"SWITCHED RELUCTANCE BRUSHLESS DC MOTORS FOR ADJUSTABLE SPEED DRIVES AND HIGH EFFICIENCY"

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ABSTRACT

The World governments are setting standards for energy efficiencies and pollution levels to preserve our earths natural resources. The use of electric motors must change and the design and utilization of materials must keep pace with the needs of the motors of the future. For example, during the past 100 years, the single phase, single speed AC induction motor was the dominate prime mover. If variable speed was required, a DC motor was used. The efficiencies of both of these machines were not very impressive in fractional HP motors.

The future motor applications requires polyphase motors from single phase sources with high efficiency and variable speed. The brushless DC motor using permanent magnets has been thought to be the solution. However, the cost of magnets, availability, and magnet integrity or retainment have all contributed to the lack luster success of these motors. The topic of this paper discusses a high efficient, rugged, robust, high speed and high temperature brushless DC motor without permanent magnets.

1.0 INTRODUCTION

1.1 AC ELECTRIC MOTORS

Since the beginning of this century the world has used either AC or DC powered electric motors because of the availability of the two power sources. The AC motor can be defined as an electric motor powered by single or polyphase sinusoidal AC voltages and this family of motors is unique in that its speed is determined by its number of poles and the AC line voltage frequency in accordance with the following formula:

$$RPM = \frac{120 \times f}{N}$$

where N = number of poles and f = frequency. There are certain very special AC synchronous motors whose RPM depend upon a slight variation of that formula. Until the recent developments of AC inverters where the frequency can be controlled, the AC motor in its induction, shaded pole and synchronous forms has been restricted to fixed speed designs. The most common have been single, two or three speed, but not variable speed. If other speeds or adjustable speeds were required, various mechanical transmissions with clutches and brakes were used including mechanical variable speed drives driven by a fixed speed AC motor.

The main advantage of this type of motor is its reliability. In many instances AC motors with squirrel cage rotors (no brushes) run continuously for 40 years or more. A 20 year old home refrigerator is seldom discarded due to a motor failure but usually to obtain a more modern full featured or larger model.

A very large portion of the motors used in industry are polyphase AC motors which convert electrical energy to mechanical energy at 90% efficiency. The principle reasons for this are due to its polyphase power source (usually 3 phase). The motors used in the home and many small retail establishments have only single phase AC power. AC single phase motors convert energy at only 35 to 50% efficiency. Up to 70% or more is achievable if expensive (unreliable) capacitors are used for the extra winding which makes it into a quasi-two phase machine.

Figure 1 shows a cross section of most of the electric motors in use which are powered by either single or polyphase AC sinewave voltages.

1.2 DC ELECTRIC MOTORS

The conventional DC motor requires a wound field stator and a wound armature or rotor. In order to connect DC voltages to the rotor, stationary brush contacts and a rotating copper commutator must be used. The two electro-magnets (stator and armature) are connected to the DC voltage supply either in series, parallel or in a combination (known as "compound wound").

Since about the decade of the 60's the stationary wound stator has been replaced with a permanent magnet stator (at least in fractional HP sizes). The rotor or armature retained its windings and commutator.

Figure 2 shows cross sections of most of the common DC brush type motors. The principle advantages with these machines are two fold and based upon the fundamental feature of a DC motor in that its RPM is controlled by voltage not frequency.

1 - Variable RPM is easily achieved.

2 - Very high speeds are easily achieved (greater than 3600 RPM).

There are other minor features such as being easily reversible and capable of very high starting torques as well as the ability to produce shaft power at very low speeds which causes severe overheating for AC induction motors compared to the DC brush type motor.

The long standing much touted disadvantage has been the relative short brush and commutator life. In reality this complaint is excessively over stated and in actual practice proven time and again not to be as serious a problem with DC motors such as being glibly claimed when

