AC, BRUSHLESS, SWITCHED RELUCTANCE MOTOR COMPARISONS

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INTRODUCTION

During the past 75 years or so we have seen a tremendous growth in the use of electric motors in the Industrial World. This activity has not subsided or leveled off as we continue to see the industrialization process take place in the third World Countries. The main workhorse of this motor industry has been the three phase induction motor with the DC shunt motor also a significant "prime mover".

Until recently the AC Induction Motor was a fixed speed machine. This required that many different power transmission products needed to be used along with the AC motor to facilitate the vast variety of motions and speeds required for various machines, appliances and other motor driven products.

After the invention of the transistor and the improvements in permanent magnets, the Brushless DC Motor has become very popular for many applications around the world. These types of machines are available in several configurations from open loop controlled multi-toothed per pole drives called Stepping Motors to both inside PM rotor and outside PM rotor closed loop machines. Due to their wide range of performance and motion control capabilities, many of the power transmission components have been eliminated.

More recently another form of the Brushless DC Motor has been revisited which does not use any permanent magnets. It is called the Switched Reluctance Motor or the Variable Reluctance Motor. It's low manufacturing cost and ruggedness makes it quite appealing for many adjustable speed or servo applications.

The purpose of this paper is to provide a brief overview of these three machine types and compare their advantages and disadvantages. Finally an analysis will be made of three identically sized machines, a Polyphase AC Induction, a Rare Earth Permanent Magnet Brushless DC and a Switched Reluctance Brushless DC Motor. They will be compared on the basis of being applied as adjustable speed machines over a very wide speed range, with each properly cooled with an external blower. Several figures of merit will be presented along with relative cost comparisons. The intent is not to favor one motor over another, but to present the three motor choices in perspective so that for a given application you will have some guidelines to assist you in making a more rational selection rather than trying to determine the best machine from catalogue data or from the sales pitch.

