A BRUSHLESS DC MOTOR FOR VEHICULAR AC/HEATER APPLICATIONS

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SUMMARY

A brushless DC motor is proposed as a potential replacement for DC commutator type motors presently used in almost all automotive applications. A prototype brushless motor has been designed and assembled into the AC blower assembly used on many Ford vehicles in order to evaluate this motor in terms of performance, cost, maintenance, operating problems, size, and weight as compared to the existing commutator motor used in this blower. The new motor operates from the 12-volt vehicle battery through an electronic controller which replaces the lossy resistive controls used on the existing blower system. The new brushless motor is expected to result in the following improvements over the present blower motors:

1. Elimination of the brush-commutator system, which is presently a source of high maintenance and warranty costs on the AC/heaters in vehicles. The motor is maintenance free, except for bearing wear. Data collected by the U.S. Department of Defense for reliability predictions shows that commutator motors have a failure rate of from two to six times that of brushless motors, depending upon operating speed(1).

2. Simpler construction of the brushless machine in which, besides eliminating the brush-commutator of the DC commutator type, a very simple, stationary, solenoidal electrical coil replaces the complex, rotating, armature winding of the commutator machine. No permanent magnets are used in the field.

3. Improved energy efficiency; the electronic control scheme eliminates the energy loss in resistors presently used to control speed.

4. The electrical winding in the brushless motor is not restricted as to shape or material, but can be adapted to suit the economic and technical restrictions of the time. Material can be copper, aluminum, or high conductivity alloys, and constructed from round, square, strip, or braided conductors.

5. The motor is insensitive to temperature variations compared to PM motors.

6. Due to the simple structure of the motor, the overall volume occupied by the blower assembly is reduced about 25%.

7. A damaged or burned out electrical coil can be quickly and simply replaced without the need for replacing any other motor parts.

BACKGROUND

The proposed brushless motor is an adaptation of the disc reluctance (3),(4),(12) machines developed for electric vehicle drives at Ford Motor Company. This development resulted in the assembly and testing of a number of prototype motors and electronic controllers and the issuing of nine U.S. patents on motor configurations, electronic controllers, and position sensors. During this development, it was realized that in order to achieve the high starting torques necessary for traction applications, considerable added cost and complexity had to be built into the electronic controller. However, for low starting torque applications, such as fan and centrifugal pump drives, the electronic circuitry required is relatively simple, in some cases, simpler than that required for the commutator motor. A second feature of the early development which added to the cost and complexity of the disc motor system was the use of an external position sensing device and associated electronics. Reluctance motors are basically synchronous machines requiring that the frequency of the electrical excitation be kept in exact synchronism with the rotor mechanical speed. Subsequent development work has eliminated the need for an external position sensor by using a low signal logic circuit that senses the variation of inductance in the machine itself. A third complicating factor in the traction motor, also related to the high starting torque requirement, is that relatively low starting torque is developed in a single phase machine and there are a fixed number of discrete angular positions on the machine at which zero torque exists. Therefore, it is necessary to use two or three phases or machine sections to insure start-up. This multiple-section technique multiplies the number of sets of power electronic devices required in the electronic controller by the same number. These three features all tended to offset the inherently simple and low-cost construction of the basic, single-phase disc motor. None of these features is necessary for low-power, low starting torque applications such as blower or fan drives, and the best attributes of the disc motor, namely its claim as the most simple configuration of rotating machine known, can be used to the fullest advantage.

Configurations very similar to the Ford disc motor have been used for several years as control type stepper motors (5), and represent one of the cheapest type of stepper presently available. The first small motor application at Ford, developed after the traction motor effort described above, was a centrifugal fuel pump. A picture of the prototype fuel pump is shown in Figure 1. This application brings out another valuable feature of the disc configuration as compared to most other types of electrical motors in which the electrical windings must be located in certain discrete positions and wound according to certain fixed rules; the disc motor rotor and stator can be assembled with an almost infinite variation in geometry. Thus, in the fuel pump, the motor rotor is also the active element of the pump and the resulting package is smaller, lighter, has far fewer component parts, and has greater fuel flow than motor-driven centrifugal fuel pumps.

BRUSHLESS MOTOR DESCRIPTION

The Ford disc motor belongs in the class of motors known as variable reluctance motors, or, simply, reluctance motors. These are synchronous type motors normally operated from a fixed frequency electrical source, and are one of the more prolific motor types since most electric clock, timing, and turntable motors are of this type. In recent years, a polyphase version of the clock motor has been developed in larger power sizes and, with the advent of high-power solid state switching devices, has supplanted many squirrel cage induction motor drives, mainly in the textile industry. Reluctance motors are also sometimes classified as "singly excited" motors, since they require only one electrical winding and have no field winding or permanent magnet excitation. The reluctance machine rotor is merely a piece of soft iron, usually laminated, having saliencies or pole projections rather than a smooth cylindrical shape. There are no brushes, commutators, slip rings, or rotating electrical windings, the primary sources of most electrical machine maintenan

