SWITCHED RELUCTANCE BRUSHLESS DC MOTORS WITH LOW LOSS MAGNETIC CIRCUITS

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Abstract: Someone has predicted that the SWITCHED RELUCTANCE motor will become the motor of the nineties. One of the many advantages of the SWITCHED RELUCTANCE type of Brushless DC motor is it's ability to provide power over a wide speed range without the incumbrance of the cost and retention of permanent magnets.

Most all electric motors operating at high speeds must use the expensive lamination grades to reduce iron losses. External or internal cooling methods are also required to reduce the effects of overheating caused by those losses.

SWITCHED RELUCTANCE motors have the same iron loss problems when their advantages are utilized either as low pole count, high RPM designs or high pole count machines for operation in direct drive low speed, high torque modes.

A magnetic circuit has been developed for SWITCHED RELUCTANCE motors which significantly reduces these iron losses caused by rapid commutation phase switching. This Patent Pending design is based upon arranging the stator poles and phase windings with respect to the rotor poles in such a way that the rotor and stator yokes or "back iron" are exclusive to each phase. In other words, unlike most all other electric motor magnetic circuits, the lamination iron used to contain magnetic flux from energization of a phase is not shared by any other phase.

Exclusive magnetic circuit iron for each phase of the SWITCHED RELUCTANCE motor results in reducing the phase switching loss frequency which reduces the heating in the motor resulting in an increase in efficiency. While previous motor magnetic circuits suffer from a loss frequency equal to the speed commutation frequency, this design limits the iron yoke loss frequency to the speed frequency divided by the number of phases.

1.0 INTRODUCTION

A switched reluctance brushless DC motor describes an electronically commutated DC motor which contains a single electromagnetic circuit to convert electrical energy to mechanical energy. The stator portion of the magnetic circuit has salient poles wound with one or more phases of copper windings. The rotor is also a salient pole structure without magnets or windings. The stator phases are connected to a supply voltage and switched on and off in a CW or CCW sequence to cause rotor rotation by the attraction of the rotor poles to the stator poles. As with all brushless DC machines, angular rotor position information is needed to instruct the phase switching to cause smooth torque and rotation in the desired direction (Ref. I). Since there are no permanent magnets or secondary windings on the rotor, only unipolar current is required for phase energization which causes a unique iron flux switching arrangement which we will analyze. Bipolar current is most commonly used for other types of brushless DC motors.[1]

The main advantages of the SR motors and drives are listed as follows:

- DC brushless without permanent magnets.
- Constant performance over wide temperature range.
- Very high low speed torque.
- Extreme high speed capability.
- Majority of losses in stator, ease of cooling.
- Rugged low cost machine.
- Zero torque under shorted conditions

The SR motor is a very simple motor to manufacture without requiring new state of the art manufacturing processes. The drives are not exotic and can accept shaft position data from all standard brushless DC shaft position sensors, encoders, resolvers, Halls, optical, etc. Sensorless commutation is practical without the possibility of rotation direction error (Ref. III).

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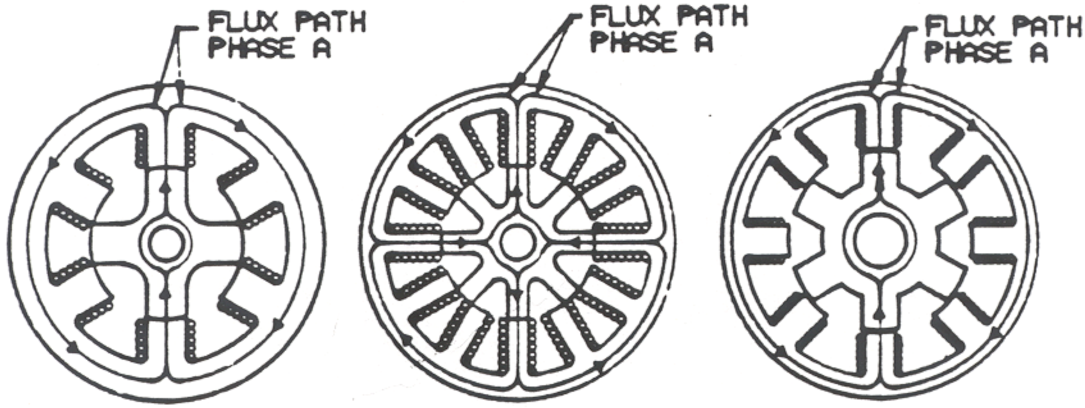
[1]For those interested in the historical origins of the VR or SR machine, see Ref. II.

There has been much published in recent years of the details of SR motors and drives. Their principles of operation in all their various forms have been well documented, little of which will be repeated here. Those interested in further reading can refer to an excellent reference book published by PCIM and edited by Dr. Tim Miller (Ref. V).

2.0 PRIOR ART SR MOTORS

Since SR motors take their modern historical beginnings from VR stepping motors, one would expect that most early designs would be either 3 phase or 4 phase types with magnetic circuits very similar to VR stepping motors. It would appear that the majority of the R&D efforts for SR systems in recent years center around the drive development to maximize motor performance both at low speeds for smooth low ripple torque and at higher speeds for best efficiency. (Noted in Ref. V). It seems that there has been a scarcity of published accounts of improved SR motor developments (except Ref. VIII).