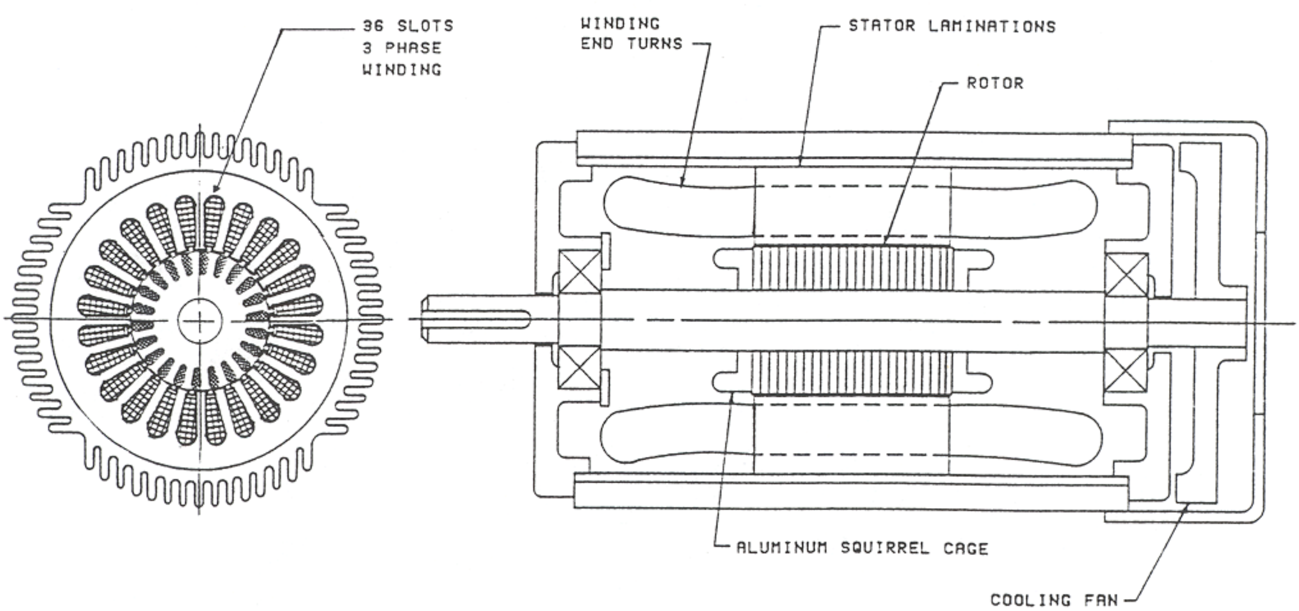


FIG 1. POLYPHASE AC INDUCTION MOTOR

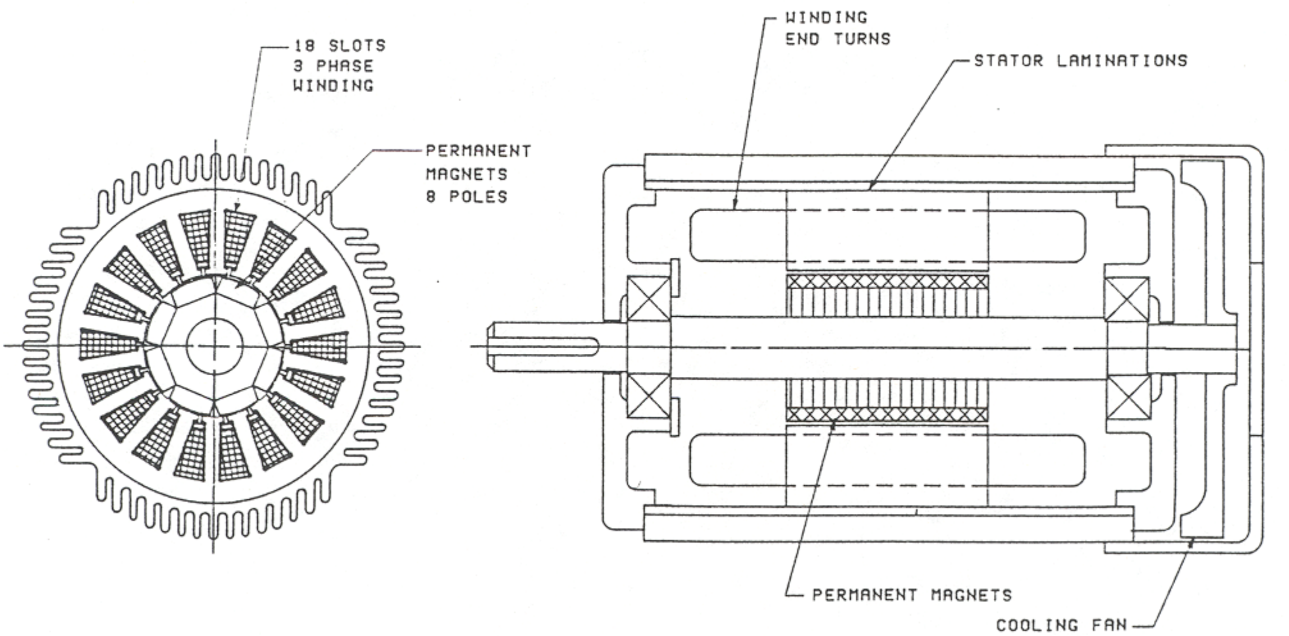


FIG 2. BRUSHLESS DC MOTOR

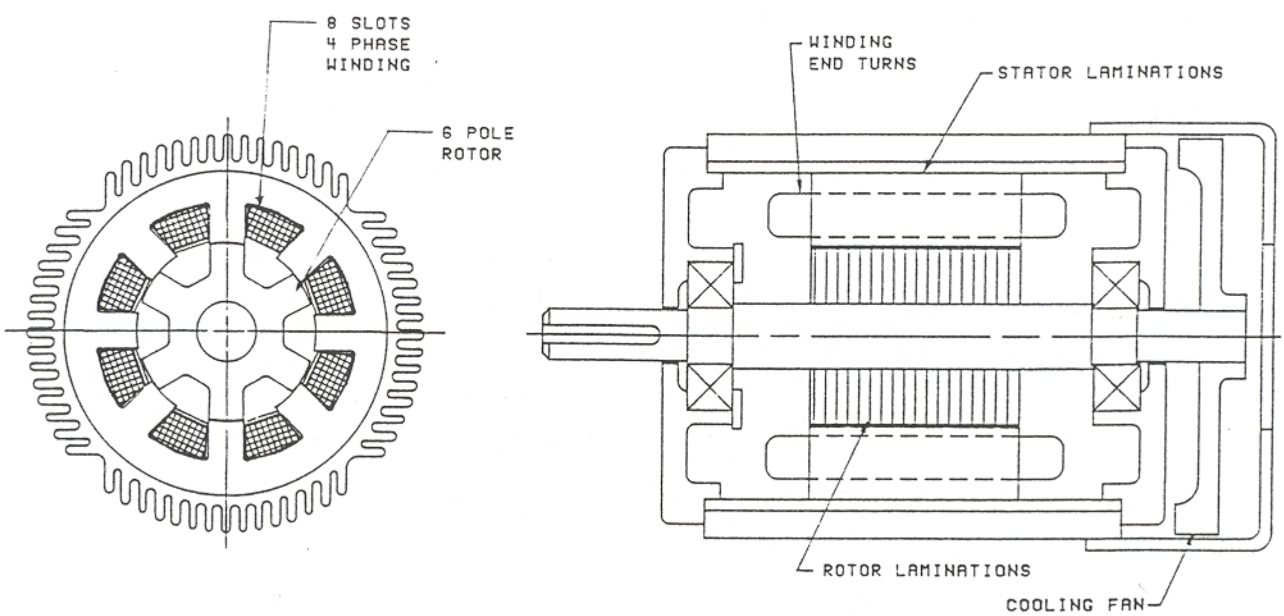


FIG 3. FOUR PHASE SWITCHED RELUCTANCE

THREE MOTOR CHOICES WITHOUT BRUSHES

The typical cross section of each of the three motor types is shown of Figures 1, 2 and 3. These particular cross sections are cut through the center of the motor and through the length to show where the windings are and where the magnets are.

It is important to note that each of these three machines is fairly easy to cool which is required to exit the losses generated from the copper windings and the iron. Perhaps the Induction Machine is at some disadvantage because it develops more heat than the other two in the rotor due to its squirrel cage winding.

The Brushless machines have only iron and permanent magnets in the rotor while the Switched Reluctance machine rotors contain only iron.

In each case the stators are similar with a considerable amount of magnetic laminated iron containing copper coils wound or inserted up and down the slots. The stator is responsible for most of the heat generated and since the stator is stationary it is simple to cool using either air or a liquid.

The Induction Motor has very large end turns of copper as does the Brushless DC Motors. The Switched Reluctance Motors have extremely short end turns and although this would appear to favor the SR machine in terms of I R losses, in fact the SR machine requires more turns than the Brushless DC because it has no permanent magnet flux to cross link the stator flux. Therefore, a single magnetic field must be produced with only the stator windings in the SR or VR machine. It is the intent of this paper to determine the significance of these differences of the three machines when we compare the three motors.

Looking at the right hand view of Figures 1, 2, and 3 the cross sections of the three motors which are cut down the length of the shaft clearly indicate some other differences.

Of particular importance is the winding overhang of the end turns past the lamination stack lengths. The two parameters which were kept identical in all three cases were the active dimensions of the magnetic iron which is the stator lamination outside diameter and the rotor and stator stack or pack lengths.

All other dimensions have been optimized in order to properly balance the use of copper, iron, air and permanent magnets if used. Since each machine utilizes these materials in a somewhat different way, the only fair comparison would be one which utilizes the materials to its particular advantage.