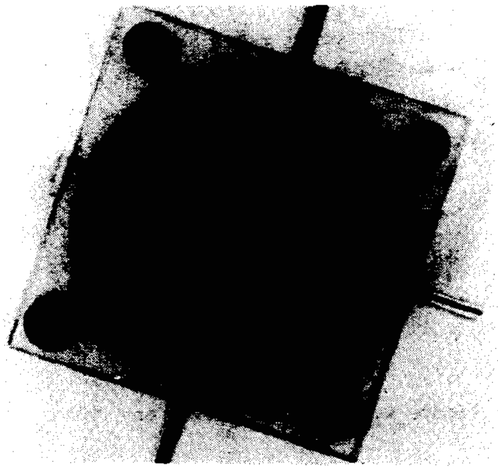


Figure 1. Prototype Fuel Pump

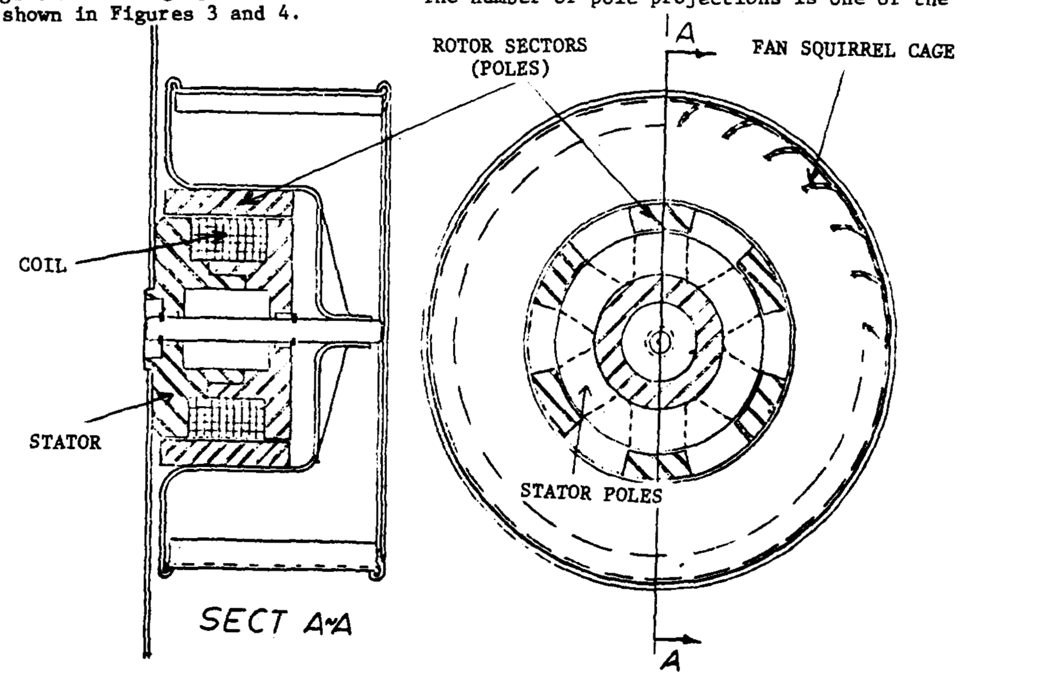
The disc motor is similar to the conventional reluctance machine except for its electrical winding which is designed to permit operation from a pulsed DC source rather than from a fixed frequency AC source. This greatly simplifies the winding construction which, in the disc motor,is merely a solenoidal coil rather than the complex windings wound in slots according to fixed rules as required by the conventional reluctance motors. This also considerably frees the shape of the stationary magnetic member of the disc machine (stator), and permits the functional roles of rotating and stationary members to be interchanged almost at will. The motors used in the traction and fuel pump applications are of the axial air gap configuration in which both the rotating and stationary members take on disc shapes. The blower motor is a radial air gap configuration and has a cylindrical shape more like a conventional motor. A schematic representation of the blower motor is shown in Figure 2. Photographs of the prototype blower motor are shown in Figures 3 and 4.

Motor action is due to the attraction between the poles or saliencies on the rotor with those on the stator when magnetically excited. The excitation is applied when the two sets of poles are unaligned and must be turned off slightly before they are fully aligned or the rotor would become locked into this aligned position, preventing further rotation as in a relay or stepper motor. The function of the controller is to turn the exciting current, which magnetizes the motor, on and off at prescribed intervals depending upon the relative positions of stator and rotor poles. To achieve good power and torque characteristics from a disc motor, these intervals must be relatively short and at a rapid repetition rate, one reason why such a motor would not be feasible without the use of modern solid state switching devices, thyristors and transistors. Although not significant in the blower application, the disc motor can be made to operate as an electrical generator by a small change in the timing of the exciting current pulses. Further descriptions of the disc motor and controllers are given in References (2)-(4).