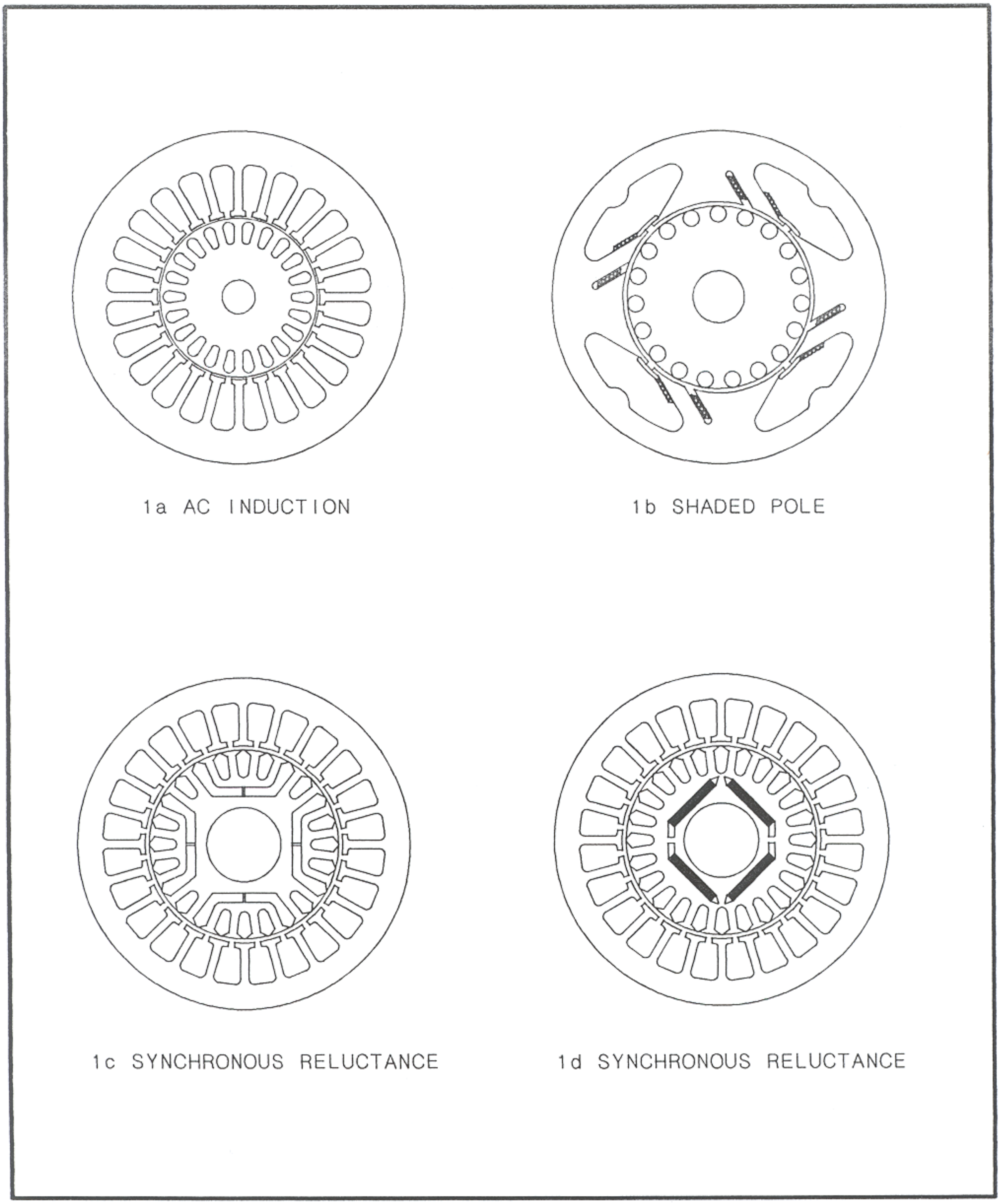


FIGURE 1 POLYPHASE AC SINEWAVE

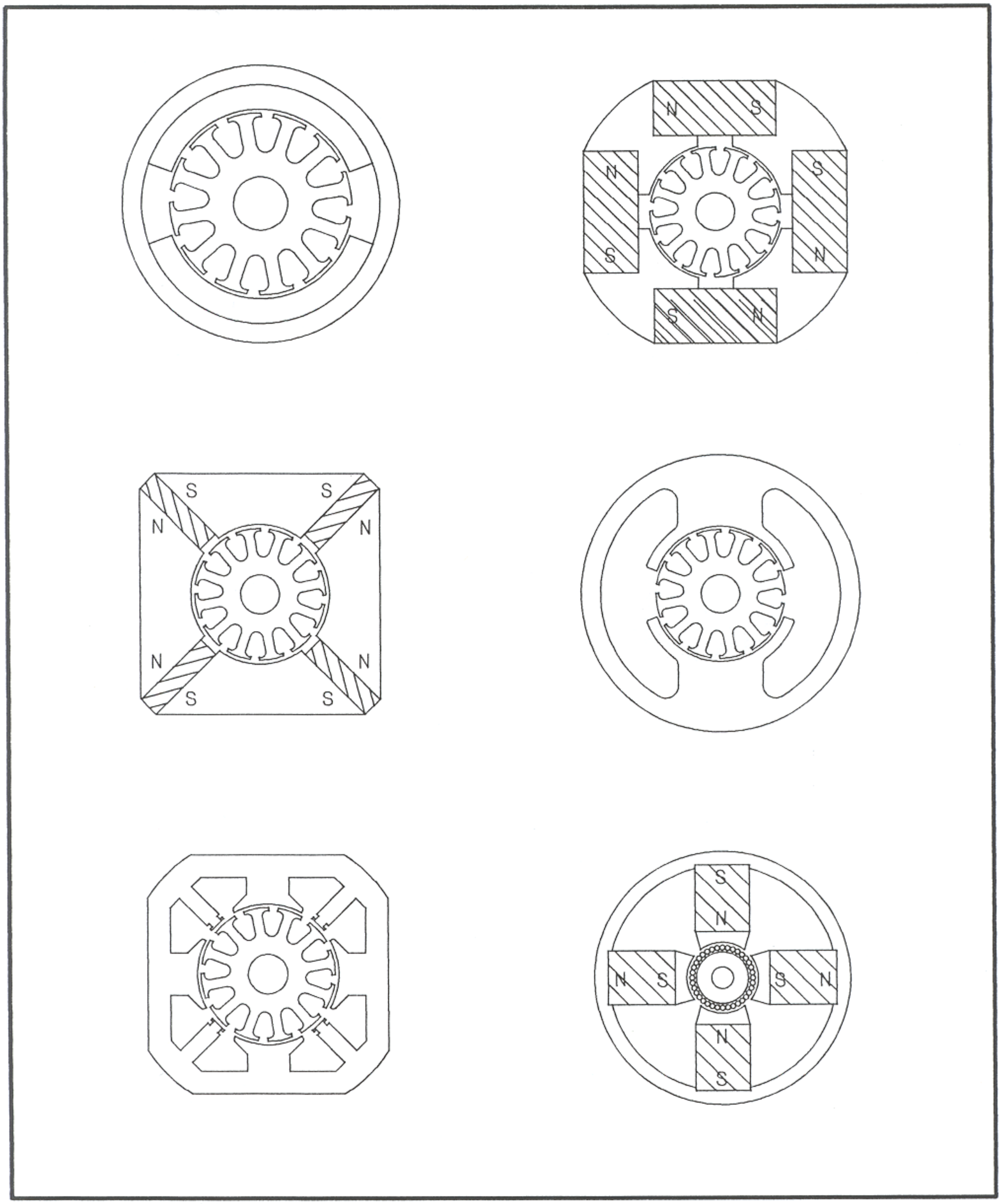


FIGURE 2 DC MOTOR CROSS SECTIONS WITH BRUSHES & COMMUTATORS

promoting some other technology.

In many instances a more important disadvantage has to do with the difficulty of cooling the rotating armature because its only thermal path to dissipate its I^2R heating is through its bearings. The brushes also generate heat at the commutator because they have their own I^2R losses plus they act as little brake pads on the commutator.

However in spite of the drawbacks attributed to the brush type DC motor it continues to be widely used in vacuum cleaners, power tools, automobile accessories (up to 75 per car), some garbage disposals, European and far eastern home laundry white goods, blenders and food processors. Besides these very large volume applications, the brush type motor continues to be used extensively in a wide variety of office machines, medical and factory automation applications.

The main reasons for this relates to a 100 year head start which produced a well automated infrastructure fully amortized so that the brush motor is a bargain. Their larger versions, either shunt, compound wound or permanent magnet are used in industrial machinery for variable speed and even reversing. A relatively simple and low cost "H" bridge controller is used to change the DC voltage to adjust the speed to the desired RPM.

1.3 PERMANENT MAGNET BRUSHLESS MOTORS

As the developments of permanent magnets progressed since about 1965 yielding magnets highly resistant to demagnetization, the windings and commutator of the DC armatures were replaced with magnets to produce the rotor flux field to be linked with a wound stator electro-magnet.

These brushless DC motors were first developed in the USA by Sperry Farragot in 1964, for the Goddard Space Center. In Europe Siemens offered the first brushless DC motors for sale. The General Electric Company in Lynn, MA developed permanent magnet brushless generators for aircraft in the late 60's and on into the 70's. (Dr. Eike Richter was a pioneer of these machines). The first industrial brushless DC tachometers were developed by Erland Perssons at Electro-Craft in the early 70's. The first industrial brushless servos were developed and introduced by Sam Noodleman at Indland in about 1974. The first low cost high volume brushless motors were developed for small cooling fans for computers and other electronic instruments. A natural evolution of these blower brushless motors moved into floppy disc and Winchester disc drives as well as VCR's, record players, and now CD players.

The purpose of the preceding historical sketch of the evolution of brushless DC motors is to point out that it has been very difficult for the brushless motor to replace either the AC induction/synchronous motors or the brush DC machines. In fact, in spite of the reliability and controllability of the permanent magnet brushless motor, the majority of the present volume is used for brand new products such as disc drives, electronic cooling fans, VCR's and CD players. Industrial brushless servo systems represent a reasonable dollar volume but very low quantities.