TABLE I

DIMENSIONS. VOLUMES & WEIGHT COMPARISONS
OF THREE MOTOR TYPES (NEMA 184 T FRAME)

MOTOR TYPE	STATOR OD	LAMINATION ID	ROTOR OD	AIR GAP	OVERHANG STATOR	OVERHANG ROTOR	STACK LENGTH	AIR GAP AREA
AC INDUCTION	7.625	4.432	4.432	.015	1.60	.70	5.00	70 SQ-IN
PM BRUSHLESS	7.625	3.780	3.750	.015	1.50	0	5.00	59 SQ-IN
SR BRUSHLESS	7.625	4.280	4.250	.015	.75	0	5.00	67 SQ-IN

ROTOR DATA	LAMINATION VOLUME (CU-IN)	LAMINATION WEIGHT (LBS)	MAGNET VOLUME (CU-IN)	MAGNET WEIGHT (LBS)	ALUMINUM VOLUME (CU-IN)	ALUMINUM WEIGHT (LBS)	TOTAL VOLUME (CU-IN)	TOTAL WEIGHT (LBS)
AC INDUCTION	56	16	0	0	31	2.8	87	18.8
PM BRUSHLESS	45	13	7.2	2.2	0	0	55	15.2
SR BRUSHLESS	49.41	14.8	0	0	0	0	71	14.8

STATOR DATA	LAMINATION VOLUME (CU-IN)	LAMINATION WEIGHT (LBS)	COPPER VOLUME (CU-IN)	COPPER WEIGHT (LBS)	TOTAL VOLUME (CU-IN)	TOTAL WEIGHT (LBS)	ROTOR & STATOR VOLUME (CU-IN)	ROTOR & STATOR WEIGHT (LBS)
AC INDUCTION	58	17	47	15.4	264	32.4	351	51.2
PM BRUSHLESS	92	27	37	12	221	39	276	54.2
SR BRUSHLESS	66	20	33	10.5	171	30.5	242	45.3

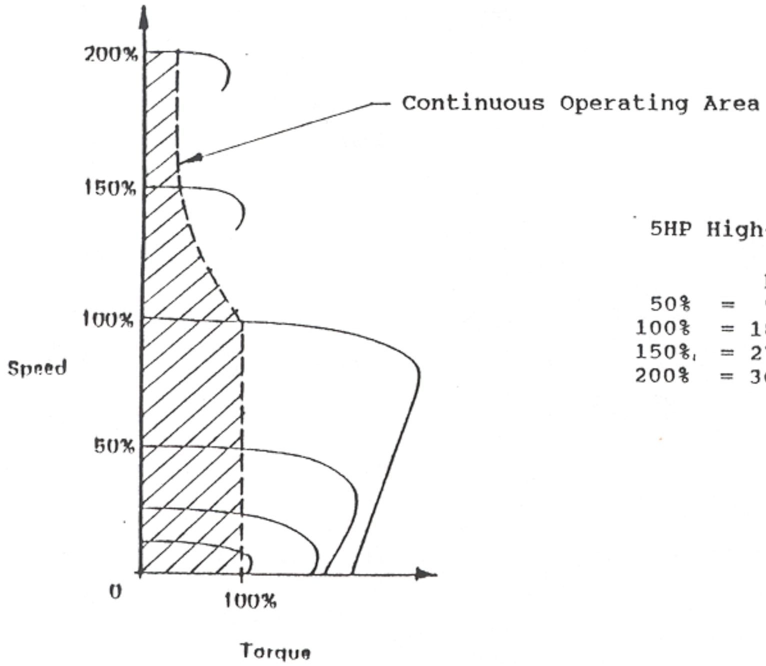
Table I shows a summary of the critical dimensions of the active of magnetic portions of the three motor types. The number of stator slots and rotor poles are also given. The material weights and volumes have been calculated from the physical dimensions and material densities.

The other important commodity (although not a material) is the input power which must be used to properly utilize the materials. Any newly designed Brushless DC Motor using modern permanent magnets or the Switched Reluctance type without magnets would naturally be designed and constructed to offer the maximum performance and efficiency possible, using the best magnets and lamination materials. Therefore it would be unfair to compare these brushless motors with any old standard commercial AC Induction which was probably designed 30 to 40 years ago when electricity was cheap.