In the blower motor configuration (Figures 2-4), the inner member is the stationary member and contains the excitation winding which is wrapped around its middle section between the pole projections on each end. The stator is formed in two tightly fitting sections which can be separated axially for insertion of the bobbin containing the solenoidal coil. The stator is fixed at one end to an aluminum plate which is mounted on the vehicle or other supporting structure. The motor rotor is merely six sets of laminated bars of rectangular cross section evenly spaced and bonded to the squirrel cage member of the blower. These bars are of approximately the same cross section as each of the six pole projections on each end of the stator, as is the annular cross section of the laminated member inside of the coil which is the magnetic - as well as physical - connection between the two stator ends. These three soft iron sections - rotor bars, stator and pole pieces, and inner annular connecting member - along with the air gaps at each end of the stator between the pole projections and rotor bars form a complete magnetic circuit through and around the solenoid when in the aligned position (that is, when the rotor bars are exactly opposite the pole projections).

The number of pole projections is one of the

Figure 2. Cross-sectional Views of Brushless Motor Blower



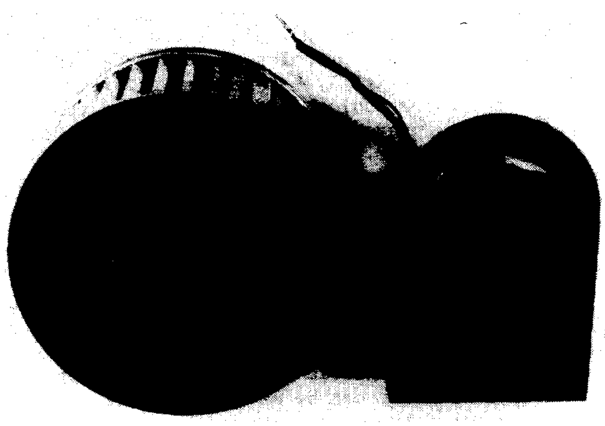


Figure 3. Dissassembled Blower Motor; Stator Circuit and Solenoidal Coil are on Right

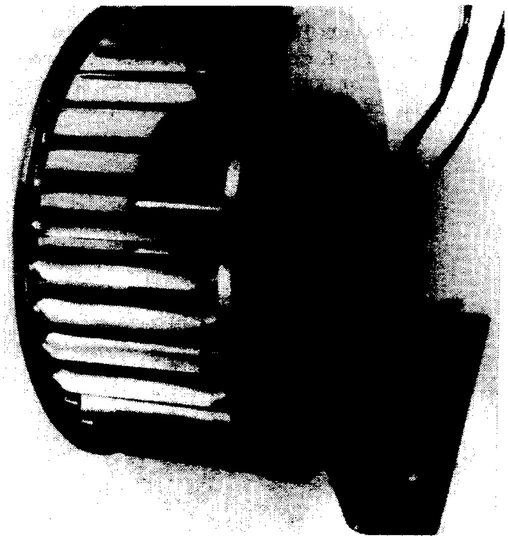


Figure 4. Assembled Blower and Motor

design parameters of this type of motor and plays a role quite analogous to that of the poles on conventional machines, even though this configuration is often called "homopolar" due to the axial flow of magnetic flux. Up to a certain number, the motor output generally increases with increasing number of poles, but so does the cost of magnetic parts, the magnetic leakage, and the required dynamic performance of the electronic control. At some number of poles, the leakage becomes sufficient to start decreasing the motor power output. This number is generally smaller in machines of smaller physical size and is also smaller for the radial air gap designs than for axial designs. The prototype blower motor has six poles.

The magnetic members can be constructed of laminated silicon or nickel alloy steel as used in transformers and small motors, powdered iron, or, possibly, solid carbon steel such as AISI type C1020. The latter should result in the lowest material and assembly costs but will increase the eddy current losses in the magnetic circuit and deteriorate the reluctance ratio of the machine. Laminations of very simple shape are possible (which is not true of the axial air gap configurations), and this technique should result in very good magnetic characteristics, low eddy current losses, and reasonable costs. Powdered iron members ultimately may prove lower in cost, but some magnetic characteristics will be sacrificed.

The exciting solenoid can be constructed of almost any standard or unconventional type of conductor. Litz wire (conductor formed from braided and transposed wires of small cross section) and flat aluminum strip were both applied successfully on the larger traction disc motors. Ohmic losses are generally higher in a disc motor than in a DC motor of similar rating due to the high current pulses required to excite the former and in machines of larger power rating, some form of coil cooling is often required. This is not expected to be necessary in the blower motor.

COMPARISON OF THE BRUSHLESS MOTOR WITH EXISTING MOTOR

The prototype brushless blower motor and the DC commutator motor used on current automotive AC blowers are compared in terms of several important parameters:

Parts Count:

Table I is a summary of the parts required for each type of motor obtained by counting the parts on two disassembled units. The brushless machine is constructed of less than half the parts of the commutator machine.

