A FIVE-PHASE SWITCHED RELUCTANCE BRUSHLESS DC MOTOR WITH A LOW-LOSS MAGNETIC CIRCUIT

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I. ABSTRACT

Most switched reluctance brushless DC motors are either 3 phase or 4 phase types with unipolar or half-wave electronic drives. The torque ripple must be carefully minimized with proper commutation of the power to each of the SR stator phase windings during the precise rotor angular positions. Frequently, phase overlapping is used to minimize torque ripple and maximize the average output torque.

A unique five phase switched reluctance DC motor has been developed which provides overlapping torques from each subsequent phase. The magnetic circuit is constructed so that the magnetic flux paths are very short and exclusive to each phase, thereby minimizing the commutation switching losses in the laminations. With always two phases energized at a time, the inherent torque ripple is very low with 72° electrical commutations. The unique stator and rotor lamination design is of the 10/8 configuration, but operation is like a 10/4 configuration with two phases on at a time with the short flux paths.

II. INTRODUCTION

The various brushless DC motor technologies have received considerable attention during the past ten years in the industrialized world. The principle reasons for this activity can be attributed to the developments of silicon power switches and microprocessors. The improvements in the high energy permanent magnets have also contributed to the growth in brushless DC motor applications. However, the cost of these magnets has certainly limited the growth of the brushless motors as compared to the volumes predicted ten and even five years ago. The magnet cost problem is more significant the larger the motor. This is probably the reason that greater than about 10 HP brushless motors have not been cost effective. In fact, the use of an invertor controller with the age old AC induction motor seems to be the most popular brushless motor in the larger HP ranges.

Motor technology is so mature that new inventions in the form of totally new motor concepts are not likely to appear unless some entirely new materials such as electrical conductors, soft iron magnetic materials or permanent magnets are developed. Due to various issues, it is even more unlikely that a new motor concept will be widely used in commercial products. However, there is a very old motor technology which has been known as the VR or variable reluctance motor. It appears upon a first glance that it is a very simple type of motor and mechanically it is, but since the air gap between the rotor and stator changes drastically during rotation, the actual optimization of performance was thought to be too much of a challenge for the past approximately one hundred years. It is true that from about 1970 until about 1980 a version of this type of motor was used in quite high volume as an open loop VR stepping motor. It served very well when coupled to a lead screw to act as a read/write head positioner for 8" floppy disc drives for computers. Many linear VR motors have also been used for printers and typewriters.

The real potential of the variable reluctance motor has perhaps lain unexplored by most and at least undeveloped by those aware of its potential for about the past one hundred years. The reasons are simple enough because most motors which have been popular over the past century were somewhat independent of the system which they operated in. For example, an AC induction or a universal series wound motor or a shaded pole AC motor each could be operated simply by applying 60 HZ AC power to the leads or terminals. Although the DC shunt motor required either battery power or rectified AC power, it operated in a similar simple manner without a controller.

The so called brushless motors on the other hand must be considered as part of an integrated drive. Each set of windings or phases must be energized at the proper position of the rotor poles - permanent magnets or soft iron salient poles. The VR motor when controlled in a closed loop fashion has been called the switched reluctance brushless DC motor rather than a VR motor or a brushless DC motor. The SR machine certainly should be included as part of modern brushless technology which includes power electronics with digital control to operate the motor.

One of the reasons that the VR or SR machine has been dormant for so long is that in spite of its simple geometry, computer-aided design is absolutely necessary to develop a system which produces respectable output power with high efficiencies and the minimum of torque ripple. As engineers begin to explore this SR technology using modern CAD systems and control systems they are often surprised to discover the level of performance achievable without permanent magnets or rotor windings. The most important advantages of the SR brushless motor/drive system includes low cost manufacturing because of the absence of permanent magnets and their retainment schemes. In addition they can operate over an extremely wide temperature range with no change in performance. The SR system is ideally suited to human safety applications due to its extensive fault tolerance. The invertor or controller is as simple and cost effective as invertor driven AC induction or permanent magnet AC or DC brushless. The controller can commutate the SR machine to operate as a very efficient brushless DC generator as well as a brushless DC motor.

The single most important disadvantage of the SR motor is that they usually are more noisy than most other motors. There is much development effort being focused on this problem which is not part of the subject of this paper.

III. BACKGROUND OF SR MACHINES

A brush/commutator type DC motor has coils in the armature slots with their start and finish conductor ends connected to copper bars of a commutator which rotates with the armature. The brushes transmit current to the copper bars and as the armature rotates the voltage to the coils is "switched" mechanically with the brushes and commutator bars. No matter how many coils there are the only ones which are switched are the ones connected to the bars of the commutator which are shorted by the brushes.

In the case of brushless motors, the coils are connected in series or parallel by sets or groups of coils of which each group is connected to a transistor pair, used for applying the voltage from the DC source. These sets or groups of coils are called phases and the number can be 1,2,3,4,5,6....up to any number. Each phase requires (usually) two switches or transistors. It is obvious that the cost of silicon becomes objectionable and unreasonable much past 6 phases, depending upon the application. The torque ripple is reduced as the number of phases increase which increases the average torque.

The benefits of a given number of phases for each type of brushless DC motor has been well thought out and decided upon for various applications. A summary list of the most common motors and their respective number of phases are given in Table I.