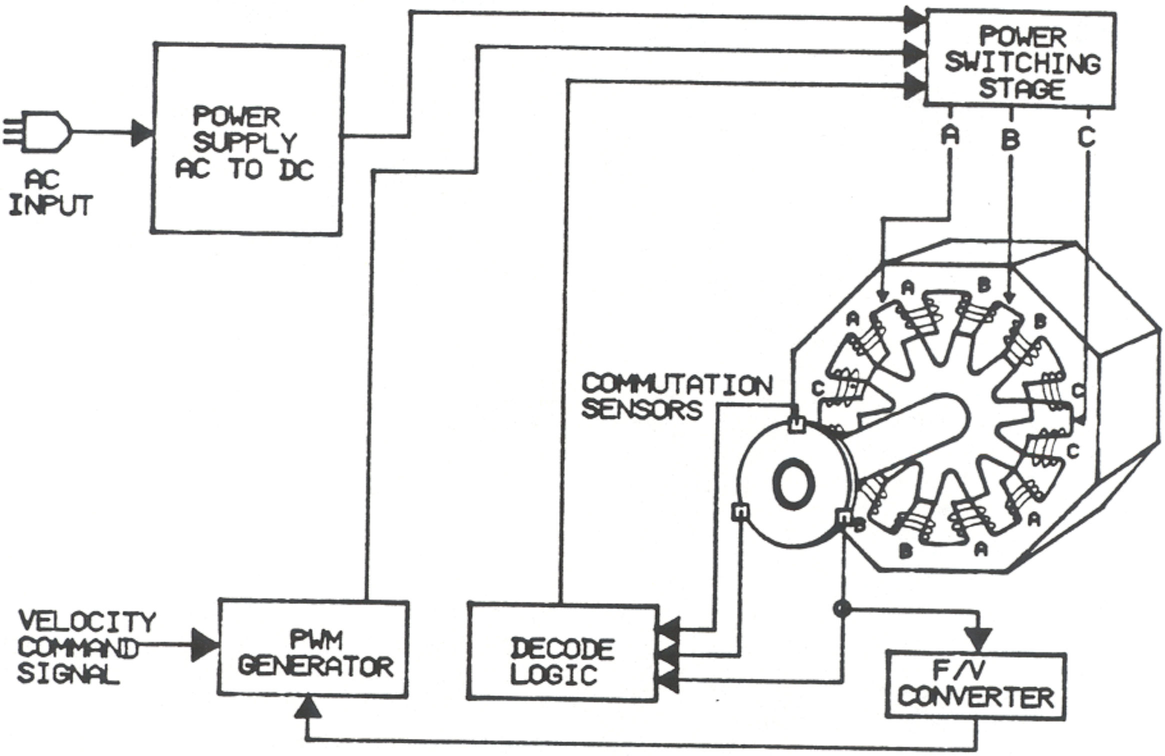


6/4 3 PHASE
FIG. 1A

12/8 3 PHASE
FIG. 1B

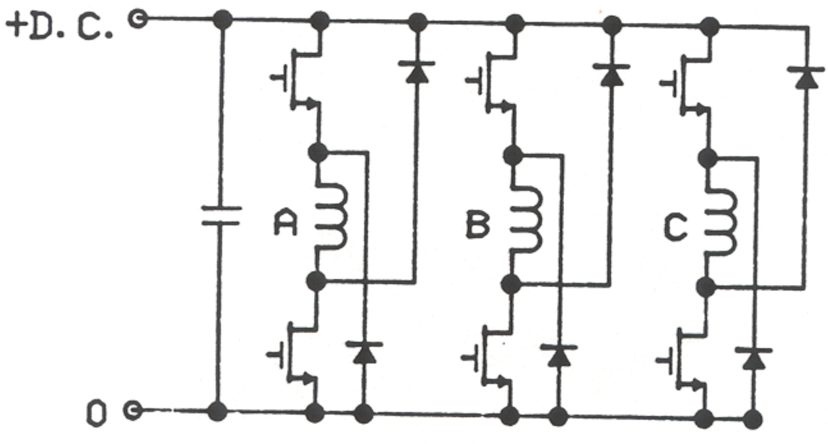
8/6 4 PHASE
FIG. 1C

The three examples shown in Figures 1A, 1B and 1C clearly illustrate the basic magnetic circuits of the most common SR motor configurations. Fig. 2A shows the general control configuration required to drive the SR motor. The three phase unipolar power circuit shown in Fig. 2B is typical for driving SR motors shown in Fig. 1A and Fig. 1B. The 4 phase motor shown in Fig. 1C requires a similar drive circuit as shown with the addition of one more transistor pair and two diodes. (A six transistor design is possible for the 4 phase.) In Fig. 1A, B, C, it is important to note the magnetic flux paths produced by the NI (amp-turns) through the poles of the energized phase around the outside stator yoke or back iron. Figures 1A and 1C each have two flux paths per phase through the stator while Fig. 1B has four flux paths through the stator per phase. When the first phase is switched OFF and the second phase is switched ON the following points are