Weight and Size:

Table I also shows that the brushless machine is lighter and occupies a smaller volume than the commutator machine.

Manufacturing Cost:

An accurate evaluation of the cost of manufacture for the brushless machine has not been made at this time. On the basis of weight alone, one could expect that the brushless machine should be approximately 46/53 = 87% of the assembly cost of the commutator machine, since the materials in both machines, with the exception of the permanent magnets, are similar. However, the method of motor assembly is entirely different for the two machines, and this difference should result in a considerable further cost advantage for the brushless machine. The coil winding machinery required to wind the slotted armature of the commutator motor is high in initial and maintenance costs, has a high percentage of down time, and the wound armatures which it turns out have a relatively high rejection rate. By contrast, the winding on the brushless machine can be assembled by much less complex, more reliable machinery of the type used to assemble the lowest cost electrical components, such as electronic transformers, inductors, relays, solenoids, etc. Secondly, the assembly of the commutator and electrically connecting each bar to an armature coil are additional complex assembly processes which are completely eliminated in the brushless machine assembly. A third major difference in the assembly of the two types of machines is that the brushless design requires no field permanent magnets. The effect of this change upon the assembly costs is difficult to evaluate, but the elimination of the hard, brittle ferrite material should result in some savings; also, the soft iron sectors should result in a materials cost savings at least over the arc-shaped ferrite magnets. Therefore, when the effects of these three major simplifications in the motor assembly process are evaluated, it is conceivable that a brushless machine could be manufactured for as little as 50-60% of the commutator machine manufacturing costs. Controller costs are discussed in a later section of this paper.

TABLE I

PARTS COUNT COMPARISON BETWEEN EXISTING
AND PROPOSED BLOWER MOTORS

	DC COMMUTATOR	BRUSHLESS RELUCTANCE
A. Rotor Parts		
1.	Laminated armature steel stack	6 - steel bars of rectangular crossection
2.	10 copper wire (#18 AWG) coils, 10 turns each	
3.	10 - insulating slot liners	
4.	10 - bar copper commutator	
5.	2 - fiber spacing cylinders	
6.	2 - stack insulating spiders	
7.	shaft	shaft
B. Stator Parts		
1.	2 - ferrite, arc-shaped magnets	2 - soft iron pole pieces
2.	cylindrical soft iron housing	aluminum end plate
3.		30 - turn copper, solenoidal coil
4.	2 - bearings	2 - bushings (or bearings)
5.	rear bearing housing	
6.	lock washer	2 - lock washers
7.	front bearing slinger guard	
8.		3 - machine screws
9.	2 - carbon brushes	
10.	2 - brush holders and springs	
11.	fiber mounting plate for brush holders	
C. Motor Weight		
	53 oz.	46 oz.
D. Dimensions		
	6.2" dia. x 3" + 3" dia. x 2.5"	6.2" dia. x 3"

Electrical Characteristics

1. Current Wave Form: The wave form of the brushless machine consists of a series of discrete current pulses rather than the steady DC of typical commutator motors. The current pulses may be of sinusoidal, trapezoidal, triangular, or other shape, depending upon the type of control used. RMS current levels are generally higher in the brushless motor than in the commutator motor for a given power output, resulting in higher armature copper losses in the former.

2. Electromagnetic Torque: In the brushless motor, electromagnetic torque, (or motor developed torque) is a function of the RMS current squared, which somewhat lessens the effect on efficiency of the higher copper losses discussed above. In a commutator motor, this torque is a function of the product of the average armature current and the field magnetic flux.

3. Losses and Efficiency: It is hard to make generalized comparisons of losses and efficiency for the two types of machines since many size, weight, and cost tradeoffs become involved. Two of the significant loss components in the commutator machine do not exist in the brushless machine: brush IR drop loss and brush friction loss. However, copper losses and iron (magnetic) losses are higher in the brushless machine due to the chopped current wave form in the brushless machine and the effect of the nonconducting ferrite pole pieces in the commutator machine. Present experience indicates that the full load, rated speed efficiency is slightly higher in the commutator motor but that partial load and/or partial speed efficiencies may be higher in the brushless motor. Also, the brushless efficiency tends to be more constant as load and speed are varied.

4. Electromagnetic Noise: Again, the two types of machines should be roughly comparable. The noise results from the chopped current wave in the brushless design and is characterized by relatively few harmonics of significant magnitudes. The commutator motor noise is more gaussian in nature and is due to sparking and improper commutation at the mechanical commutator. Small, permanent-magnet excited commutator motors tend to be noisier than electrically excited machines since the conventional compensation techniques for improving commutation (interpoles, etc.) cannot be applied to permanent magnet machines.

5. Magnetic Flux: The brushless machine operates at significantly higher levels of magnetic flux density than the commutator machine due to the use of ferrite permanent magnets in the latter. This is one of the reasons for the reduced brushless machine weight.

