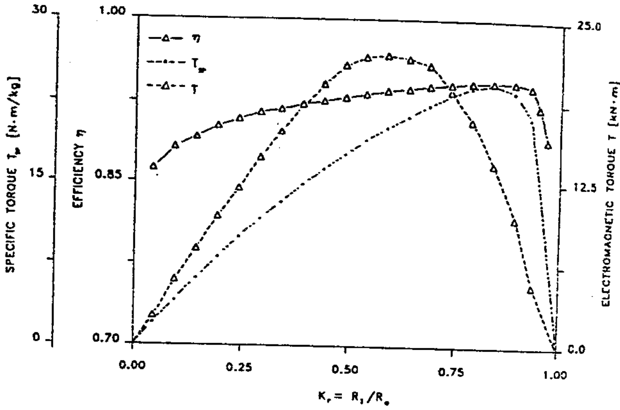


Figure 4. Design characteristics vs. K_r for axial-flux machines having 30 pairs of poles.

Finally, evaluating the losses from the machine geometrical characteristics allows to calculate the efficiency expected from the machine [3]. The results show that for machines having low number of poles the specific torque. On the other hand, design analysis for machines having a high number of poles indicates that a maximum of efficiency does exist, and it corresponds to a K_r value which is close to that one which maximizes the specific torque. In order to compare significant characteristics influenced by the machine design, Figure 4 reports torque, specific torque and efficiency as functions of K_r for a machine having 30 pair of poles. In this case it clearly appears that designing the machine for the maximum torque adversely affects both specific torque and efficiency. Hence, a machine design which aims to achieve saving of active materials and reduced losses should take into account a value of K_r which corresponds to maximizing both the specific torque and the efficiency. By this approach the design analysis results indicate that the optimum value of K_r has to be chosen into the range between 0.65 and 0.85, depending the choice on the machine pairs of poles.

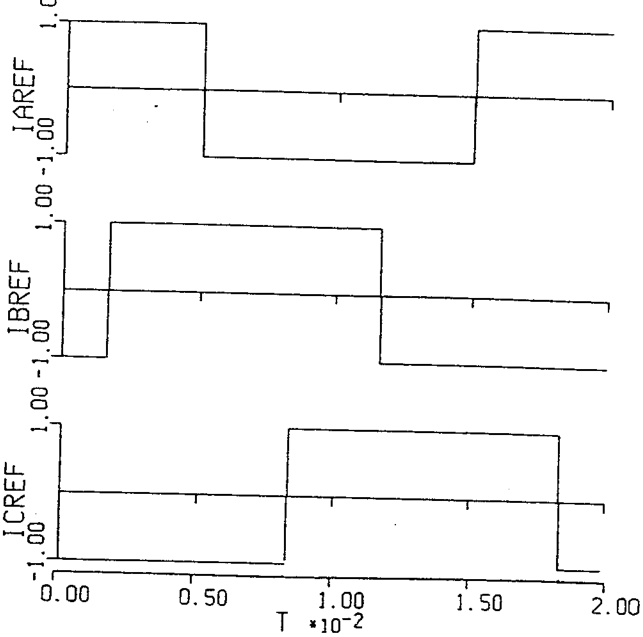
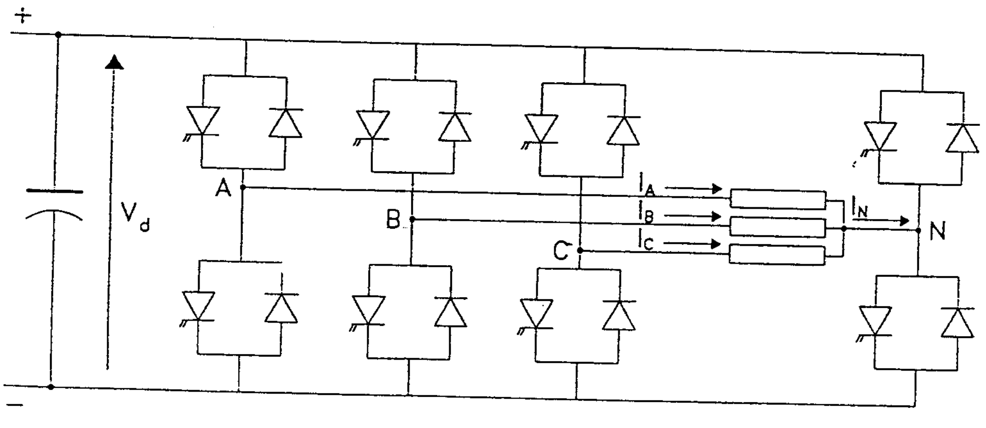


Figure 5. Three-phase square-wave current waveform required for supplying an axial-flux machine.