SR MOTOR CONTROL DIAGRAM

FIG. 2A



3 PHASE SR DRIVE CIRCUIT

FIG. 2B

important:

- Flux path from ON phase travels around outside of stator through center of rotor (longest possible path).
- Phase OFF when inductance is high (small air gap).
- Phase ON when inductance is low (large air gap).
- Flux reversals in stator yoke
- Flux reversals in rotor yoke
- $\pm \frac{d\phi}{dt}$ or collapsing/increasing fields in magnetic iron
- A tangential force (torque) results between rotor and stator poles of ON phase.
- Stator and rotor yoke iron shared by magnetic flux produced by all phases.

The preceding points relate to the losses in the iron of the SR machine. Although high grade annealed laminations can be used to reduce eddy current and hysteresis losses, it would be desirable to develop a magnetic circuit which would significantly reduce those losses. Increasing the number of poles of a SR machine both increases the average torque output and contributes to a decrease in the torque ripple. The drawback of increasing poles is higher commutation frequencies at the same speed which causes greater iron losses. If those could be reduced without added cost, the SR motor could offer additional performance enhancements as a prime mover, adjustable speed drive or servo motor.

It is well known that SR motors are capable of very high speeds (30,000 RPM or higher). The losses in any electric motor consists of copper losses, iron losses, windage and bearing friction. As we know, many motors contain fans to cool the iron and copper since that benefit far offsets the slight additional windage loss from the fan. At low speeds the I^2R or copper losses are by far the largest contributor to heat and poor efficiency. As the speed is increased the iron losses exceed the copper losses. All high speed motors have this characteristic. Very expensive, thin laminations can be used with interlaminar insulation which will reduces eddy currents at a certain cost penalty.

3.0 IRON LOSSES IN MOTORS

As phases are energized and de-energized in brushless DC motors, step motors, or SR motors, the dI/dt yields dø/dt flux). Since ferromagnetic materials must be used to contain and focus ø (magnetic flux), a phenomenon takes place in the iron to alter its magnetization. The material contains magnetic domains which are repeatedly aligned and realigned during the phase switching. The changing magnetic alignment causes a "friction" within the iron which results in its heating. This energy loss is called "Hysteresis" loss which prevents the magnetization process from being completely reversible.

Magnetic hysteresis can be displayed graphically as shown in Fig. 3 which traces a B-H curve through it's complete magnetizing, demagnetizing, remagnetizing and redemagnetizing cycles until one complete loop is completed. The area inside a, b, c, d, a represents the magnitude of the energy loss/cycle. Any portion of the motor iron subjected to AC current or a cyclical flux having equal positive and negative values experiences this hysteresis loss as contained in some portions of all SR motors (and most other types of motors as well).

All of the remaining iron in a motor circuit experiences what is known as minor loop hysteresis losses. Some texts refer to this as DC hysteresis losses where flux increases from zero to some peak value then decreases back to zero. A close approximation of this minor loop looks like the first quadrant of the full loop in Fig. 3. However in the case of the SR or VR motors where the air gap varies so greatly during one stroke or cycle, the actual value is quite complicated and left for another time.

What is most important is that the loss in watts/lb is given by the following:

$$W_H = \frac{454 \times 10^{-7}}{4\pi} \frac{Af}{\delta}$$

where: A= loop area in Gauss-Oersteds
f= Switching frequency
δ= Iron density Gauss/cm^2

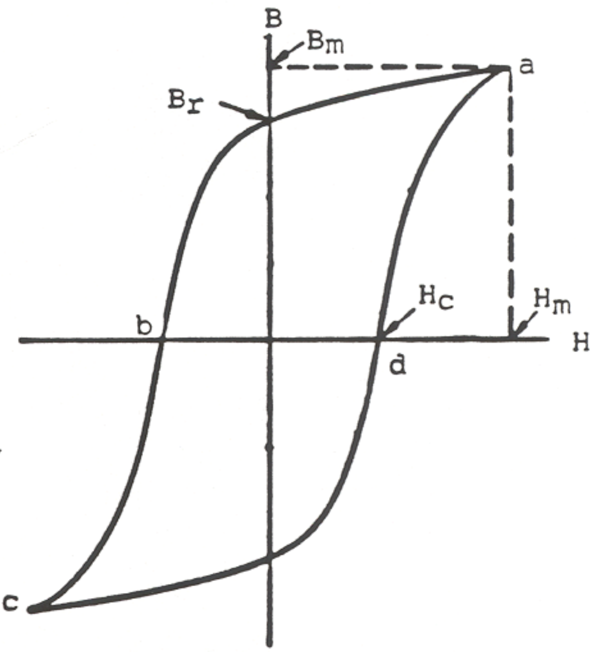


FIG. 3

This clearly shows that the hysteresis loss is dependent on commutation switching frequency, and magnetic induction.

The other magnetic loss in the iron is caused by Eddy currents inside the iron itself caused by either of the following events.