ELECTRONIC CONTROLLER FOR BRUSHLESS MOTOR

Series SCR Controller

The power circuit for a very simple type of electronic controller capable of driving the brushless blower motor is shown schematically in Figure 5.

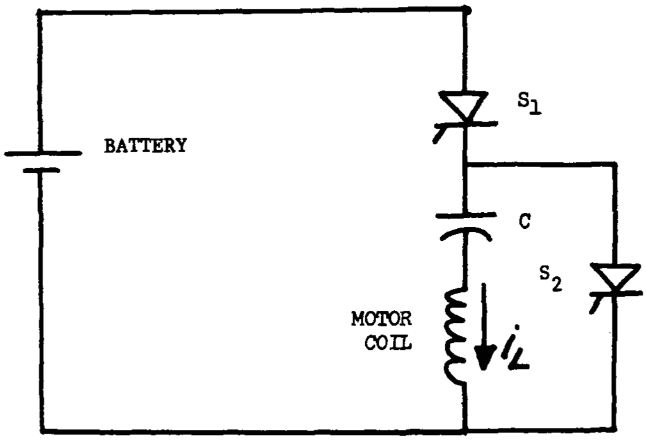


Figure 5. Series SCR Controller

Typical current wave forms are illustrated in Figure 6;

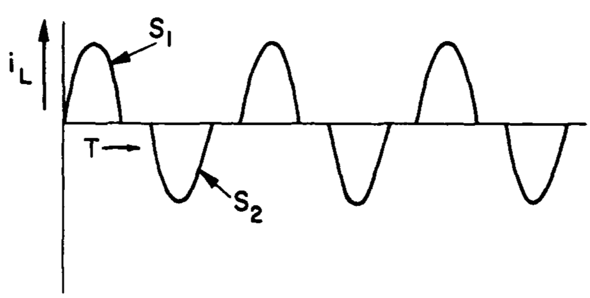


Figure 6. Series Controller Current Wave Form

this wave form is an example of a "chopped" sine wave, i.e., a sine wave "chopped off" or turned off after each positive and negative portion of the sine wave and followed by a short off time. The on pulse is applied during periods of increasing inductance (decreasing reluctance). The width of the sine pulses is determined by the product of the motor inductance and series capacitance, and is designed to be about 10% longer than the period of increasing inductance at the desired maximum speed. This means that at very low speeds, the current pulse covers only a short portion of the time period of increasing inductance resulting in low RMS currents and low electromagnetic torque. The torque at starting and low speeds can be increased by increasing the number of current pulses during each period of increasing inductance, although this scheme is not considered necessary for the light starting loads of fans and blowers. Operation at partial speeds is achieved by skipping the application of current pulses during a certain number of periods of increasing inductance during a certain time period. For example, in the motor of Figure 2, at rated speed and load, six current pulses per revolution would normally be applied to the exciting coil. At a speed of 3600 RPM, this would result in a pulse rate of 360 pulses per second. If the rate were reduced to 240 pps, it can be shown that the RMS current would be reduced by a factor of $\sqrt{240/360}$ or 81.5%; the developed torque, proportional to the square of RMS current, would be reduced to 240/360 or two thirds of the rated value.

This type of motor control has been used successfully on both the larger traction motors and the small centrifugal fuel pump during many hours of operation. It can operate with any type of positioning information and requires a minimum of logic circuitry for proper operation of the power SCRs. The salient features of this control may be summarized as follows:

1. Power circuitry consists of the minimum number of the lowest cost power switching devices (SCRs). SCRs do not require the high quality, high cost dynamic characteristics associated with inverter SCRs.

2. Uses simplest logic system for control of power devices.

3. The capacitor is the dominant cost item in this controller.

4. This circuit is one of the few types of control in which bilateral current exist. This imposes a slight penalty in efficiency, since the magnetic current of the motor is taken through the complete swing between plus and minus maximum flux values, increasing the motor hysteresis losses over the unilateral excitation schemes.

5. At rated speed and torque, the current wave form of this motor approaches a sine wave and the motor is excited in a manner very similar to conventional synchronous motors. Voltage and current harmonics are probably minimized in this scheme.

Transistor-SCR Controller

A more sophisticated control scheme is shown in Figure 7, with associated motor voltage and current wave forms illustrated in Figure 8. This scheme achieves a current pulse approaching a square shape which increases the RMS current for a given value of maximum current and greatly enhances the control over motor torque and speed. The capacitor size is smaller than that of the series SCR controller but more power switching devices are required. This scheme is used to drive the prototype brushless blower motor. The salient features of this control are summarized below:

1. Full torque control at all speeds.

2. Optimum motor current wave form; unilateral current.

3. Smaller capacitance but more power switching components required than in series controller.

Other Control Schemes

At least 20 additional control circuits have been studied in considerable detail and about 10 of these have been built and tested with various disc motors. Further discussions of the circuit operation and theory of some of these schemes may be found in References 4 and 6-11. The simplest type of control is a single power transistor which is switched on and off so as to permit current flow during periods of increasing motor inductance. This scheme has been used during much of the centrifugal pump testing, and may be applicable for relatively low power levels in applications where efficiency is not an important factor. The three main limitations of the single transistor switch are:

a. The current builds up at a rate determined by the motor winding inductance and battery voltage (rather than by means of capacitor forcing as in the above two controllers).

b. The energy in the motor coil when the current pulse is to be turned off is dissipated in the transistor, greatly reducing system efficiency and increasing the required transistor size in order to dissipate this added heat load. The use of freewheeling diode around the motor coil will remove the heat dissipation in the transistor but greatly reduce the maximum motor speed due to the long trailing off of the current pulse. Also, system efficiency is little improved since part of the coil energy ends up developing negative motor torque, slowing down the motor.

Some of the other control schemes are being evaluated towards the goal of achieving the minimum cost controller capable of satisfying the technical performance requirements of the motor. The control circuit configuration will doubtlessly be different in each application.

CONTROLLER LOGIC AND POSITION SENSING

Logic and position sensing circuitry is required in order to synchronize the current pulses with the mechanical time periods of increasing motor inductance, as noted above. Although this circuitry involves some of the most interesting technical problems and design challenges, its cost will generally be a very small percentage of the total system cost. Hopefully, for either controller A or B above, the total logic and position circuitry can be fabricated on a single semiconductor chip. Experience has shown that the cost of such circuitry becomes very low in the large quantities associated with automotive applications and generally decreases with time even in inflationary economic conditions. The only additional item required in the brushless motor system is a tiny ceramic permanent magnet, the cost of which will be miniscule.

Four major types of position sensing have been applied to the disc motor:

1. light sensing with an encoder-type disc, using light activated SCRs and diodes.

2. variable reluctance of an external magnetic circuit.

3. permanent magnet actuation of reed switches.

4. permanent magnet enhanced sensing of the internal motor reluctance variations.

The latter system has proven to be the least costly method yet conceived and is adequate to satisfy the technical performance requirements of small disc motors. Since this concept is relatively new and has not been fully described, a short description is contained here:

Internal Position-Sensing System:

In a variable reluctance motor, if a residual magnetic field exists in the magnetic circuit, an output voltage will appear at the motor windings during rotation which relates to the minimum and maximum inductance points of the motor. This magnetism may also be externally produced either through bias currents in the motor winding or a permanent magnet placed in the vicinity of the motor's magnetic circuit. An operational demonstration of this system used the bias current in the motor windings approach as part of the logic control for the power circuit of Figure 7. The zero crossover points of the A.C. component of the output voltage wave form indicated the minimum and maximum inductance points of the motor.

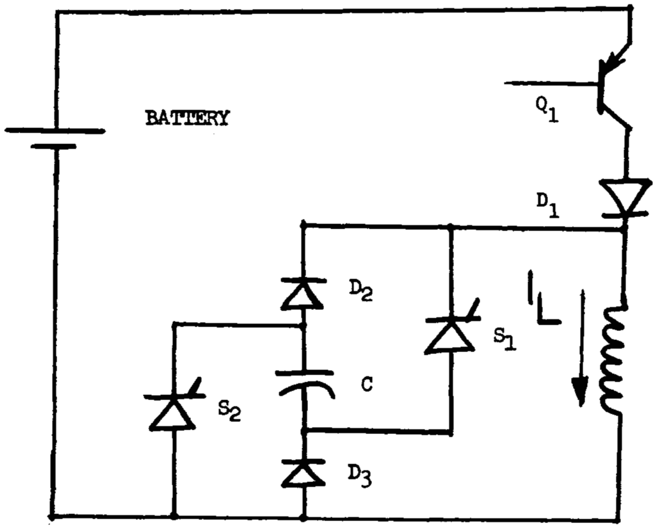


Figure 7. Transistor-SCR Controller

The slope polarity at the crossover point identified which inductance point the motor was at. Therefore, detection of the minimum inductance point was simply achieved through the use of a standard polarity sensitive voltage comparator. Upon detection of the minimum inductance point, a one shot multivibrator was fired for a predetermined on-time energizing a power transistor which powered the windings of the motor. For the duration of this on-time plus a small amount of additional time to allow the motor currents to settle, the comparator was gated off. This prevented erroneous outputs from the comparator during this power cycle. When the comparator was gated on again it was only necessary for it to detect the zero voltage crossover point of the proper slope polarity to initiate the new cycle. This was the basic operation of the position sense scheme and its associated logic. In practice, other circuitry may be necessary. For example, it may be desirable to vary the on-time of the power transistor multivibrator as a function of motor speed to satisfy motor torque requirements. This adjustment can be made over several cycles rather than on a cycle per cycle basis. This technique can result in maximum motor torque over its entire speed range. Additional circuitry is also necessary to insure proper start-up of the non-moving machine, since no position sense signals are available at this time.