TABLE 1

PHASES	DRIVE	MOTOR TYPE
1	Uni-Polar	SR Brushless
1	Bi-Polar	PM Brushless
2	Bi-Polar	Hybrid/PM Steppers
3	Uni-Polar	VR Steppers
3	Uni-Polar	SR Brushless
3	Bi-Polar	PM Brushless
4	Uni-Polar	VR Stepper
4	Uni-Polar	PM Brushless
4	Uni-Polar	SR Brushless
4	Bi-Polar	PM Brushless
5	Uni-Polar	SR Brushless
5	Bi-Polar	Hybrid Stepper
6	Uni-Polar	Tachometer
6	Uni-Polar	SR Brushless
6	Bi-Polar	PM Brushless

Having provided the list of phases from one to six, each with single current polarity (uni-polar) and dual current polarity (bi-polar), the facts are that there are brushless machines in production which are representative of each and every one of those on the list. Since the subject of this paper is a five phase switched reluctance brushless DC motor, the uni-polar driven SR motors will be briefly compared as to the affects of different numbers of phases.

IV. A COMPARISON OF 3,4, & 5 PHASES IN A SWITCHED RELUCTANCE MOTOR

There are single and two phase SR motors under development for blowers and fans which only rotate one direction. The starting problems and high torque ripple characteristics of these one or two phase SR motors are acceptable and can be dealt with for moving air. The benefits, of course, have to do with the cost savings associated with the minimal number of phases which require fewer transistors and sensors. For reasonably smooth performance, direction of rotation prediction, good torque ripple, and good efficiency, the need for three or more phases is undisputed. Therefore, the analysis of the selection of the number of phases for the uni-polar driven switched reluctance brushless DC motor is limited to 3,4, and 5.

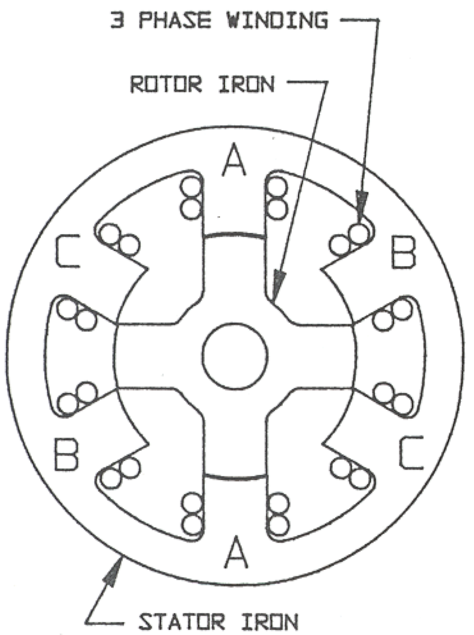


FIGURE 1 - THREE PHASE 6/4 SR MOTOR

The cross section of the typical three phase SR motor is shown in Figure 1. The four salient rotor poles are made of soft iron, usually laminated. The six stator poles are each wound with a concentric coil. Each pair of coils located 180° apart or across from one another is connected either in series or in parallel to serve as one phase. Therefore, there are three phases with two coils in each phase as shown.

Another version of the three phase SR motor would exhibit a cross section similar to the one shown in Figure 1 except the number of rotor and stator poles would be doubled to 8 rotor poles and 12 stator poles and coils. In this case there would be four coils and poles per phase, each one being located 90° apart. Similarly other versions are possible such as 12 rotor poles and 18 stator poles.

There are also other possibilities such as designs having combinations of 6 stator poles and 6 coils - 2 per phase and 8 rotor poles. A design such as this has been developed by Hewlett Packard for use as a servo motor for paper and pen drives on an x-y plotter (ref.1).

It is also possible to have pole numbers equivalent to those discussed, but to construct the rotor and stator laminations with two or more teeth on each pole. These sorts of designs are said to provide a vernier effect upon torque multiplication or as some refer to as "electronic gearing." (ref. 2,3,4)

Shown in Figure 2 is the cross section of a uni-polar driven four phase switched reluctance brushless DC motor. The rotor is configured with 6 soft iron salient poles without windings or magnets. Because of four phases, the number of stator poles must be divisible by 4 as was the case with the 3 phase example. The 8 stator poles each contain a concentric wound coil. Each phase has two coils connected either in series or parallel located 180° apart or opposite one another. (Motors of this configuration are manufactured and sold by TASC Drives in Greensboro, N.C.). As was the case with the three phase, there are many other pole combinations as well as multiple teeth per pole configurations.