Stepping motors using permanent magnets have enjoyed a much greater success in motion control or servo applications than has brushless in the 4" diameter motor and smaller. Brushless motors, larger than 4" in diameter, are finally making some progress but the applications must be developed one at a time. The main reason for this slow growth of brushless drives is high cost. The cost of permanent magnets, magnet retentation and magnetizing make these machines not cost competitive to other older motor types such as induction and shunt motors, especially in the larger sizes. Usually standard AC stators cannot be used for brushless designs so an additional cost is burdened upon the brushless motor because of new laminations. Either hand insertion of the phase windings must be used or extremely high capital equipment cost to automatic wind and insert must be invested.

Certain companies such as GE, Emerson, Fasco, Reliance and a few others have put ceramic/ferrite magnet rotors in their standard AC induction motor frames. This is a very cost effective strategy to test the market with a very low risk investment. The main drawback with these programs is the inferior performance of these motors using ferrite magnets. If rare earth magnets were used new laminations would be required because the copper to iron ratio is much different for rare earth motors where the ferrite is similar to the induction motor. Therefore, the use of the rare earth design would require an entirely new design with new tooling throughout.

2.0 ADJUSTABLE SPEED DRIVES

Since the development of micro-processors and power electronics using FETS & IGBT's the interest in adjustable speed motors has intensified for a variety of compelling reasons beyond the scope of this paper. However, now that the limitation of the fixed speed motor is somewhat easy to overcome, most all products are being re-thought and many re-designed to take advantage of variable speed electric motors. Even though the brush/commutator motors will be widely used for many more years, it seems that the choices for adjustable speed prime movers are limited to four types of motors known as inverter driven AC induction, inverter driven synchronous reluctance, permanent magnet rotor brushless and switched reluctance brushless. Figure 3 shows the basic cross sections of a few of the standard types of these machines.

The AC induction and PM brushless are both quite familiar to most of us with the other two reluctance (synchronous and switched) motors not nearly as well known or understood. The author of this paper has conducted an extensive and detailed computer analysis and performance comparison of three 5 HP motors built into identical NEMA frames of identical magnetic material mass. These three motors were 3 phase AC induction, 3 phase PM brushless and 3 phase switched reluctance. The thermal continuous ratings of these motors were as follows: AC Induction 5 HP, SR Brushless 9 HP, PM Brushless 14 HP. Each motor

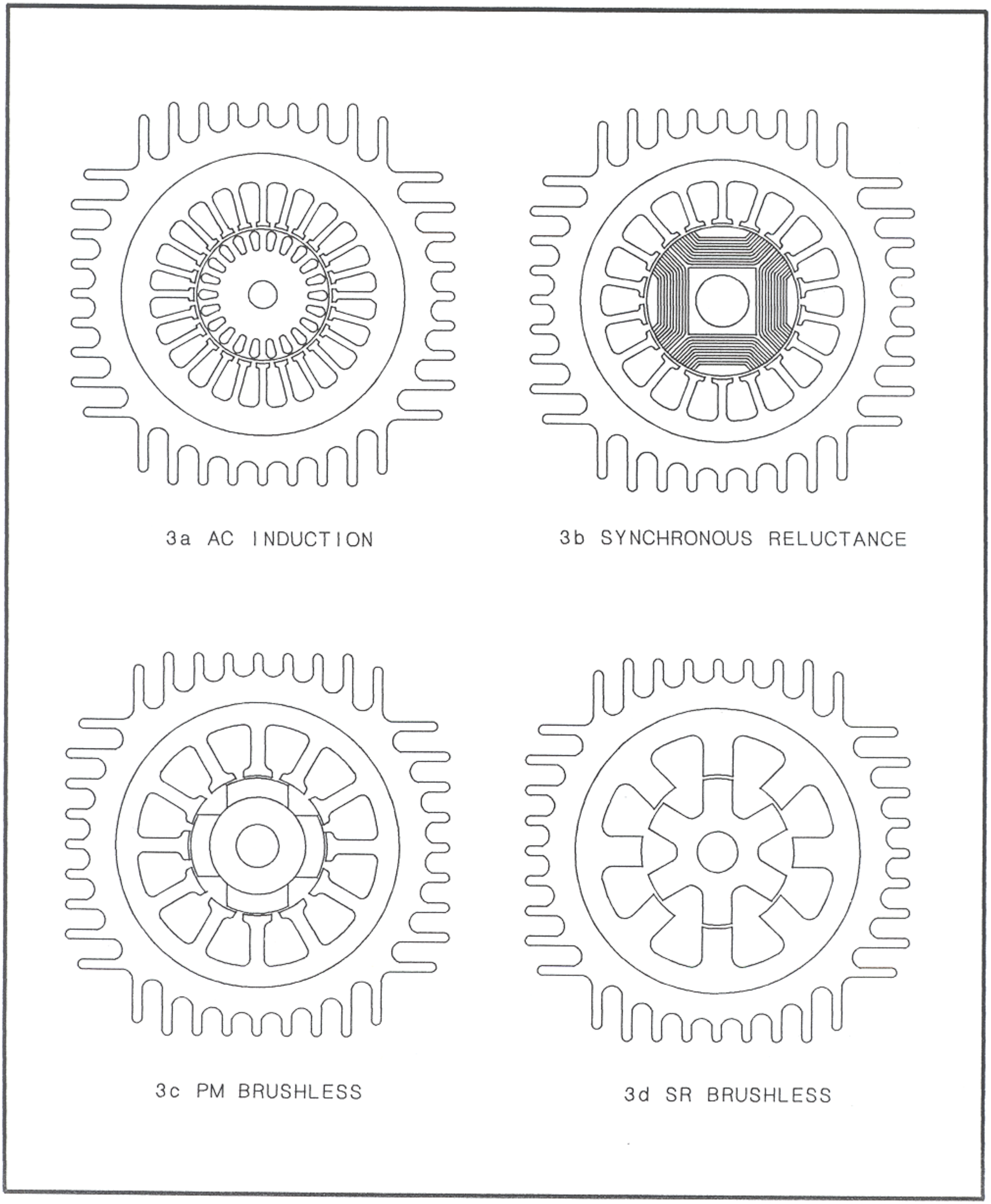


FIGURE 3 ADJUSTABLE SPEED MOTOR CHOICES

was computer designed for maximum performance at 50°C rise, air over cooled, totally enclosed using silicon steel lams and in the case of the brushless, 27 MGO rare earth magnets. The synchronous reluctance motor design was not compared in this study but other similar studies show it to be nearly comparable to the SR motor. (See references 1 & 2). All of the similar comparative trade studies known to this author show that the power densities of these three types of electric motors compare in general regardless of size as follows:

TYPE	HP/LB
Rare Earth PM Brushless	Highest
Switched Reluctance Brushless	Higher
Synchronous Reluctance	Medium
Ferrite PM Brushless	Lower
AC Polyphase Induction	Lowest

2.1 NEW AC VECTOR CONTROLLED SYSTEM

It must be reported that there is a significant amount of development work on a special vector controlled inverter technology used with special designed AC polyphase induction motors using copper barred rotors. The reports available indicate that with a special AC motor and control topology, the performance can be brought to the level of the rare earth PM brushless system at a significantly lower cost. (Probably not as cost effective as the SR brushless).