The logic system developed for Figure 7 is illustrated in the block diagram of Figure 8. The position sensor monitors the motor induced EMF during the unexcited portions of the motor cycle. Its input gate is switched off for the duration of the power transistor on time (power pulse to the motor windings) plus a small amount of additional time to allow currents to settle within the motor winding. The variable time one shot multivibrator is triggered by the position sensor and drives the power transistor. An on-time detector monitors the output of the variable time one shot and continually adjusts its on-time to 50% of the mechanical period. This adjustment is accomplished slowly over several cycles. The pulse rate tachometer monitors the cyclic frequency and reduces the variable time one shot on-time to less than 50% when the maximum desired speed has been exceeded. This

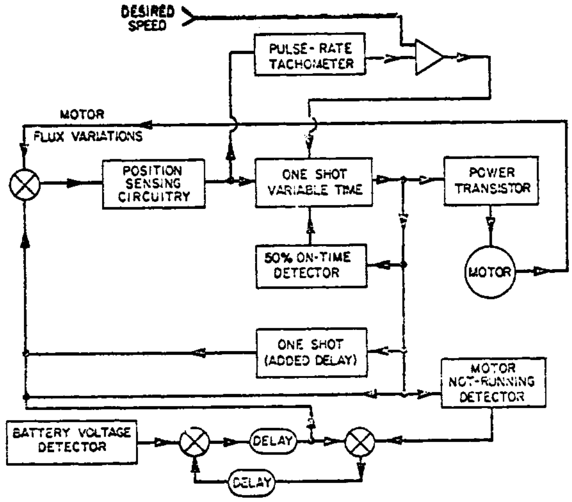


Figure 8. Logic Block Diagram for Control of Figure 7.

overrides the 50% on-time detector function. The start-up circuitry, consisting of a battery voltage detector and a motor not-running detector, basically holds the normal logic in an off state until a minimum battery voltage has been achieved for a given length of time. It then gates on the normal logic and triggers the variable on-time one shot once only in an effort to start the machine rotating. Should the motor not achieve rotation with this first pulse, there will be no position sense signals available at the motor winding. The motor not running detector senses this absence of position signals and initiates a new start-up sequence. This start-up cycling will continue until position signals are achieved.

Logic for Series SCR Chopper Operation:

The normal running modes and start-up mode is the same as that described for the power transistor logic with the following exceptions: the position sensor feeds the SCR chopper directly, which eliminates the variable on-time one shot multivibrator and its associated circuitry. The speed regulator simply gates the SCR chopper off whenever the desired speed has been exceeded. This logic description does not include the logic necessary to properly sequence the firing of the chopper SCRs since this requirement is determined by the chopping scheme chosen.

EXPERIMENTAL RESULTS

The six-pole configuration illustrated in Figures 2-4 has been assembled and operated with several different control circuits. The principal dimensions of the active elements of the motor are as follows: The inner stationary member has a total axial length of 1.95 in.; the saliencies or poles at each end of this member have an active axial length of 0.35 inches; outer diameter of saliencies (air gap diameter) is 2.78 inches; the six rotor bars (attached to the fan squirrel cage) have 1.70 inch axial length and .35 inch radial thickness; the active circumferential length of the saliencies and the bars is 0.72 inches, giving a ratio of active pole arc length to pole pitch length of 0.5; the exciting coil has an inner diameter of approximately 1.7 inch. The number of turns on the coil have been varied in an effort to achieve the best motor performance with a given set of controller power device current and voltage ratings. It is felt that the optimum number of coil turns has not been realized at this stage of development, and further improvement in motor performance may be possible. All magnetic members of the motor are constructed of .014 inch 3% silicon steel laminations.

With 26 turns of #30 AWG magnet wire in the coil, inductance measurements were made of a fully assembled motor using a Marconi inductance bridge, Type TF1313A, at 1000 Hz. With the motor in an aligned position (rotor bars directly opposite stator saliencies), which results in the maximum inductance, the measured inductance was 790 μh. This gives a ratio of maximum to minimum inductance of 3.29.

The principal purpose of the experimental program was to compare two identical blowers, the one powered by a conventional automotive DC commutator motor and the second powered by a brushless motor/controller system. The conventional blower used was a Motorcraft model D5AF, the squirrel cage one which is identical to that on the brushless configuration shown in Figures 2-4. The two blowers were operated in an identical environment without the shrouds surrounding the squirrel cage fan at the same speeds. It was assumed this resulted in identical torque loadings on the two machines. At 3050 rpm, the following measurements were made at the battery terminals in both cases:

	DC Commutator	Brushless
Volts, ave.	11.4	12.0
Current (amp.), ave.	16.05	12.5
Power (watt)	183	150

Since measurements were made at the battery terminals, controller losses are included in the above measurements. The improved power efficiency of the brushless configuration is apparent from the above measurements. This difference in efficiency is widened at partial speed conditions, where an armature resistance is used in the conventional system for speed control.