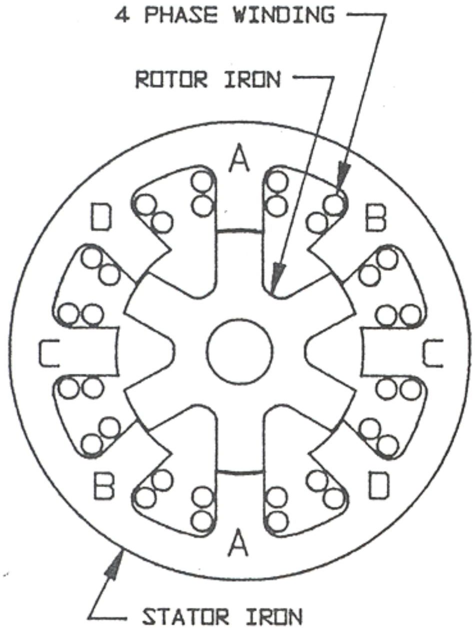


FIGURE 2 - FOUR PHASE 8/6 SR MOTOR

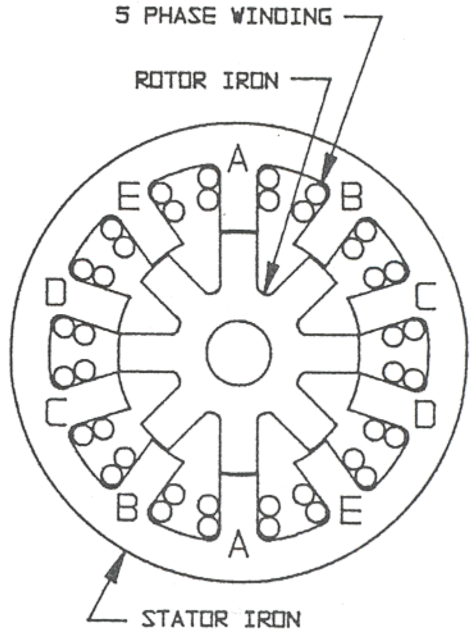


FIGURE 3 - FIVE PHASE 10/8 SR MOTOR

Figures 3, 4, & 5 shows the typical five phase configurations of the switched reluctance brushless DC machine. In Figure 3 there are 8 soft iron salient rotor poles shown with 10 stator poles, each wound with a concentric coil. As was the case with both the 3 and 4 phase SR machines, each phase consists of two coils located opposite one another connected either in series or in parallel. The same sort of pole number variations are possible with the five phase as was the three and four. In addition, since the total number of poles is so large even on the basic stator design, it is possible to configure the rotor with 4 or 6 salient poles to be used with the 10 pole stator as shown in Figure 4 & 5. The pole angle or widths would be the same for each case.

The point to remember about these different pole numbers and phase number combinations is the angle of the phase separation. The electrical angle is found by dividing the number of phases into 360° since SR machines are unipolar driven. (SEE FIGURE 6)

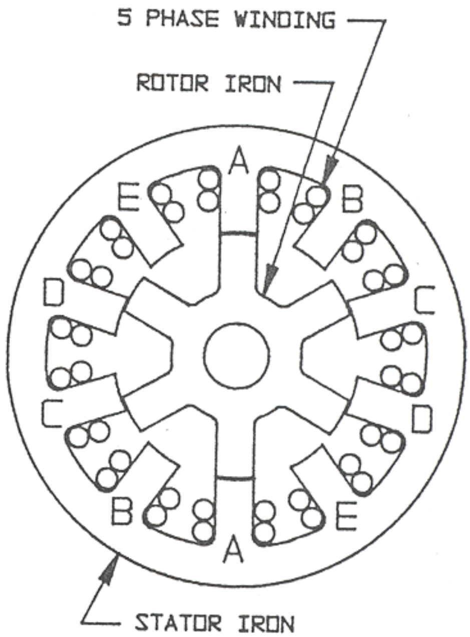


FIGURE 4 - FIVE PHASE 10/6 MOTOR

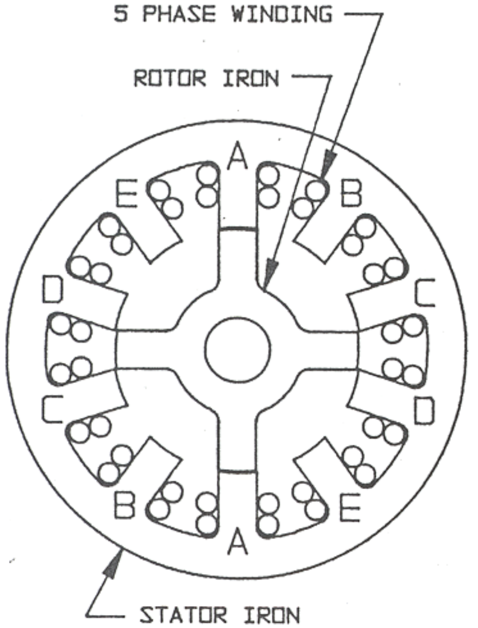


FIGURE 5 - FIVE PHASE 10/4 MOTOR

The maximum positive torque strokes produced by each phase is determined by the number of rotor and stator poles. If multiple teeth per pole are configured then the torque stroke is reduced by those ratios. For example Table 2 shows a list of most of the common phase and pole configurations for 3,4,and 5 phase SR machines. The stroke angle is given by **N** (rotor poles) x 360/**N** (phases).

TABLE 2

POLES STATOR/ROTOR	NUMBER PHASES	MAX STROKE	STROKES REV.
6/4	3	30°	12
6/8	3	15°	24
12/8	3	15°	24
12/10	3	12°	30
12/16	3	7.5°	48
18/12	3	10°	36
18/24	3	5°	72
8/6	4	15°	24
8/12	4	7.5°	48
16/12	4	7.5°	48
10/4	5	18°	20
10/6	5	12°	30
10/8	5	9°	40

The greater the number of strokes per revolution, the less the amount of time available for current to rise in a phase as commutation takes place. The greater number of strokes also makes torque smoother in one revolution. This would suggest that for low speed a larger number of poles are desired and for higher speed applications a fewer number of poles are desired. This should be no surprise because this is true of all motors.