INVERTER SUPPLY ARRANGEMENT

Since the product of current and back emf is directly related to the torque, it can be demonstrated easily that considering the machine back emf waveform indicated in Figure 2c a ripple-free output torque is achieved if the machine is fed by the three-phase square-wave current waveform shown in Figure 5. However, this machine supply involves a large 3rd harmonic current which, thereby, has to be allowed to flow in the neutral resulting from a star connection of the machine phases. Hence, such an approach requires that the machine neutral is connected to the inverter d.c. link, and, furthermore, the average value of the neutral voltage has to be kept at half the value of the d.c. link voltage.

From above considerations arises the PWM converter topology shown in Figure 6. Such a new configuration results from standard layout of a three-phase voltage source inverter by adding a fourth branch devoted to control suitably the neutral voltage. Generally speaking, the inverter branches connected to the machine input terminals can be operated in either a square-wave or PWM mode, whereas the fourth branch acts to modulate the neutral voltage so that the required average value is achieved. In order to reduce the current ripple resulting from the neutral voltage modulation, the switching frequency of the neutral-connected branch has to be chosen several times higher than the inverter output frequency. Considering the converter modes of operation, it appears that adding the fourth branch splits up each mode related to operation of a conventional square-wave VSI or PWM-VSI into two extra modes, which are due to connecting the neutral alternately to the positive and negative bus of



gure 6. Novel PWM inverter topology considering load neutral switching.

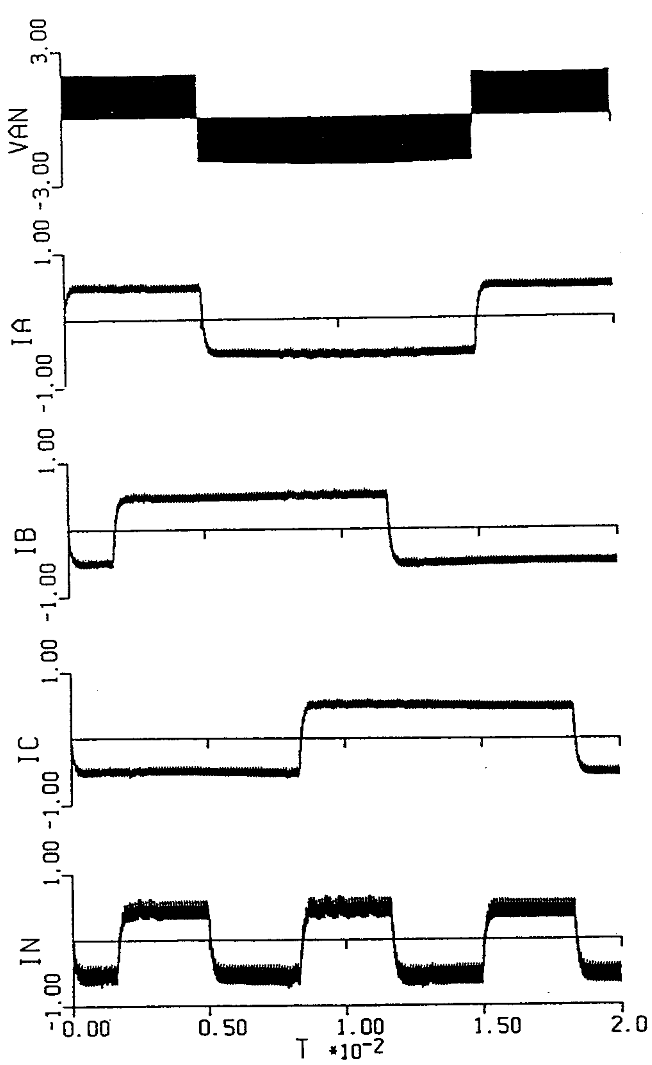


Figure 7. Computer simulation of the PWM inverter modes of operation (VAN: phase voltage; IA, IB, IC: phase currents; IN: neutral current).

the d.c. link.

The new converter topology has been investigated by simulating the inverter modes of operation on a digital computer. As an example, Figure 7 reports simulation results related to the converter supplying a three-phase star-connected R, L load, as indicated in previous Figure 6. The waveforms of the output phase voltage and the output currents are shown, as well as the current flowing in the neutral. In this case the inverter switches connected to the load input terminals are operated as in a conventional current-regulated PWM-VSI, being the reference value of the peak current set at 0.5 p.u.. The inverter output frequency is 50 Hz, whereas the neutral voltage is modulated by a switching frequency of 30 kHz. It can be noted that the current waveforms include a current ripple at the modulation frequency, which, however, is expected to have no effect on the machine output torque in the case of converter feeding an axial-flux PM motor. The amplitude of such a current ripple depends on both the load inductance value and the switching frequency of the neutral-connected branch. For a given machine an acceptable current ripple amplitude can be achieved by operating the converter at a suitable value of the switching frequency.