PROBLEMS AND LIMITATIONS

It has not been possible to evaluate the large-volume electronic controller cost during the development of the brushless motor system. This evaluation will require a fairly major effort and considerable interaction between automotive manufacturing engineers and electronic component suppliers. However, this evaluation must be made before serious consideration can be given to adoption of this blower motor for automotive applications. The electronic controller will cost more than the presently used simple resistance controller. However, the motor developers feel that the total brushless motor/controller package cost can be less costly than the existing DC commutator motor system. Achieving this goal will depend largely upon the minimization of the number of power semiconductors and capacitor size in the controller which is the goal of present development work.

One limitation of the brushless system is a relatively low starting torque as compared to that available from a DC commutator motor. For most blower applications this is not a problem, although longer accelerating times must be accepted. The starting torque can be increased to values almost comparable with DC commutator motor values, but only with a large penalty in controller cost and complexity.

Audible noise generation has been a problem with some of the larger, traction-type disc motors[3], but has not been noticeable in the blower motor. Noise results mainly from steep wave fronts in the controller current wave form, and this must be considered in the controller design.

Finally, effort is still required to insure that the controller is designed for maximum reliability and serviceability in the automotive environment.

CONCLUSIONS

There is much interest within the automotive industry today in improving efficiency, reducing warranty costs, and reducing packaging size and complexity for the many auxiliary components used in automobiles and trucks. With the gradual acceptance of electronic circuits for emissions control, engine control, speed control, etc., it is appropriate to evaluate the potential benefits that electronic controls might have in some of the vehicle auxiliaries. This paper describes an electronically controlled, brushless motor for use in AC and heater blowers. Compared to presently used DC commutator motors, the brushless motor has potential for improving operating efficiency, reduced warranty problems, reduced weight and overall blower package size, and continuously-variable speed control. This motor/controller system is proposed as a viable candidate for future use in vehicular blower and fan applications.

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(10) U. S. Patent #3,560,817, "Reluctance Motor Power Circuit", February, 1971.

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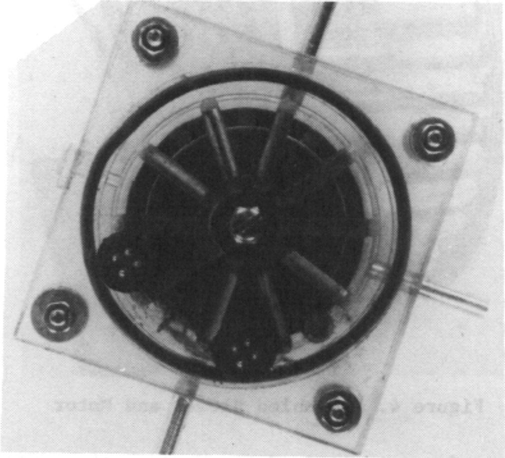

Figure 1. Prototype Fuel Pump

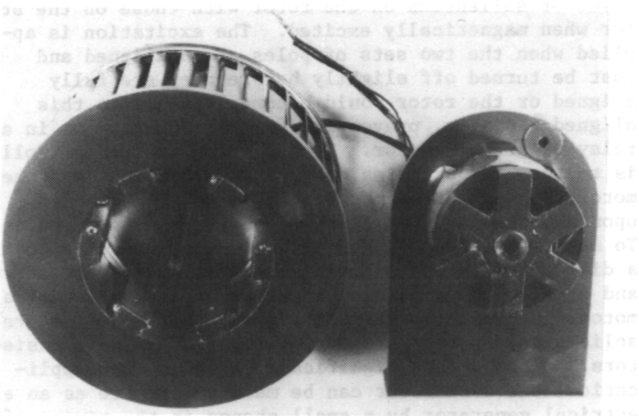

Figure 3. Dissassembled Blower Motor; Stator Circuit and Solenoidal Coil are on Right

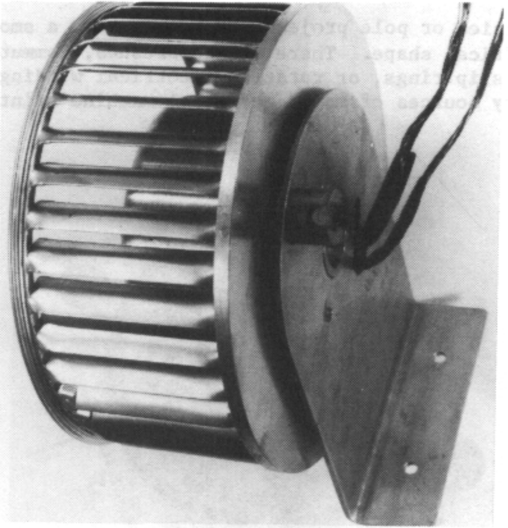

Figure 4. Assembled Blower and Motor