The Induction Motor used in this study is a modern high efficiency model designed and built for a rapid pay back in energy savings over the higher initial cost. This motor was designed to be used as either a single speed line start poly-phase machine or an inverter driven variable speed machine. The inverter was a variable frequency and adjustable voltage system to provide a boost voltage at low frequencies (low speeds). From about 20 HZ up to 60 HZ the voltage would increase proportionally and remain constant from 60 HZ on up to 120 HZ.

The Brushless Machine was driven by a six step trapezoidal drive with the phases commutated from an optical encoder. The control loops included current, commutation and RPM. The 3 phase wye connected brushless motor utilized 2/3 of the copper windings at a time with bi-polar current commutating one phase at a time with each phase energized for two commutation cycles.

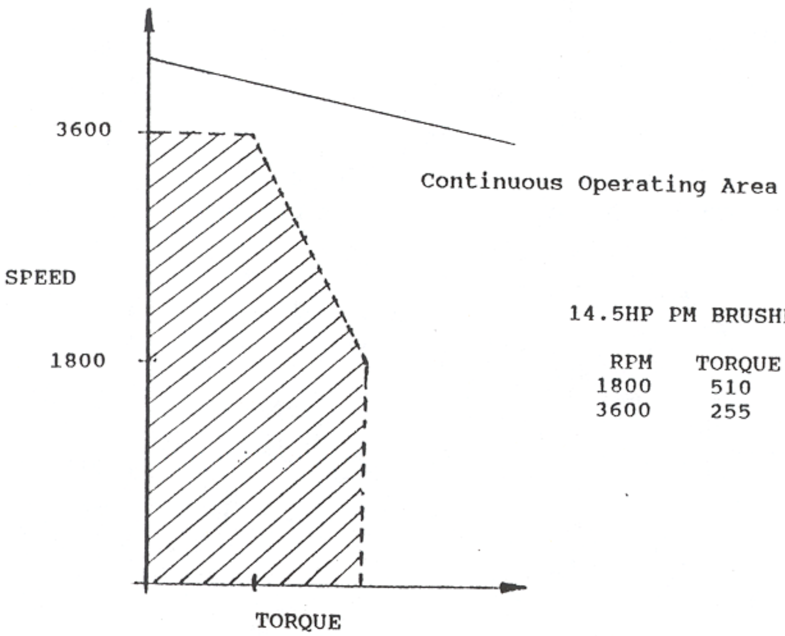
The Switched Reluctance Machine was driven by a 4 phase unipolar inverter. The control loops included current, RPM and half wave or unipolar commutation which provided for advance and phase overlap. At low RPM the phases are commutated at "Top Dead Center" with phase overlap to minimize torque ripple and maximize average torque output. As the RPM is increased, the commutation is advanced (or early phase turn-on) which greatly increases the torque of this type of machine.