This author knows very little about this technology (see ref. 18, 19) other than some published articles but no personal experience. This development is credited to Erving Hanson of Lewis Labs NASA in Cleveland, OH. The special AC motors were designed by Jay Vaija and built by Sundstrand in Rockford, IL. These systems have been used as flight-control surface actuators on the Advanced Tactical Fighter program at General Dynamics in Fort Worth. (It is with due respect and completeness that this development is reported).

2.2 SYNCHRONOUS RELUCTANCE MOTORS

The synchronous reluctance motors which are inverter driven, have been built for many years by both GE and Siemens for variable speed synchronized drives in textile applications (principly carpet yarn machines) in staggering volumes. Mr. Kreso Mikulic of Reuland Electric has recently been awarded US patent #5,097,166 for a very powerful and efficient synchronous reluctance motor utilizing internal rare earth magnets. Also, extensive development work is currently underway at the University of Wisconsin with their WEMPEC research consortium and at the University of Glasgow with their SPEED research consortium for these synchronous reluctance motors and drives. Their main advantage is that they perform like switched reluctance motors, but their stator polyphase winding configurations are taken exactly from poly-phase induction motors. Only a new rotor is required which makes them very attractive.

2.3 PM BRUSHLESS MOTOR

Much has been said about these machines including their maximum power density. The permanent magnet is as close to getting something for nothing as there is because once the magnets are charged and paid for they continue to produce a force field for ever without further cost, fuel or energy. However, their cost of purchase, assembly and retention is always a disadvantage and difficult to justify when compared to the alternative motors for adjustable speed drives for integral HP designs. FANUC of Japan produces a very clever brushless design (attributed to Dr. E. Richter of GE) using a fairly complicated rotor structure with imbedded flat ferrite ceramic magnets placed between soft iron pole pieces which "focus" the flux. These PM brushless designs (also made by Pacific Scientific) yield the performance of the best rare earth motors using $2.00 per pound magnets.

Other than the Fanuc motors who are the servo market leaders the cost of the magnets plus the new tooling for the special brushless stators has limited their use for adjustable speed applications. The converted AC induction motors using simple ferrite surface mounted magnets on the rotor are very low in cost but also limited in performance and not any better than a polyphase AC induction. The current promotion and advertising for these motors (made by GE) in the industrial trade journal editorials claim much improved efficiency for home appliances at great national energy savings. This is certainly true enough when the polyphase brushless motor is compared with the single phase AC induction motor. However, when these highly tooled ECM's ® are compared with other polyphase motors and drives such as the switched reluctance they offer no advantage whatsoever and in fact, are inferior to the SR in several respects.

Even the polyphase AC induction motor is as efficient as the ECM ® PM brushless motor over a very limited speed range. The main issue which improves the motor efficiency is polyphase vs. single phase. There is little real differences in the efficiencies of the 4 motors mentioned if all are polyphase. The differences then come down to other features but mainly cost.

2.4 AC INDUCTION

By a large margin the polyphase AC induction motor is the dominate variable speed motor in existence. The reason for this is the simplicity of its proliferation. The AC motor is widely available on existing equipment and a good value for new equipment. To achieve adjustable speed, the AC variable frequency/voltage inverter is used. For existing machinery, there is an advantage to "speed up" for higher production rates. With 60 Hz from the power company, higher speed is only possible if an inverter is used to increase the frequency up to even 120 Hz for 2 x speed plus variable speed is a by product. At higher speeds the motor is well cooled because of constant HP so the only limitation is the mechanical integrity of the machine and bearings. The scenario of this market for adjustable speed would suggest that no technology can unseat or compete with an AC inverter controlling existing AC induction motors in the field until the machines wear out.

The other market for adjustable speed is new equipment where speed control over a wide speed range can greatly simplify the power transmission components and offer programmable, flexible machine performance. For these applications, the AC induction motor with low cost inverters is not so attractive. The reason is that when an AC induction motor operates over a wide speed range the motor overheats at low speeds. A rule of thumb states that a 2 HP motor is required for inverter use where a 1 HP motor would suffice at rated constant speed. Frequently, this oversizing problem for inverter drives can be solved by adding an external AC blower with serious air flow ducted to the inverter driven induction prime mover.

3.0 POWER AND CONTROL ELECTRONICS FOR ADJUSTABLE SPEED DRIVES

The lowest cost power/controller would have to be the SCR controller or H bridge transistor drive for brush type DC motors where the only control issue is voltage to set speed. The reason for this is that the phase switching is accomplished by the mechanical brush/commutator assembly. If it is decided that a brushless system is required for any number of reasons unique to each instance, then the choices have been stated as AC induction inverter, synchronous AC inverter, Permanent Magnet brushless and Switched Reluctance brushless.

Once the control parameters have been parametrically synthesized for each technology and "chip-a-fied", the cost of the individual inverter is based upon the power converter which includes the power switches, heat sink and filter capacitors (if required). The power switches recommended are IGBT's for 300 VDC up to 650 VDC and low drain HEXFETS for 12 to 200 VDC drives such as automotive. It is certain, however, that each technology will overlap the other over time. Special packaging is becoming common place which include termination screws and protection diodes and even some are packaged with current detection.

A final comment about the drives is that as volumes grow the cost of inverters/controllers for each of the four motors will be almost identical. (Various vendors might not sell at equivalent prices but the cost are the same).

4.0 SWITCHED RELUCTANCE MOTOR AND DRIVES FOR ADJUSTABLE SPEED

4.1 INTRODUCTION

It has been stated that the SR or VR motor is capable of very high power density and furthermore it is available in a variety of configurations in accordance with its application requirements. Figures 4 & 5 shows the cross sections of most of the common SR motors. In all cases it is clear that the SR motor is a doubly salient motor with only electrical voltages connected to the stator phase windings. The rotor contains no magnets, windings or squirrel cages so it is extremely simple, rugged and low cost. The rotor has no I^2R heating losses to dissipate, only eddy current hysteresis losses.