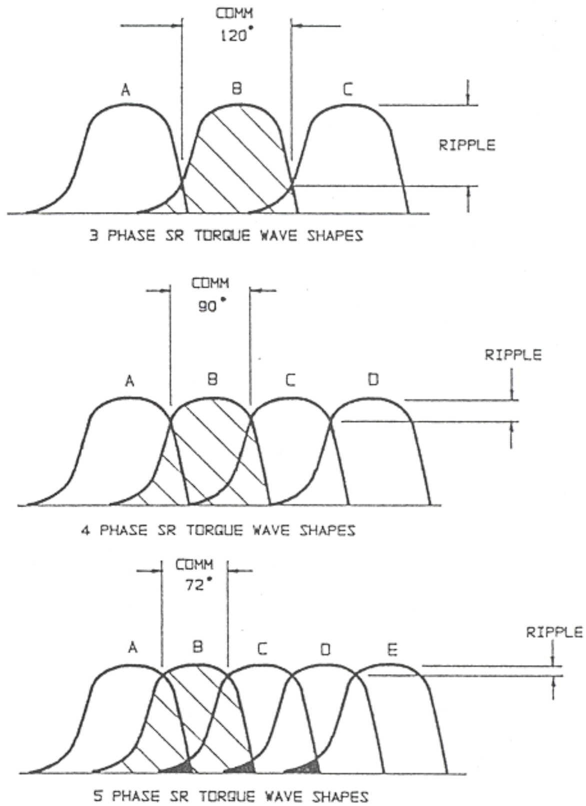


FIGURE 6 - TORQUE VS. ROTOR ANGLE

The actual details of design of a switched reluctance motor is a very difficult undertaking because of the large number of variables which must be optimized for maximum dynamic torque production. A modeler such as PC-SRD from the University of Glasgow is an excellent software package for performing the modeling to predict the dynamic performance of 3, 4, and 5 phase switched reluctance motors. The optimum commutation angles can be predicted as well as the number of turns for the phase windings. For the best design of the lamination configuration some sort of a finite element or boundary element modeler must be used.

With the solution of Maxwell's equations, with a given ampere turn input to the coils, the torque cross product can be calculated to estimate the torque from various rotor positions. If these are plotted as a function of angle, then a comparison can be made from actual static torque measurements using a torque transducer and a rotary table. Before any of these design techniques are employed, one must decide on the number of phases. Figure 6 shows the torque produced vs. rotor angle for a 3 phase, 4 phase, and 5 phase SR motors. Notice the torque overlap from phase to phase which is determined by the previously mentioned electrical angles between the phases, 120° 3 phase, 90° 4 phase, 72° 5 phase. It is very clear from careful study of the three torque curves that the torque ripple decrease as the number of phases increases. In fact, the 5 phase SR motor is the only one of the three that produces torque at all rotor positions even if one phase is shorted or open. The 3 phase exhibits a very large dead zone where no torque is produced if one phase is open. The 4 phase has a very small zero torque position with only three phases able to produce torque.

The greater the number of phases along with the maximum number of salient rotor poles, (2 less than the number of stator salient poles), the lower the torque ripple. The commutation frequency and iron losses increase as explained in the next section. This means that the selection of the number of phases and poles is based upon the application considering the torque ripple vs iron losses and electronics cost trade offs.

Very careful commutation schemes can be employed to utilize two phases on during portions of the rotation to minimize torque ripple. In the case of the 5 phase motor as many as 3 phases can be energized at a time. The purpose of this would be to increase the average output torque. However, utilizing two phases on could be beneficial in reducing torque ripple as well.

V. MAGNETIC CIRCUIT LOSS

Even though the greater the number of phases, the higher the average torque and the lower the torque ripple, there is a price to pay for the benefits of higher number of phases. The commutation frequency or switching frequency of each phase causes hysteresis and eddy current losses to be generated in the soft iron of the magnetic circuit. The greater the number of phases and the greater the number of poles the higher the switching frequencies for a given RPM.

Various drive schemes can be used to energize the phases. Two very popular configurations involve either using one transistor per phase and the other involves two transistors per phase. However, in either case the penalty for the increase in number of phases is a greater cost for electronics. Figure 7 shows the two circuits.

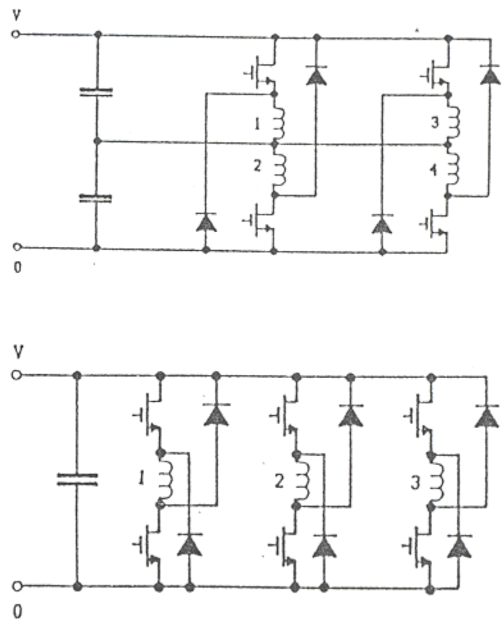


FIGURE 7 - SR INVERTOR CIRCUITS

These losses are most significant in the yoke of the stator (sometimes called "back iron") which in the case of SR motors, brushless motors or induction motors. With the coils of each phase 180° apart or 90° apart, the flux is split and goes around both outside paths of this stator yoke which causes flux reversals in the yoke when subsequent phases are energized. During the course of the flux reversals the fields are collapsed and rebuilt as the next phase is energized and the previous de-energized. The losses caused from this generates considerable heat in the