1. Motion of a low resistivity material (iron or copper) through a magnetic field (or the reverse).
2. Increasing or decreasing the current in coils of wire within the iron.

These Eddy currents also produce their own magnetic field which oppose or cancel the electromagnetic fields caused by the phase coils thus subtracting from motor torque. Fig. 4A shows a simple representation of Eddy currents and how laminating can reduce them in Fig. 4B.

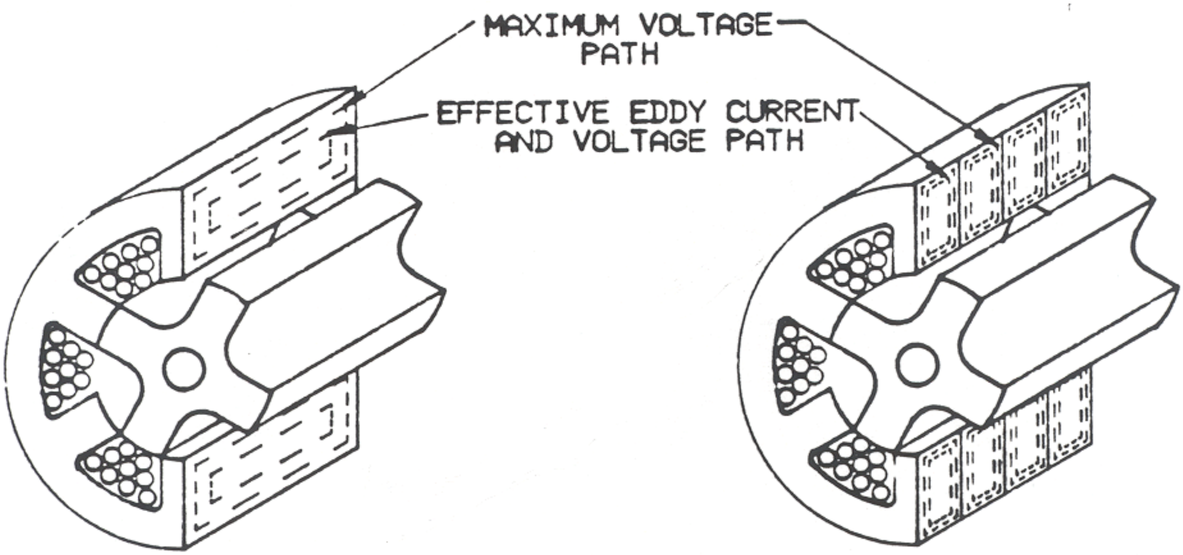


FIG. 4A FIG. 4B

EDDY CURRENT PATHS

Eddy current loss is defined as:

$$W_e = \frac{Kt^2 \quad B^2 \, f^2}{\rho}$$

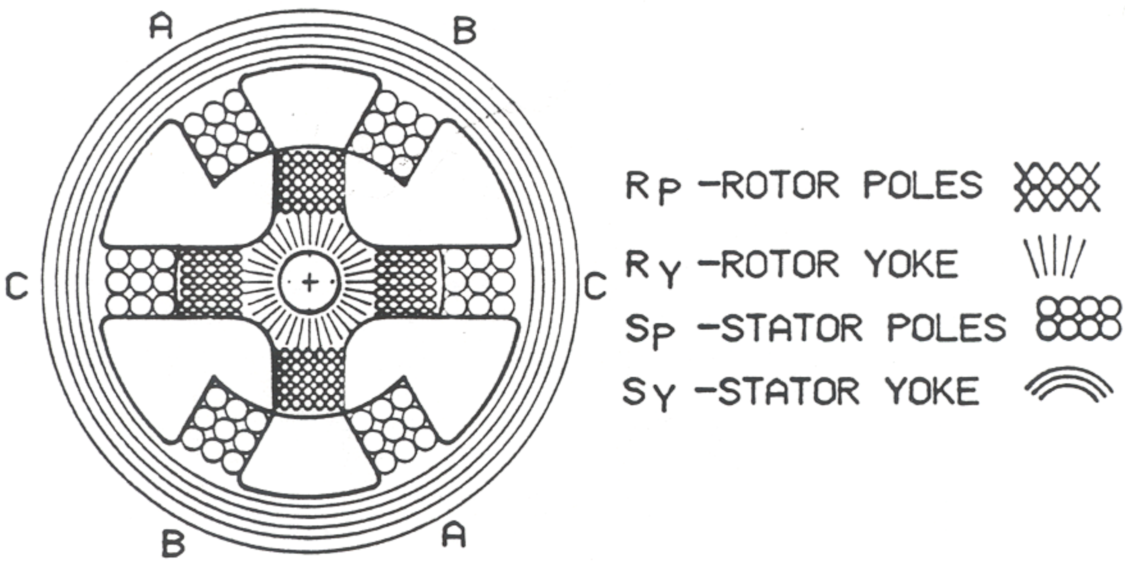
t= lam thickness
B= magnetic induction
f= switching frequency
ρ= lam resistivity

It is clear that Eddy current losses are affected by t^2, B^2 f^2 and ρ. Therefore it is desirable to make the lam thickness as thin as practical, of the highest resistivity iron material and keep the switching frequency as low as possible. Fig. 4B shows the same motor circuit as 4A but with the stator iron divided into 4 laminations. The flux in each lamination is 1/4 of the total flux and the voltage induced in the iron is 1/4 of the former value. If the Eddy current path were unchanged the currents would also be quartered but the corresponding losses would be 1/16. The direction of the Eddy currents is such that it counteracts the flux change which produced the currents and they are opposite to the current in the windings. The result of these negative Eddy currents, besides causing heating, is that they prevent the flux from penetrating the iron core material so that a skin effect results and the effective iron area is reduced.