The stator coils are easily machine wound and

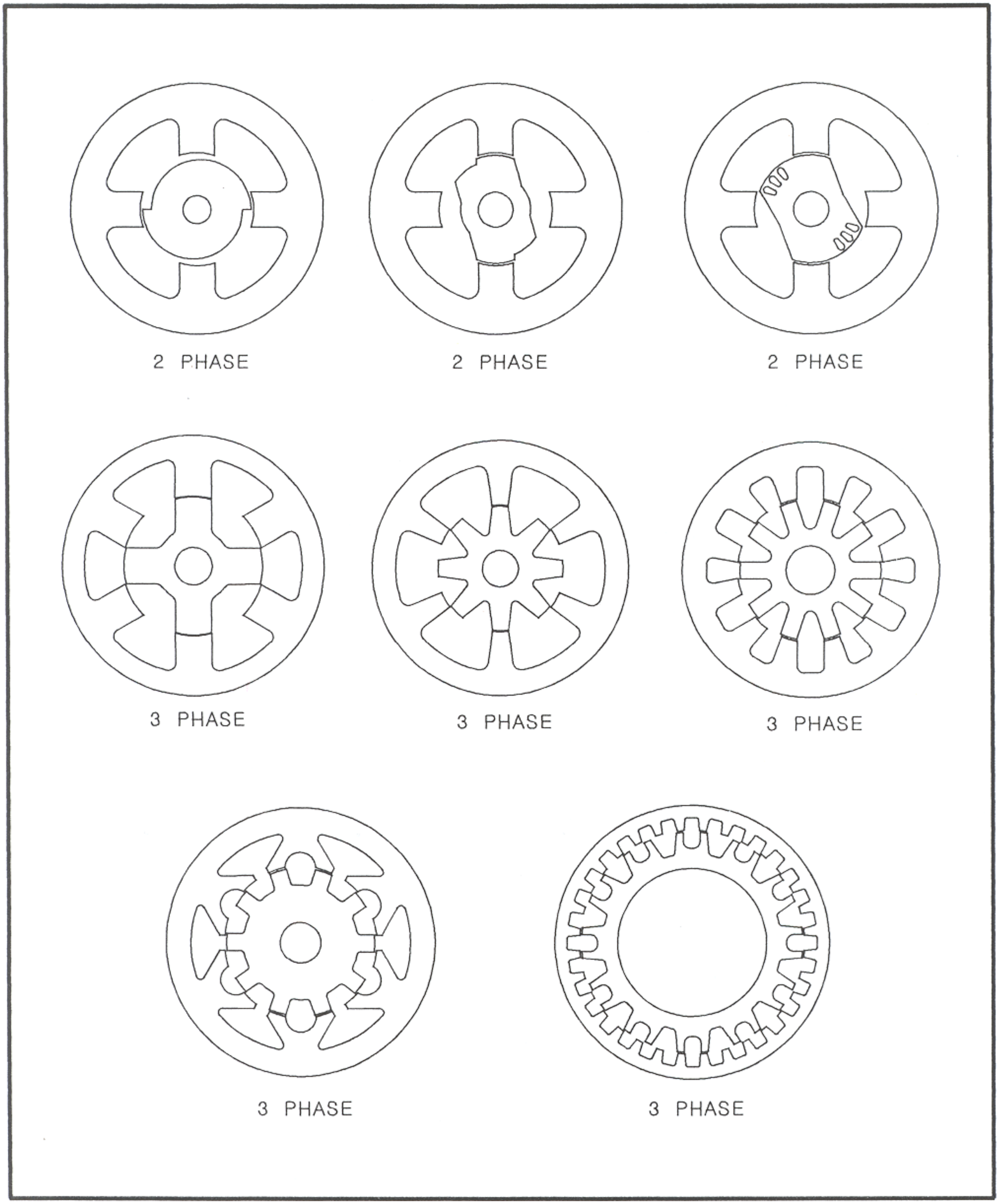


FIGURE 4 CROSS SECTION OF SWITCHED RELUCTANCE MOTORS

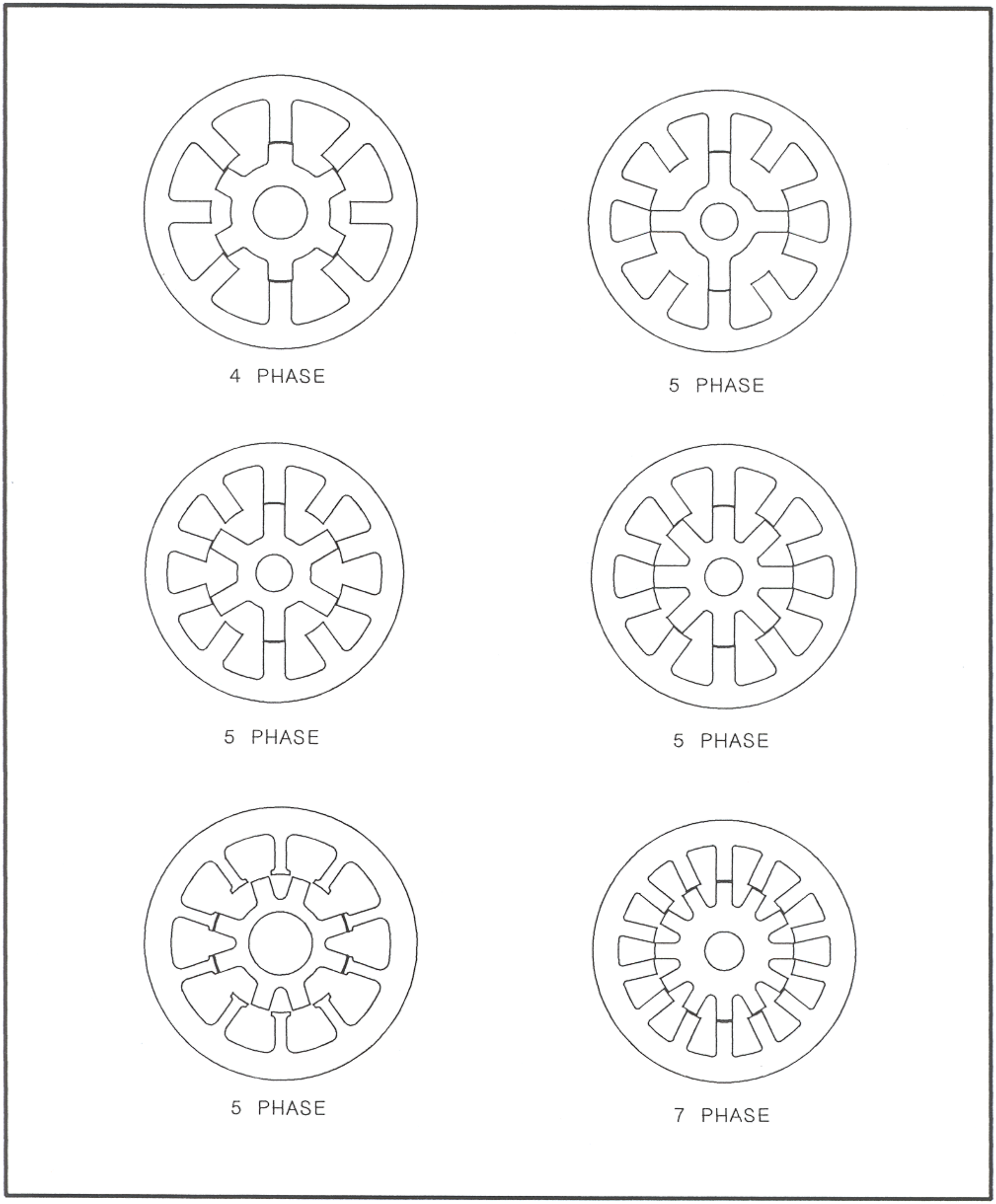


FIGURE 5 CROSS SECTIONS OF SWITCHED RELUCTANCE MOTORS

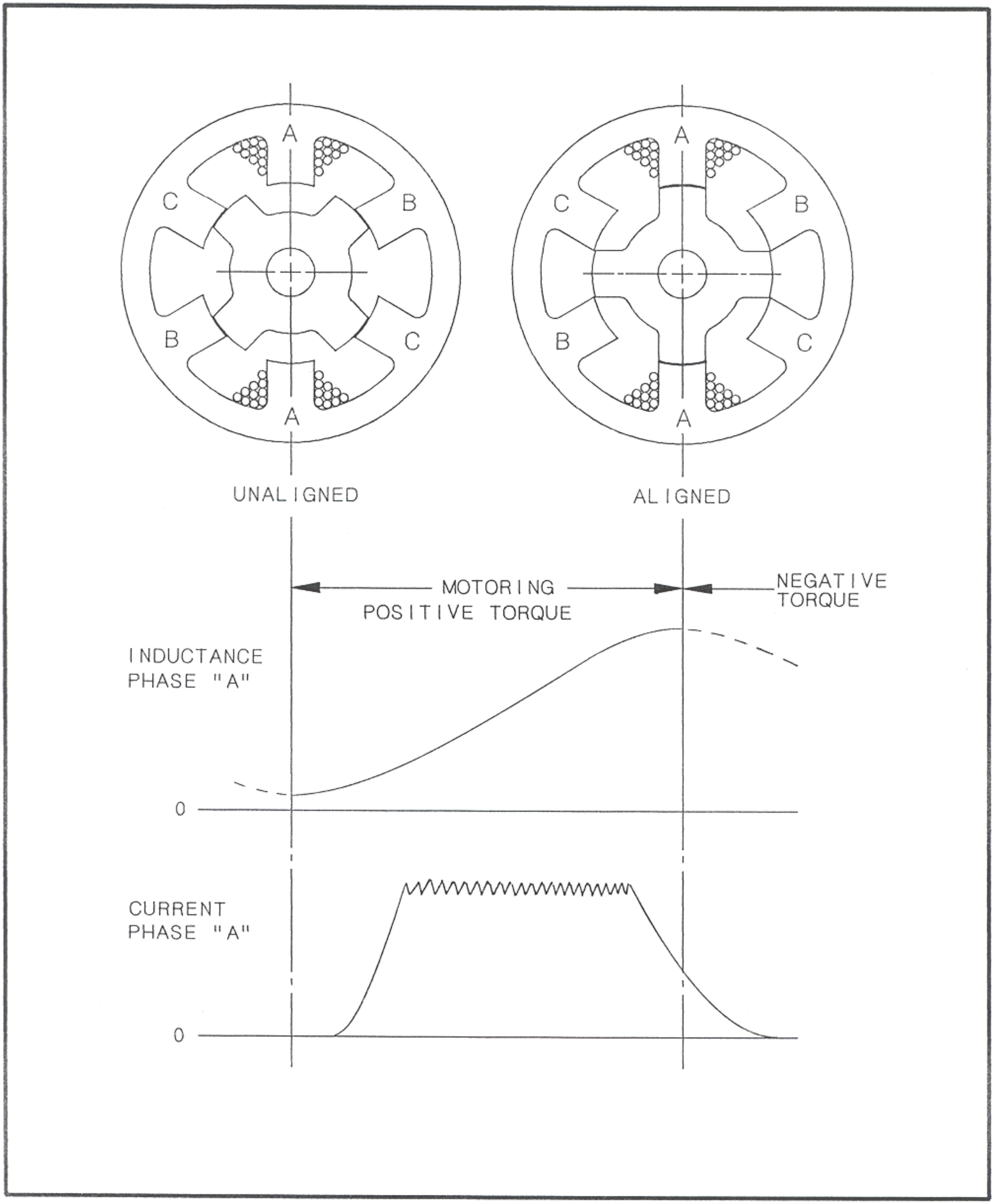


FIGURE 6 SALIENT POLE UNALIGNED/ALIGNED SR MOTOR CHARACTERISTICS

hand inserted in a few seconds or automatically wound in place. Torque is produced when the phase coils in the stator magnetize poles which attract the rotor poles which are rotated to a position where the inductance of the excited windings is maximized. Slightly before this angle position is reached the next stator pole pair is energized at the minimum reluctance position and the first pair is turned off. This repeated process produces continuous torque. There is a flux linkage from salient stator poles to attracted rotor salient poles phase to phase as a sequence of current pulses is applied to each successive phase.

For the purposes of references Figure 6 shows a 6/4 SR 3 phase motor with the rotor in the unaligned position which is close to its position to be energized. Figure 6 shows the aligned rotor location which occurs just after the phase circuit is opened. The phase "A" inductance is shown at its minimum when the rotor salient poles are precisely unaligned to the salient poles of phase "A". Shortly after unalignment the phase voltage is switched on and the current rises very rapidly as is shown on Figure 6. Positive motoring torque is produced due to the attraction of the salient rotor poles to phase "A" stator poles. The torque causes the rotor to rotate (either cw or ccw depending upon electronic commutation direction). Shortly before the rotor poles are aligned with phase "A" stator poles, the phase "A" circuit is "opened" and the current decays as is shown in Figure A. Notice due to the higher inductance close to alignment causes the current to decay much slower than the current rise of phase turn-on.

Continuous rotation is caused by then energizing phase "B" for ccw rotation or phase "C" for cw rotation because in either case the salient poles of either B or C are in the same physical location as phase "A" poles were when energized.