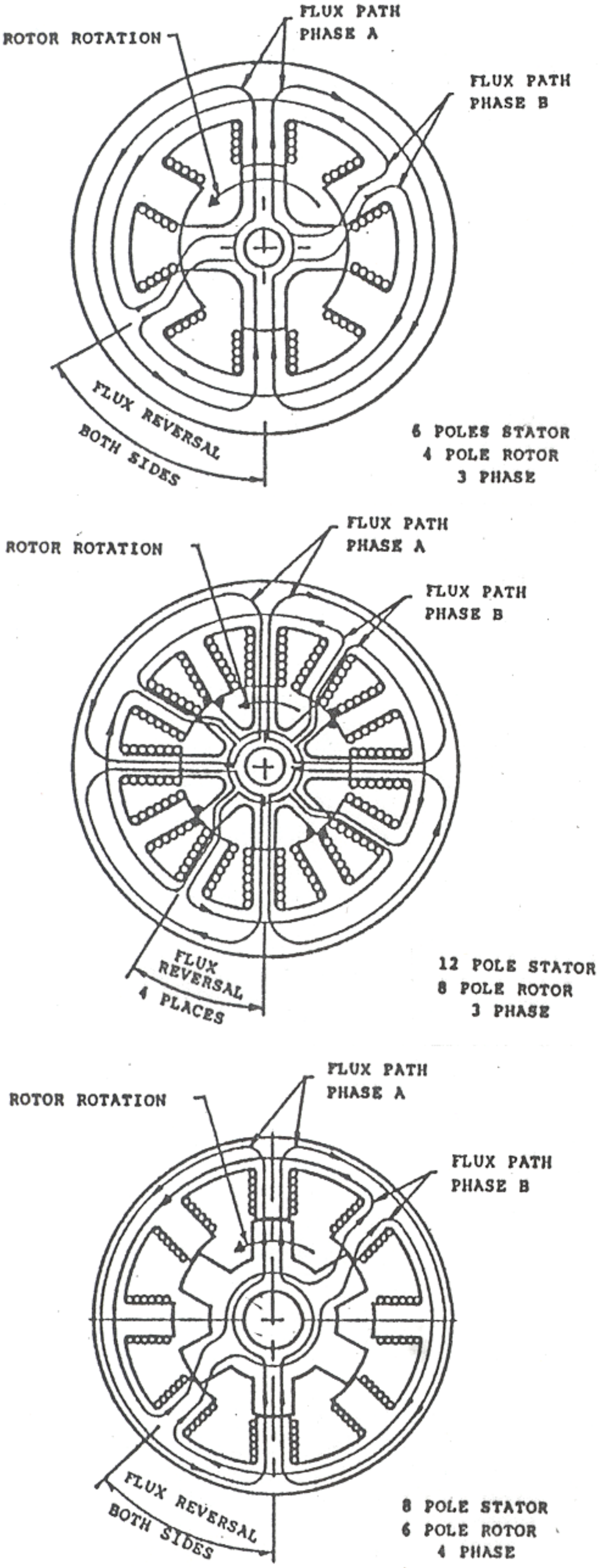


FIGURE 8 - SR MAGNETIC CIRCUITS

iron even though low loss lamination materials, usually of a thin gage, can be utilized. Figure 8 depicts the flux paths generated by subsequent phases as commutation occurs for 3, & 4 phase SR motors. The portions of the yoke where flux reversals occur are indicated by arrows in the flux path. These sorts of designs yield an iron loss frequency of a single phase times the number of phases.

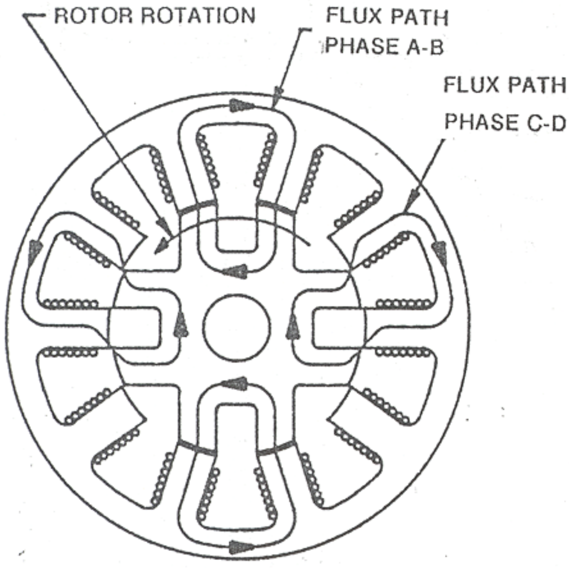
This paper describes a low loss magnetic circuit used in a 5 phase SR motor. Unique circuits for SR motors utilizing short and exclusive flux paths have been developed which greatly reduce these iron losses (see ref. 5,6,7 & 8) and are covered by two US patents. (4,883,999, 4,995,159) With these designs the iron loss frequency equals the single phase commutation frequency.

The other main loss in a switched reluctance motor is the I^2R of the copper windings. With many brushless DC motors and AC induction motors the end turns of the stator windings which connect the conductors from slot to slot are equal or greater in length than those slot conductors producing torque which affects the I^2R losses. In the switched reluctance motors all of the windings are known as concentric windings or coils wound around a single pole of the stator laminations.

This type of winding requires copper end turns to cover only the width of a single pole rather than several poles as is required of distributed windings. Since the mean turn length of each turn per coil is greatly reduced the 1•R losses are reduced which improves efficiency.