In all electric motors it is desirable that the magnetic induction B be as high as possible to achieve the most usable output torque at high speeds.

If we look at Fig. 5 we have a typical SR rotor and stator iron circuit which is divided into four regions. For any type of SR motor with various stator, rotor pole and phase combinations, each region of the motor magnetic circuit is subject to a specific switching loss frequency. Each region experiences a different frequency which is dependent upon the number of phases, number of poles, RPM and the flux paths. These will be analyzed in more detail. Both hysteresis and Eddy current losses are generated in each region. The actual value depends upon the value of the variables in the loss equations above.

Air by fan cooling or in some cases even water cooling or refrigeration cooling must be used to prolong the motor's life due to these losses.



REGIONS OF MAGNETIC IRON SUBJECTED TO CORE LOSSES

FIG. 5

4.0 A LOW LOSS MAGNETIC CIRCUIT

Figures 6A through 6L depict a typical 6/4 3 phase SR or

6/4 3 PHASE SR MOTOR 3 COMMUTATION/POWER STROKES MAGNETIC FLUX ANALYSIS

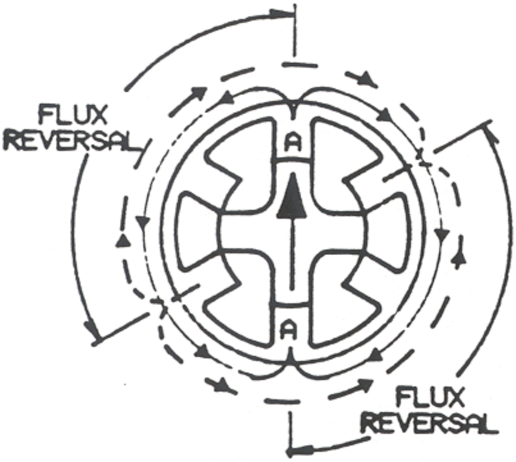


FIG. 7A

- Flux cycle of + peak occurs in 1/3 of volume of Sy in 2 strokes out of 3 and 2/3 of volume in 1 stroke out of 3
- No flux reversals in volume of Sp.
- Rp flux reversals 2 per REV.
- Ry flux reversals 2 per REV.

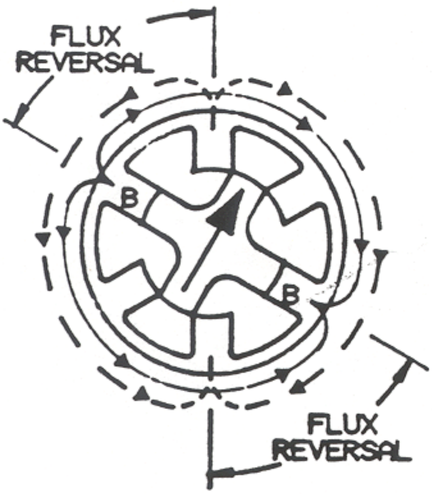


FIG. 7B

SWITCHING FREQUENCIES OF IRON REGIONS

	f_e Eddy	f_{hDC} 0 + 0 Hyst.	f_{hAC} + 0 - Hyst.
Sy	RPS (12)	RPS (4)	RPS (8)
Sp	RPS (4)	RPS (4)	0
Ry	RPS (6)	RPS (6)	RPS
Rp	RPS (6)	RPS (6)	RPS

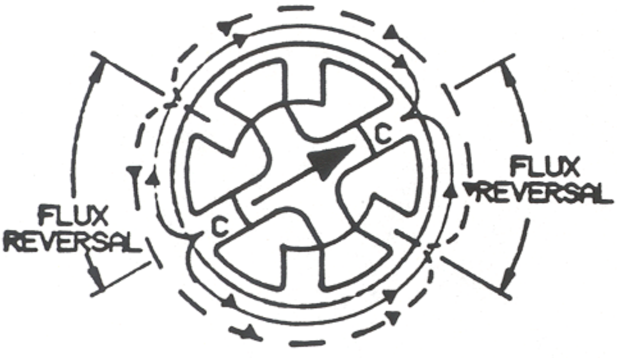


FIG. 7C

VR motor. (Six stator poles, six stator coils, 2 coils/phase and 4 rotor poles). One complete revolution of the rotor is shown through 12 strokes. Notice the arrow showing rotor position as each phase is switched ON and OFF. The magnetic flux through the iron is shown going through the rotor and on through the stator portion, splitting and going around the outside of the stator-- the longest path possible. Since these motors have no magnets or conductors on the rotor the flux paths through the iron repeats four times out of twelve strokes to cause torque during one complete revolution.