Using the converter topology illustrated above permits improvements in the performances of an axial-flux PM motor, since it leads to a machine torque of increased value and ripple-free. Because of the machine back emf waveform, the converter has to be operated in a PWM mode in order to regulate suitably the average value of the converter output voltage and force the required average current thereby into the machine phases. In this case the same switching frequency is used for all the four inverter branches, and a PWM strategy considering a constant-switching frequency current control can be implemented easily. As a consequence, machine speed and torque control can be operated as for conventional synchronous servomotor drives, by sensing the rotor position and regulating suitably the inverter output in terms of frequency and peak current value.

PROTOTYPE CHARACTERISTICS

Technical solutions discussed above were taken into account to design and build up a prototype of an axial-flux motor drive which combines a IGBT PWM inverter driving a 1.3 kW axial-flux PM machine. Table I reports the main characteristics of the machine prototype in terms of electrical and geometrical parameters. According with the results of the design analysis presented above, the machine prototype was designed considering the value of K_r which maximizes the specific torque (i.e. $K_r = 0.75$). The resulting value of the specific torque is 3.8 Nm/kg, which actually corresponds to the maximum of the specific torque vs. K_r curve indicated in the preceding Figure 3 for machines having 8 pairs of poles, considering that the value of the specific torque depends also on the square-root of the machine outer radius value. Besides a high specific torque, it can be noted from Table I

TABLE I

Power Rating	1.3	kW
Pairs of Poles	8	
Rated Speed	375	rpm
Electromagnetic Torque	33	Nm
Specific Torque	3.8	Nm/kg
Efficiency	0.83	
Outer Radius	0.12	m
Inner Radius	0.09	m
Rotor Weight	4.3	kg
Stator Weight	2.4	kg
Permanent Magnets Weight	0.95	kg
Stator Winding Weight	0.96	kg

that the machine prototype exhibits reduced overall losses, which fact indicates a good exploitation of the active materials. Photo 1 reports a view of the machine general arrangement during assembling the prototype in laboratory.

For purposes of motor control an INTEL 80C196KC microcontroller and a 5000 count rotary encoder are used, whereas a power converter having the new configuration discussed above was set up using Mitsubishi IGBTs rated 500 V, 25 A. Assembling the overall motor drive is in progress, and experimental results will be presented extensively in a future paper.

CONCLUSIONS

This paper has dealt with the development of axial-flux motor drives which can be used advantageously in applications having requirements of a low-speed and high-torque, such as in the case of systems driving the wheels of electrical vehicles or gearless wind power plants.

Design criteria of axial-flux PM synchronous machines have been illustrated, and the analysis results show that a suitable choice of the machine geometrical parameters permits maximization of either the torque or the specific torque, which fact leads to a different machine design. It has been shown that for a machine structure characterized by a high number of poles the criterion which maximizes the torque/weight ratio permits also achievement of a high machine efficiency.

In order to improve the torque performance of axial-flux PM motor drives, a novel PWM converter topology can be arranged to supply suitably the machine. Such a new converter configuration allows control of the voltage of the neutral resulting from a star connection of the machine phases, so that square-wave current waveforms are allowed to flow and the machine torque ripple is thereby greatly reduced.

Finally, the paper has reported the characteristics of a prototype of axial-flux motor drive, which has been realized building up a 1.3 kW PM machine and an IGBT PWM inverter. It is shown that the machine prototype exhibits a high torque/weight ratio and reduced losses, which fact indicates a good exploitation of the active materials.

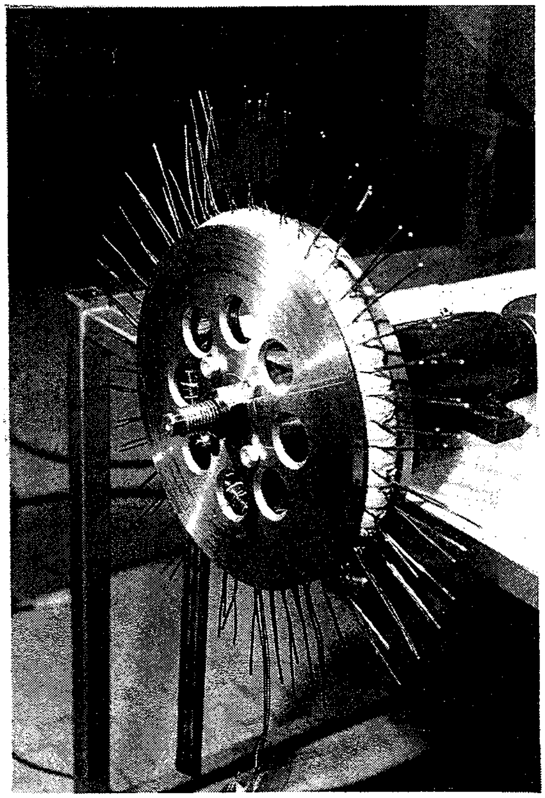


Photo 1. View of the 1.3 kW machine prototype.

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