There are many appropriate power switching circuits possible for the SR motor but one of the most common and most efficient is the one shown on Figure 7. Notice that the SR motor is a unipolar motor. The magnetic flux polarity is important

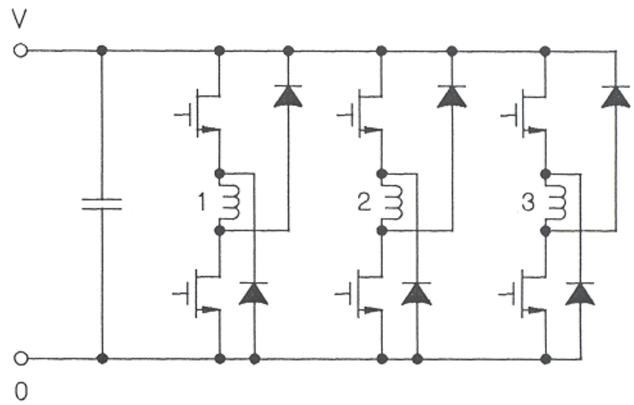


FIGURE 7 SR INVERTER CIRCUIT

because there are no permanent magnets. Figure 7 shows two transistors and two diodes per phase so that each phase is electronically commutated independently so that phase advance ("field weakening") and phase overlap ("vector control") can easily be accomplished. The number of phases used in a PM brushless motor or an AC induction motor has customarily been (3) phase because of the sinusoidal voltage properties of these machines. Even the 6-step or trapezoidal PM brushless machines produce smooth torque over one revolution with a minimum of torque ripple

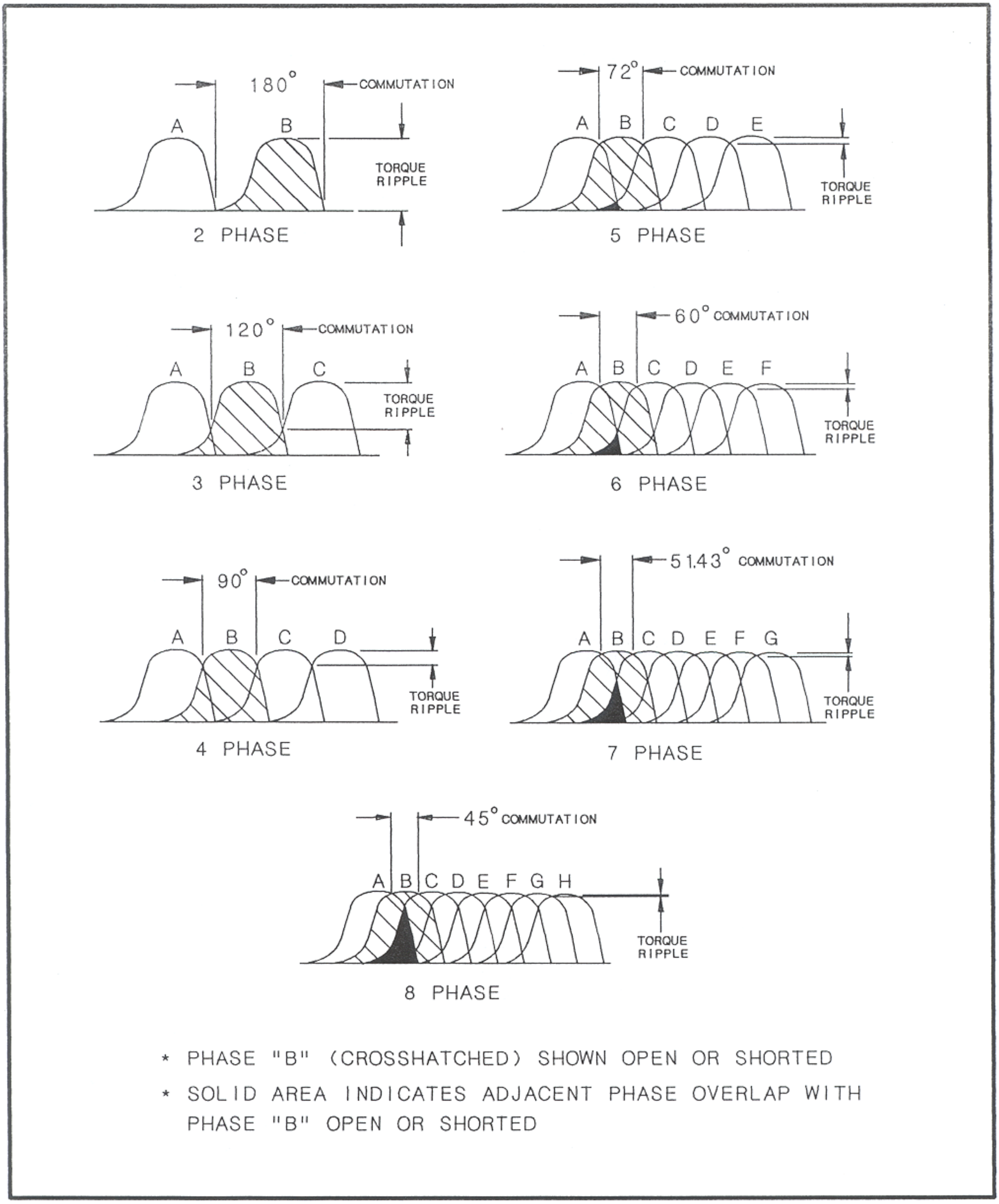


FIGURE 8 TORQUE VS. ANGLE

using (3) phases.

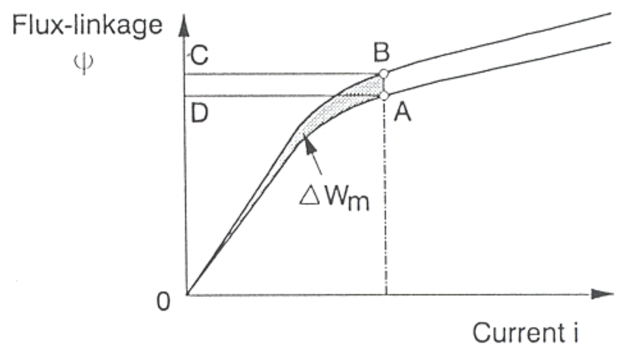
The SR motor is not sinusoidal due to its salient poles and due to the tendency of these poles to magnetically saturate especially on the tips. This causes the torque vs. rotor angle to be very non-linear and have a strange shape. Figure 8 shows the relationship of the torque vs. angle. The most common examples are shown for 2, 3, 4, 5, 6 and 7 phases. If constant voltage from the inverter is switched to each subsequent phase, the torque ripple for each number of phases is shown on Figure 8. Furthermore, the crossed hatched phase area indicates what the loss of a phase would yield. The darkened areas indicate the resulting torque overlap produced by the adjacent phases if the cross hatched phase is either shorted or open. The number of transistors and diodes increases with the number of phases so that the selection is based upon the cost and required performance. It is usually determined that either (3) or (4) phases are common. Perhaps (5) phases or higher would be appropriate for high performance servo systems of an aerospace application where fault tolerance for life support systems is required. For high speed low cost applications such as vacuum cleaners, the (2) phase design might be sufficient.

4.2 TORQUE PRODUCTION FOR SR MOTOR

The general expression for the torque produced by a single phase at a single rotor position is given by:

W^1 is the co-energy bound inside this magnetization curve on a flux linkage vs. current plot (see Figure 9) or

Using these torque and co-energy equations the torque can be determined graphically. For example, Figure 9 shows the work ΔW_m divided by $\Delta\theta$ at constant current as the rotor rotates through a small angular displacement ($\Delta\theta$). During this displacement there is an exchange of energy from the supply and also a change in the stored field energy. As long as the current is constant during the displacement, the mechanical work performed is equal to the change in co-energy.