Figures 7A, 7B, 7C shows just the first three strokes (the ones which repeat) of the previous figures. But in Fig. 7A, B, C we analyze in more detail the flux path created by the turned ON phase (in solid) along with the flux path of the turned OFF phase (dotted). Notice the arrows which depict the direction of magnetic flux. Further study indicates that there are complete loop hysteresis losses in 2/3 of the Sy (stator yoke) in one out of three strokes and in 1/3 of the Sy, in two out of three strokes (twelve strokes per rev.). A study of figures 6A through 6L reveals that the rotor pole (Rp) region goes through a hysteresis loop 1/4 of the time, every fourth stroke or 4 times/revolution. The rotor yoke Ry is subjected to exactly the same or 4 times/ revolution. The stator poles Sp never see a flux reversal due to the unipolar excitation.

All regions are subjected to Eddy current losses due to the switching of the phases. This Eddy current loss is greatly affected by the switching frequency in spite of using thin, insulated, high resistivity material grades.

Another point to keep in mind regarding iron losses has to do with the volume of magnetic iron. The iron losses are given in watts per pound at different frequencies and flux densities. Increasing B, t, f and weight or volume increases the losses. Therefore if the flux density B in all regions of the circuit is constant, then the losses are much greater in the stator yoke than anywhere else.

And finally since the hysteresis losses are affected by B and f to the first power and Eddy current losses are affected by B^2 f^2 it follows that the Eddy current losses would appear to dominate at high speeds.

Fig. 8A through 8O shows a 6/4 - 3 phase modified into a 6/5 - 3 phase motor. Notice that the two excited poles per phase are adjacent to each others so that the flux travels through very little of the iron around a very short path. In addition the stator yoke iron for phase A is not used when phase B or C is energized. We have a new magnetic circuit with exclusive magnetic iron for each phase which significantly reduces the commutation switching frequency in the yoke portions of the stator and rotor iron.

6/5 3 PHASE MOTOR ROTATION
15 COMMUTATION/POWER STROKES FOR 1 REVOLUTION

FIG. 8A

FIG. 8B

FIG. 8C

FIG. 8D

FIG. 8E

FIG. 8F

FIG. 8G

FIG. 8H

FIG. 8I

FIG. 8J

FIG. 8K

FIG. 8L

FIG. 8M

FIG. 8N

FIG. 8O

To achieve this (Patents Pending) low loss circuit several fundamental rules must be followed regardless of the number of poles and phases.

- Rotor poles are equally spaced
- Number of rotor poles can be odd or even
- Number of stator poles must be even
- Stator poles must be in pairs with angle between equal to rotor pole angle
- Stator pole angle between phase wound pairs can not be equal to wound pair angles
- The number of stator poles must be divisible by the number of phases

The low loss SR magnetic circuit described herein can be configured for any number of phases. It follows then that the minimum number of stator poles is always equal to two times the number of phases since there must be at least two poles per phase which are always adjacent to each other and of opposite magnetic polarity to assure the short adjacent flux paths.

For a given number of stator poles the minimum number of rotor poles can be determined by the following formula:

$$N_R = \frac{360°}{720°/N_S - \alpha}$$

N_S = number of stator poles
α = angle between stator pole pairs

The example shown in Figures 8A thru 8O is intended to describe a 3-phase version of the SR low loss magnetic circuit design using the minimum number of stator poles which must be six. Using the above formula the minimum number comes out to 5 rotor poles which will minimize the switching frequency. This is only one more pole than a conventional 6/4 3-phase SR design. Five rotor poles times three phases equals 15 strokes per revolution or 24° per stroke. This is a slight increase in commutation switching frequency over the conventional 6/4 design but due to the exclusive iron circuit the decrease in iron losses will more than compensate.

The phase pole pair angle works out to be 72° which is equal to the rotor pole angles. The angle between the stator phase pole pairs is equal to 120° - 72° = 48°. Figures 8A through 8O shows the rotation of the rotor as the phases are commutated for each of the 15 strokes for one complete revolution. The magnetic flux path through the stator and rotor repeats every three strokes. This is no different than the twelve stroke 3-phase conventional SR motor shown in Figures 6A through 6L. However, it is obvious that the short flux paths for each phase energization are exclusive and the repetition of the unipolar flux paths does not cause any flux reversals as in the conventional SR designs. This is obvious from Fig. 8A through 8O (I.E. Hysteresis losses). It is

6/5 3 PHASE SR MOTOR 3 COMMUTATION/POWER STROKES MAGNETIC FLUX ANALYSIS

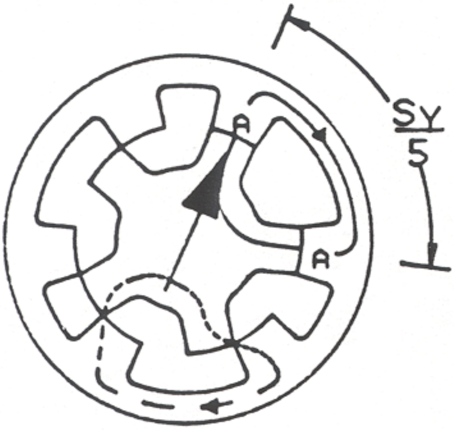


FIG. 9A

- Flux cycle of + peak to zero occurs in 1/5 of volume of Sy per stroke (no reversals)
- No flux reversals in volume of Sp.
- Flux reverses in one Rp every 3rd stroke or once per rev. for all rotor poles.
- Ry is identical to Rp or one reversal/rev.