5HP High-Efficiency

		RPM	TORQUE
50%	=	900	175
100%	=	1800	175
150%	=	2700	88
200%	=	3600	88

FIG 4. SPEED - TORQUE AC INDUCTION MOTOR/INVERTER



14.5HP PM BRUSHLESS

RPM	TORQUE
1800	510
3600	255

FIG 5. SPEED - TORQUE PM BRUSHLESS MOTOR/INVERTER

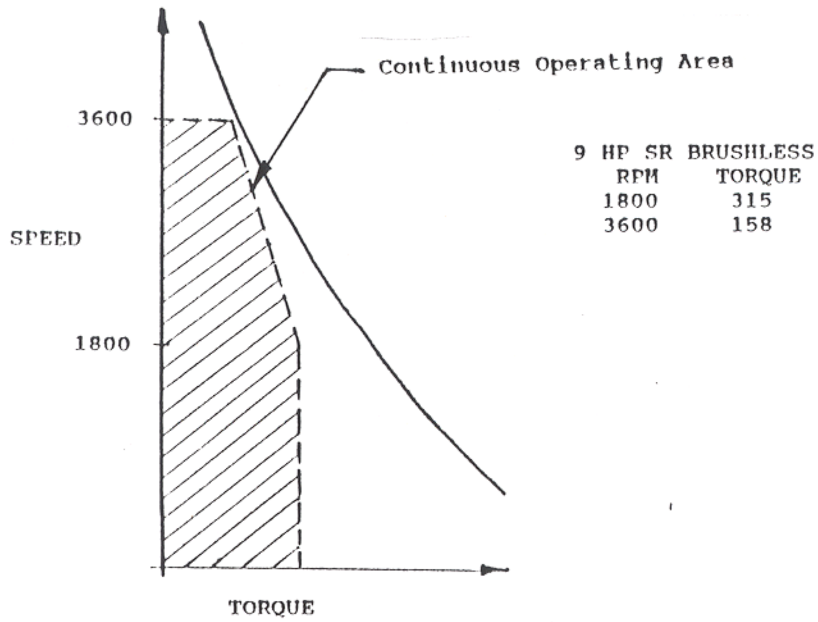


FIG 6. SPEED - TORQUE SR BRUSHLESS MOTOR/INVERTER

Figure 4, 5, and 6 show the typical speed vs. torque curves of the three types of motors so that a clear picture of their inherent differences can be understood. The full excursion of the machines capabilities of torque production at all speeds is not usable in real practice. The continuous operating area is shown as a shaded portion, this is due to heating of course.

The summary of the comparative data is shown on Table II in terms of each respective rated continuous output power and efficiency. Several ratios are calculated to provide a more detailed comparison of the three machines with respect to iron and copper usage as well as the air gap magnetic loading of the three machines.

Perhaps the most important aspect to this comparison is the significance of consistent cooling with each machine. For example, other comparisons of these three technologies normally rate machines of the same HP or continuous rating. Because of the differences in copper, iron, magnet and air gap utilization of each machine, similar HP rated machines of these three technologies differ significantly in terms of their size and mass. This fact

TABLE II
PERFORMANCE COMPARISON

MOTOR TYPE	CONTINOUS TORQUE 1800 RPM	CONTINOUS HP (75°C)	EFFICIENCY	CURRENT DENSITY
AC INDUCTION	175 LB-IN LOADED	5.0	90% CATALOGUE	7.8 A/mm^2
PM BRUSHLESS	500 LB-IN LOADED	14.5	94% MEASURED	7.65 A/mm^2
SR BRUSHLESS	315 LB-IN LOADED	9.0	92% MEASURED	7.7 A/mm^2

ALL DATA AT RATED TORQUE & POWER

MOTOR TYPE	GAP STRESS PSI	TORQUE/LB (LB-IN/LB) ROTOR	STATOR	TOTAL	POWER/LB (HP/LB) ROTOR	STATOR	TOTAL
AC INDUCTION	1.12	9.31	5.40	3.42	.27	.15	.10
PM BRUSHLESS	4.59	33.55	13.08	9.41	.95	.37	.26
SR BRUSHLESS	2.20	21.28	10.33	6.95	.61	.30	.20

MOTOR TYPE	TORQUE/LB (LB-IN/LB) LAMINATIONS	CONDUCTORS	POWER/LB (HP/LB) LAMINATIONS	CONDUCTORS
AC INDUCTION	5.30	9.61	.15	.27
PM BRUSHLESS	12.75	42.5	.36	1.21
SR BRUSHLESS	9.05	30.0	.26	.86

causes the cooling to be inconsistent and not equally affective for each motor which makes the comparison suspect.

By comparing the three motors of equal magnetic diameter and length with the same housing material and shape, the affects of "air over" fan cooling is consistent from one motor to another.

The continuous output ratings will then be different for each motor technology which is exactly what the data shows. At least, however, the affects of different sizes of physical dimensions and mass will not detract from the output capability comparison of one machine to another. With the same amount of cooling air removing the heat from I^2R and iron losses the true comparison of these three machines can be analyzed.

The results listed in Table II show clearly significant differences in rated output HP of each machine. It is also important to keep in mind what was stated earlier that even though the air gap between the rotor and stator is .015" for each machine the actual rotor diameter is not the same as this had to be optimized for each machine. In fact the high efficiency AC induction motor was just disassembled and the actual dimensions were measured. Since this design is a new one it was assumed that the dimensions were optimized. The Brushless Motor rotor diameter was designed in accord with the best utilization of the permanent magnet flux and the use of copper.