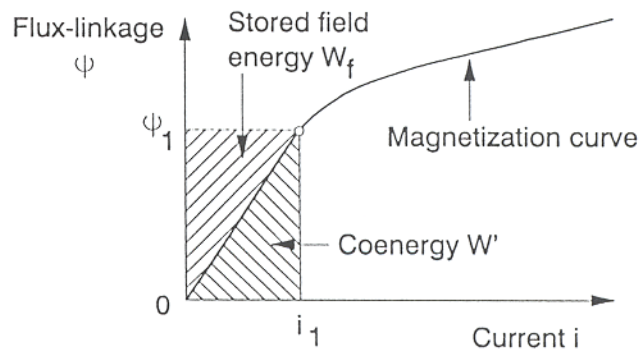


FIGURE 9 INSTANTANEOUS TORQUE FROM CO-ENERGY

In the displacement $\Delta\theta$ from A to B in Figure 9 with constant current, the energy exchanged with the supply is:

$$\Delta W_e = ABCD$$

The change in stored field energy is:

$$\Delta W_f = OBC - OAD$$

The mechanical work done is:

$$\begin{aligned} \Delta W_m &= T\Delta\theta \\ &= \Delta W_e - \Delta W_f \\ &= ABCD - (OBC - OAD) \\ &= (ABDC + OAD) - OBC \\ &= OAB \end{aligned}$$

(For more reading on the design details of Switched Reluctance Motors, refer to SWITCHED RELUCTANCE MOTORS AND THEIR CONTROLS by TJE Miller, 1993 *Magna Physics Publishing and Oxford University Press*).

For variable speed applications the Switched Reluctance motor requires a reasonably smooth torque at maximum efficiency over a very wide RPM range. Certain applications require a very high starting torque for overcoming high friction and inertia loads. Therefore, either the (3) or (4) phase SR motor can easily be used. The torque can be controlled and maintained by properly controlling the phase firing angles with a microprocessor and electronic commutation.

4.3 SWITCHED RELUCTANCE NEMA MOTOR DESIGNS FOR VARIABLE SPEED

This section reports on three NEMA frame size SR motor designs which were designed using new laminations which were the same diameter as those used in AC induction motors. The performance of the (4) phase SR motors is compared to the corresponding AC induction motors. Both single phase and three phase induction motors are compared. All of the SR machines are based upon a 160 VDC bus which resulted from a rectified 115 V single phase AC source. The SR motors were designed for similar speed ranges as the AC induction motors, best efficiency and totally enclosed without any fan cooling. The allowable current density was based upon a 50°C rise in temperature when the SR motors were mounted to a 9" square 1/4" thick aluminum plate. The AC motor ratings and performance data used in the comparison comes from the manufacturers catalogue.

The data summary is given for the three motor frames including several lengths along with the AC motor data on Figure 10.

5.0 SUMMARY

The Switched Reluctance motor designs show a significant improvement in power density over the AC induction motors. The same available volume (diameter and length) was used for both designs. Also it should be pointed out that the SR designs used the same air gaps between the rotor and stator as the induction motors. If smaller gaps had been used the power density would have been much higher. However, small gaps make SR motors too noisy.

The magnetic circuit designs of the SR motor were based upon 1.5 to 1.6 Tesla in the stator and rotor poles but only 0.6 to 0.7 Tesla in the stator

NEMA 42 FRAME 5" DIAMETER

	LG	RATED RPM	RATED KW	EFF. %	MAX RPM	NO PHASES
AC	6.13	3450	.37	65	6000	3
AC	7.63	3450	.56	66	6000	3
SR	6.13	3450	.58	88	12000	4
SR	7.63	3450	1.0	89	10000	4

NEMA 48 FRAME 5 5/8" DIAMETER

	LG.	RATED RPM	RATED KW	EFF. %	MAX RPM	NO PHASES
AC	6.75	3450	.37	-	6000	1
AC	6.75	3450	.56	69	6000	3
AC	8.50	3450	.56	-	6000	1
AC	8.50	3450	.75	75	6000	3
SR	6.75	3450	1.2	91	10000	4
SR	8.50	3450	2.3	92	10000	4

NEMA 56 FRAME 6 5/8" DIAMETER

	LG.	RATED RPM	RATED KW	EFF. %	MAX RPM	NO PHASES
AC	7.75	3450	.56	-	6000	1
AC	7.75	3450	.75	75	6000	3
AC	9.25	3450	1.1	-	6000	1
AC	9.25	3450	1.5	78	6000	3
SR	7.75	3450	2.3	92	10000	4
SR	9.25	3450	3.5	93	8000	4

FIGURE 10

yoke. The purpose of this is to minimize the iron losses to achieve the high efficiencies. These designs are 4 phase which means the stator iron loss switching frequency equals the following:

$$\frac{3450\ \text{RPM}}{60} \times 24 = 1.38\ \text{KHZ}$$

Since there are 4 phases and 6 rotor poles there are 24 flux changes in the stator yoke per revolution. The stator poles experience only 8 flux changes per revolution. The stator poles experience 6 flux changes per revolution while the rotor yoke is the same as the stator yoke.

The principal reasons for the higher power density and higher efficiency of the SR designs over the AC induction motor designs is as follows:

1 - No I^2R losses in rotor.
2 - Very short phase winding end turns.
3 - Greater number of energy conversion strokes per revolution.

The most important single performance advantage the SR motor has over the induction motor is that the efficiency remains very constant over a very wide RPM range. The induction motor efficiency drops off very rapidly as speed is reduce due to its increasing rotor losses at low speeds.

The SR motor performs much better at higher RPM than the induction motor because the phase firing angles can be easily advanced proportional to RPM. These features make the SR motor ideally suited for variable speed applications over a wide RPM range. Due to their simplicity they are robust and much lower in cost than permanent magnet brushless motors of comparable performance.

One final point is well documented by comparing the single phase AC induction motor with the polyphase SR motor. The efficiencies of these AC motors are seldom given in sales literature because they are so poor. The SR motors in these size ranges produce significantly higher efficiencies than the polyphase AC motors. In larger HP sizes the efficiencies of all motor types exceeds 90%.

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3 - Greater number of energy conversion strokes per revolution.

The most important single performance advantage the SR motor has over the induction motor is that the efficiency remains very constant over a very wide RPM range. The induction motor efficiency drops off very rapidly as speed is reduce due to its increasing rotor losses at low speeds.

The SR motor performs much better at higher RPM than the induction motor because the phase firing angles can be easily advanced proportional to RPM. These features make the SR motor ideally suited for variable speed applications over a wide RPM range. Due to their simplicity they are robust and much lower in cost than permanent magnet brushless motors of comparable performance.

One final point is well documented by comparing the single phase AC induction motor with the polyphase SR motor. The efficiencies of these AC motors are seldom given in sales literature because they are so poor. The SR motors in these size ranges produce significantly higher efficiencies than the polyphase AC motors. In larger HP sizes the efficiencies of all motor types exceeds 90%.

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