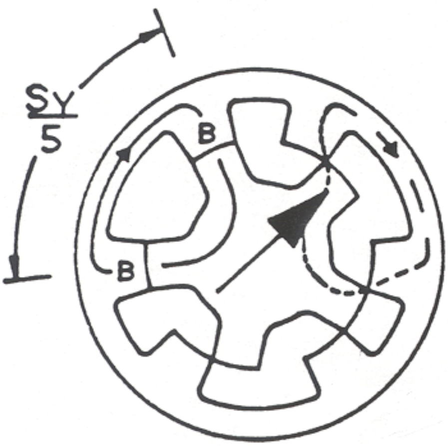


FIG. 9B

SWITCHING FREQUENCIES
OF IRON REGIONS

	f_e Eddy	f_{hDC} 0 + 0 Hyst.	f_{hAC} + 0 - Hyst.
Sy	RPS (5)	RPS (5)	0
Sp	RPS (5)	RPS (5)	0
Ry	RPS (6)	RPS (6)	RPS $\frac{(6)}{(5)}$
Rp	RPS (6)	RPS (6)	RPS $\frac{(6)}{(5)}$

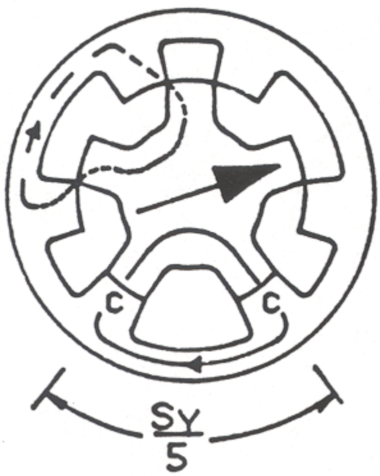


FIG. 9C

6/4 3 PHASE SR MOTOR ROTATION
12 COMMUTATION/POWER STROKES FOR 1 REVOLUTION

FIG. 6A

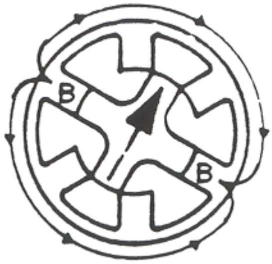


FIG. 6B

FIG. 6C

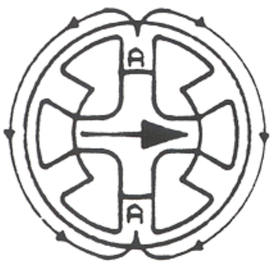


FIG. 6D

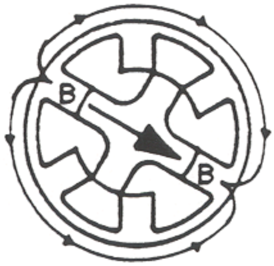


FIG. 6E

FIG. 6F

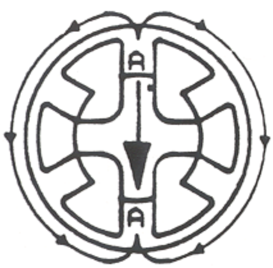


FIG. 6G

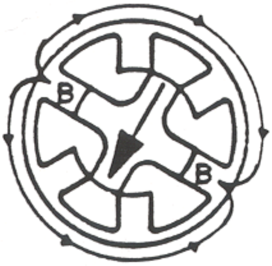


FIG. 6H

FIG. 6I

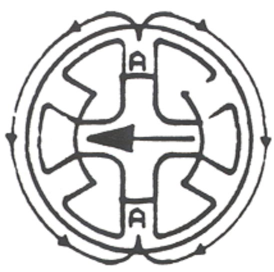


FIG. 6J

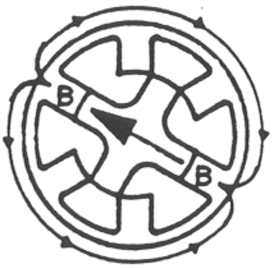
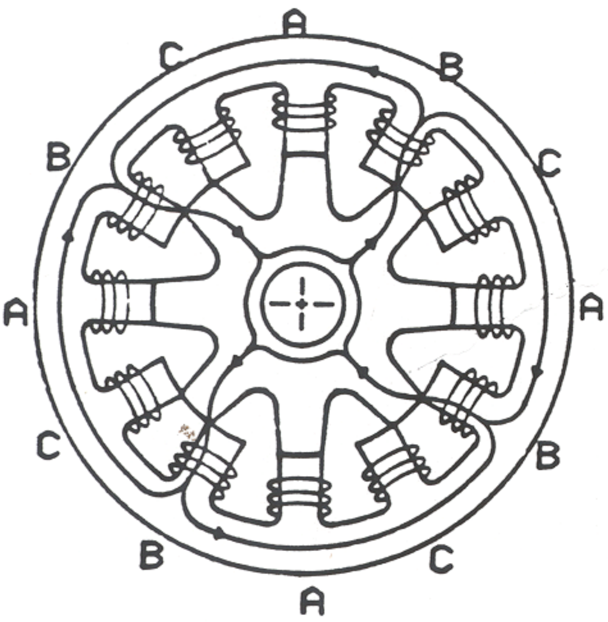