The SR machine rotor diameter was selected based on careful computer modeling to select the rotor diameter (as the only independent variable) to achieve the maximum output power with the least input power at the mid speed range. The stator diameter and length were kept fixed to the AC Induction Motor dimensions.

For the purpose of analyzing the cost of the three motors, we should assume that the housing, shaft, end frames, ball bearings, fan cover and junction box are the same cost for each motor. Whatever design or material used in one motor could be used for all three. In fact, the AC Induction Motor mechanical parts were used for the Brushless DC and the SRDC machines.

The AC Induction Motor does not require any shaft position feed back sensors such as hall switches or an encoder if a vector control inverter is not used. Normally the brushless and SR machine would require sensors, but electronic or sensorless commutation can be used for adjustable speed drives, so this is not a significant advantage for the AC Induction Motor.

TABLE III

COST COMPARISON - MATERIAL ONLY

MOTOR TYPE	COPPER $2.00/LB	IRON $.75/LB	ALUM. $1.50/LB	MAGNETS $150.00/LB	TOTAL COST
AC INDUCTION	30.80	24.75	4.20	-0-	$59.75
PM BRUSHLESS	24.00	30.00	-0-	330.00	$384.00
SR BRUSHLESS	21.00	26.10	-0-	-0-	$47.10

MOTOR TYPE	TORQUE/DOLLAR	DOLLAR/HP	TORQUE/$/LB
AC INDUCTION	2.93 LB-IN/$	11.95 $/HP	.057
PM BRUSHLESS	1.33 LB-IN/$	26.48 $/HP	.025
SR BRUSHLESS	6.69 LB-IN/$	5.23 $/HP	.148

The only parts which vary significantly between the AC Induction, PM Brushless, and SR Brushless are the stator assemblies and the rotor assemblies. Table III compares the cost of the various materials used in each machine based upon the weights and volumes from Table I. Finally a total cost per pound is determined for each type of machine along with a figure of merit which should be relevant to the potential user of one of these motors. This decimal number is equal to the rated continuous torque output divided by the cost of the active magnetic materials without labor, divided by their weight.

Two other ways of quickly determining the relative merits of one machine verses the other is to look at the continuous rated torque output divided by the cost of the magnetic materials. The second way is to take the cost of those active magnetic materials and divide by the continuous rated output power. All of these figures of merit are shown in Table III.

There is one comparative piece of data that has not been analyzed in this study because these motors are used in adjustable or variable speed drives. This piece of data is the rotating inertia. The data would indicate that a brushless motor using either samarium cobalt or neodymium boron magnets could never be cost effective against the AC Induction/Inverter adjustable speed drive or the Switched Reluctance Drive. It would seem that the distinct advantage of low inertia would be the only feature that would warrant the selection of a rare earth permanent magnet brushless motor.

There are, however, two (or more) possible permanent magnet rotor designs which would achieve acceptable torque per dollar, dollar per horse power, and torque per dollar per pound figures of merit. One of these involves decreasing the number of magnets in half with a consequent pole design and the other involves the use of imbedded ferrite magnets which are approximately $3.00 per pound.

The copper overhang inside the stator is significantly different for each of the three machines. Even though the stack length was equal (5") for each of the three machines, the stator volume was quite a bit different because of the copper winding end turns. In fact, all three motors were built into the same NEMA frame 184T, but the brushless motor could have been made about 1.5 inches shorter and the SR motor could have been made about 4 inches shorter because of this end turn volume. The finned cast housing from the original high efficiency AC Induction Motor was used for both the other designs to assure equal fan over cooling. As a matter of fact, the identical fan impeller was used for all three machines.

It was quite a surprise that the Switched Reluctance Motor achieved the favorable figures of merit resulting from this study. The labor content was not compared but it would appear that if all production facilities were equal that the Switched Reluctance labor would be less than the AC Induction and considerably less than labor required to fabricate a Permanent Magnet Brushless Rotor. It will be interesting to determine if this sort of comparison would yield similar results with sub-fractional motors as well as large integral horse power machines.