VI. A NEW FIVE PHASE SR MOTOR

Figure 9 shows a cross sectional view of a magnetic circuit of a 10/8 switched reluctance motor. The intent of this design is to provide a 5 phase motor with a low loss magnetic circuit which would produce more torque than a normal 5 phase motor because two phases would always be energized at a time. The design shown in Figure 9 utilizes a stator having 10 evenly spaced salient poles and a rotor containing 8 unevenly spaced salient poles arranged in pairs



10 POLE STATOR
8 POLE ROTOR

FIGURE 9 - 5 PHASE LOW LOSS SR MOTOR

of an angle spacing equal to the stator pole angles. The stator phase locations are adjacent to each other as is with all switched reluctance designs, but they are energized in adjacent pairs simultaneously. The windings are wound around the poles of the stator in a manner that causes the poles to be energized as pairs of adjacent poles having opposite polarities so as to create a magnetic circuit between the poles of each pair. The primary magnetic circuit formed by each pair of poles is through the back iron area of the stator bridging the two adjacent poles. This assures that the primary magnetic circuit formed by either pole in a pair is between the poles of the pair and flux reversals in the stator are therefore eliminated. Figure 10 shows the exclusive and short flux paths generated by energizing adjacent phase pairs through one electrical resolution which causes the rotor to rotate 90° mechanical degrees. The 360° electrical rotation would be performed 4 times for a 360° rotor rotation. The commutation strokes per rotor revolution are equal to a conventual 10/4 SR 5 phase motor or 20 per revolution rather than 40 per revolution of the conventional 10/8-5 phase SR motor shown on Figure 3. This reduces the switching losses and allows higher RPM's.

To analyze several 5 phase SR motor configurations in terms of magnetic flux distribution and torque, a Boundary Element Magnetic Solver was used on a high speed computer. ("Magneto", available from Integrated Engineering Software in Winnipeg, Manitoba).

Figure 11A shows the calculated flux distribution from phase A energized. Notice the long flux paths through the rotor and around both sides of the stator yoke or back iron, When the next phase is energized and the preceding de energized, the flux reversals similar to Figure 8 takes place causing hysteresis and eddy current losses. Figure 11B shows the calculated flux distribution of the new low loss 5 phase circuit with both phase A and B energized. Notice the exclusive short flux paths which do not go through the rotor or around the stator. When the next pair of phases are energized the flux paths are as shown on figure 9 without reversals.

The actual torque produced from several 5 phase SR motor configurations was calculated using MAGNETO by solving every three degrees of rotor rotation. The data for each motor was then plotted using Quattro for each phase to study the torque wave shape/phase to phase which shows the torque ripple characteristics of each design. Figure 12A shows the 10/8-5 phase plot with 9° mechanical displacement between phases. Figure 12B shows the 10/6 motor with 12° mechanical displacement between phases. Figure 12C depicts the 10/4 motor with an 18° mechanical displacement. The motor torque data shown in Figure 12D represents the new exclusive flux path 10/8 motor with an 18° mechanical separation between phases.

All four motors were modeled using the exact same stator, coil NI and air gap. Only the rotors were changed for each set of torque solutions. The peak torques were the same for the 10/8, 10/6 and 10/4 conventional designs. The short flux path 10/8 however, achieved 1.9 times the peak torque of the others due to having two phases on at a time.