FIG. 6K

FIG. 6L

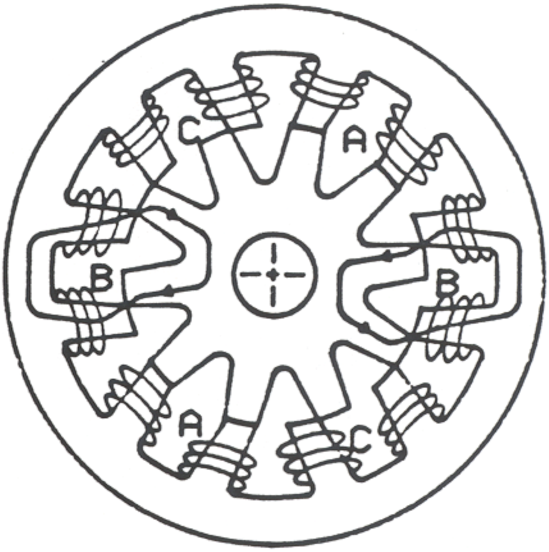
important to remember that the portion of the iron (by weight or volume) subjected to commutation switching frequencies is greatly reduced. In addition, the exclusive stator and rotor yoke iron, since it is not shared, is subjected to a much lower commutation loss frequency which equals the RPM commutation frequency divided by the number of phases. In the examples shown at 10,000 RPM the stator yoke iron would be subjected to a RPM commutation frequency of 2 KHz for the 6/4 motor in Figures 6 and 7. The 6/5 low loss design yields a iron commutation frequency of 833 Hz shown in Fig. 8 and 9. This difference is clearly shown upon careful analyzes of Figures 7 and 9.

The 6/4 versus the 6/5 examples are used to show the concept of this low loss design. However there are many other possibilities such as a 12/8 shown in Figure 10A versus a 12/10 shown in Figure 10B. The exact same sort of analyzes can be used and the results are equally useful in lowering the switching frequency losses and heating in high speed switched reluctance motors.



12/8 3 PHASE
SR MOTOR

FIG. 10A



12/10 3 PHASE
SR MOTOR

FIG. 10B

5.0 SUMMARY

A magnetic circuit has been developed for Switched Reluctance Brushless DC motors which reduces the switching frequencies as compared to conventional switched reluctance motors. This enables the motor to operate at higher efficiencies at high rotation speeds or high electrical switching frequencies. This is possible due to a special arrangement pattern of the stator poles and the placing of the phase coils to use the yoke or back iron of the stator and rotor exclusively to each phase flux. That is not to permit sharing of the iron for flux from all phases in the same portion of the yoke iron.

At the present time software is being developed at the University of Glasgow by Miller/McGilp to carefully calculate the various hysteresis losses and Eddy current losses in each region of the iron. This will permit a modeled comparison of various motor types such as 6/4 vs. 6/5, 12/8 vs. 12/10, both 3-phase and 8/6 vs. 8/7, the most common 4-phase configuration. The important points concern the comparison of the volume or weight of the back iron or yoke in the conventional SR design compared to the exclusive iron version. For example in the 6/4 3-phase 50% of the iron is in the stator yoke and all of it is subjected to hysteresis and Eddy current losses during each commutation stroke. The Eddy current frequency is 12 times the RPS while in the 6/5 the Eddy current frequency is 5 times the RPS. Since the Eddy current losses vary as the square of frequency $5^2 = 25$ vs. $12^2 = 144$ indicates that this lower switching frequency of the 6/5 significantly reduces the Eddy current losses. There is not much difference in Eddy current losses in the other circuit portions.

The hysteresis losses vary directly with the switching frequency not its square but notice that there are no plus to zero to minus flux reversals in the 6/5 stator yoke so there is no full loop hysteresis loss. However the conventional 6/4 motor is subjected to a full loop hysteresis loss in 2/3 of the yoke 1/3 of the switch strokes and 1/3 of the yoke in 2/3 of the switch strokes. This is equivalent to a loss frequency of the RPS times 8 compared to 0 for the 6/5.

The average torque of the 6/5 motor could be 5/4= 1.25 or 25% higher than the 6/4 because there are 25% more strokes per revolution but the inductance ratios will be lower which will reduce to higher rotor pole count advantages. A possible 10% increase in torque is expected but with a much higher efficiency due to less iron losses. Along with the design software efforts for performance modeling, many prototype motors are being fabricated to run careful performance and efficiency tests to verify the actual benefits of this new low loss SR motor configuration.

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