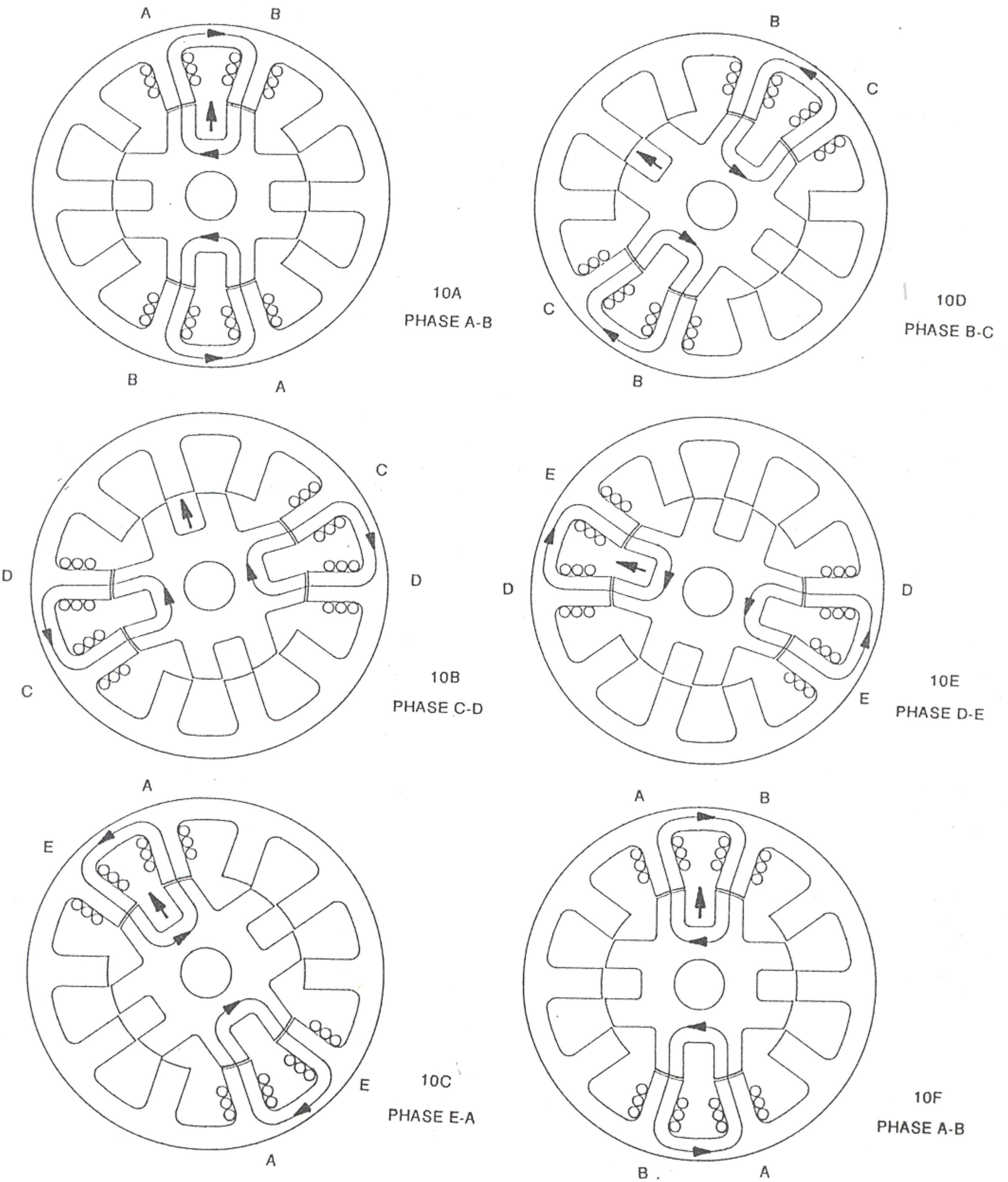


FIGURE 10 - LOW LOSS 10/8 5 PHASE ROTATION

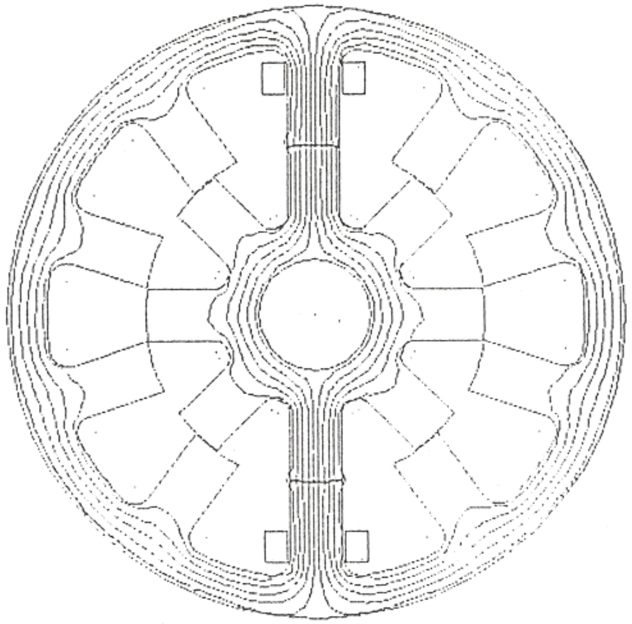


FIGURE 11A - CONVENTIONAL 10/8 - 5 PHASE FLUX PLOT
ONE PHASE ENERGIZED

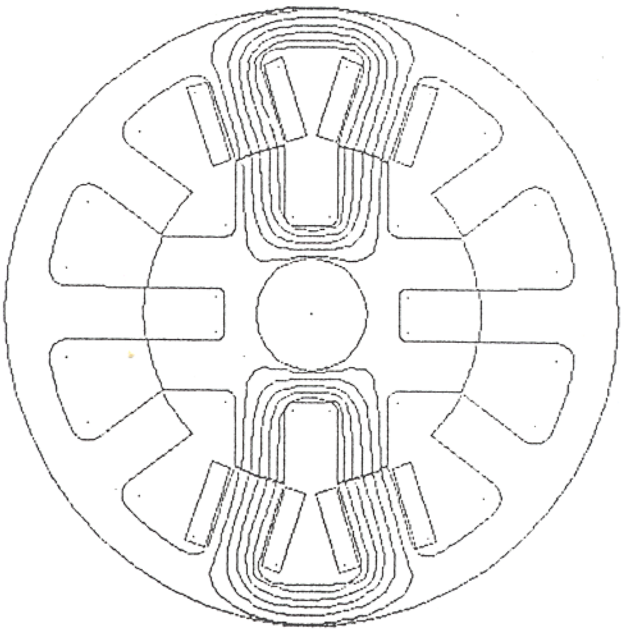


FIGURE 11B - LOW LOSS 10/8 - 5 PHASE FLUX PLOT
TWO PHASE ENERGIZED

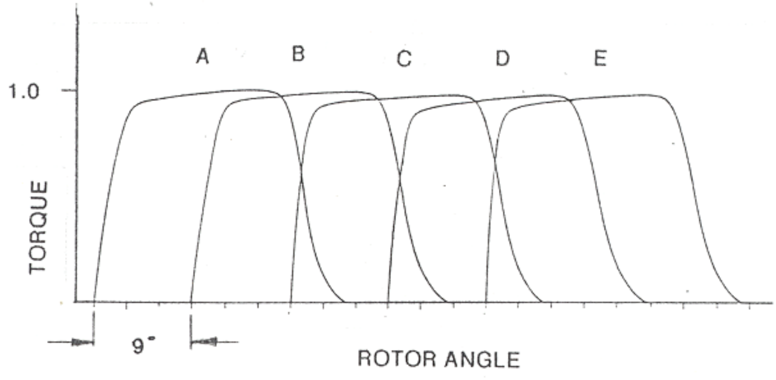


FIGURE 12A 10/8 - 5 PHASE TORQUE VS. ROTOR ANGLE
ONE PHASE ENERGIZED

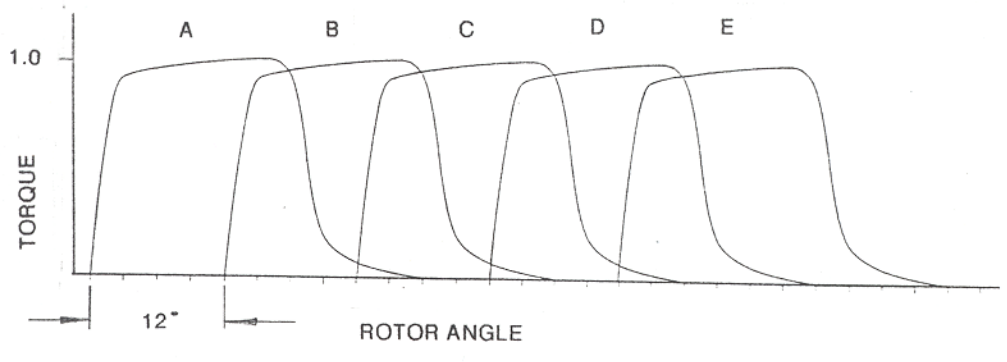


FIGURE 12B 10/6 - 5 PHASE TORQUE VS. ROTOR ANGLE
ONE PHASES ENERGIZED

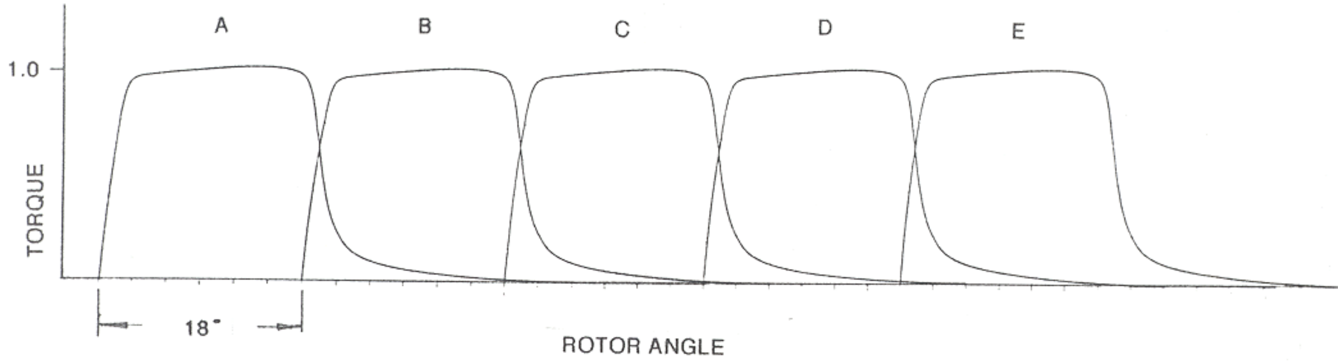


FIGURE 12C 10/4 - 5 PHASE TORQUE VS. ROTOR ANGLE
ONE PHASE ENERGIZED

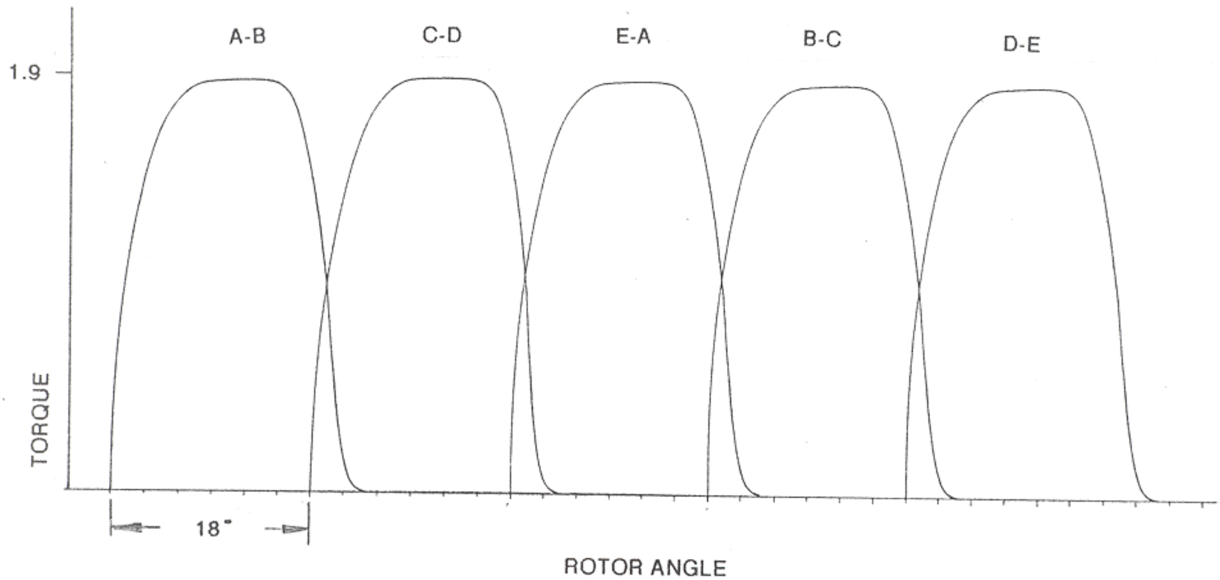


FIGURE 12D 10/8 - 5 PHASE TORQUE VS. ROTOR ANGLE
TWO PHASES ENERGIZED

III. CONCLUSION

The new 10/8 short flux path low loss 5 phase SR motor yields nearly two times the torque of other 5 phase SR motors with very low losses in the iron due to commutation switching frequency. The torque ripple turned out to be no better than the conventional 10/4-5 phase SR motor. For a low speed low torque ripple SR motor for servo applications the conventional 10/8 or 10/6 designs would appear to be very attractive for higher power machines where the cost of permanent magnets would be prohibitive. For adjustable speed applications operating at fairly high RPM's the new low loss 5 phase design would provide a high torque to size machine without using permanent magnets. The same stator design and construction could be used for either the 10/8 conventional rotor or the 10/8 low loss rotor.

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PATENTS PENDING