INTEGRATED
ENGINEERING SOFTWARE

Brushless D.C. Motors without Permanent Magnets

James R. Hendershot, Jr.
Pacific Scientific
Rockford Illinois, USA

I. Introduction

Brushless D.C. motors have received considerable attention throughout the industrial world since the early 1970's. However their use is still very limited as we approach 1990's. Computer disc drives and small fans are exclusively D.C. permanent magnet brushless motors. The D.C. servo world is slowly and methodically on an application by application basis being painfully converted to permanent magnet D.C. brushless.

Some vendors call these A.C. servos if the drive is a sine drive even though the motor is a permanent magnetic D.C. brushless.

A.C. induction inverter products are the fastest growing motor drives because somewhat standard NEMA A.C. motors are used. Serious performance limitations are currently being improved by using special A.C. motors and adding microprocessors for vector control and other optimizing tricks.

This paper describes yet another motor which is competitive to permanent magnet D.C. brushless, A.C. servo, A.C. inverter, D.C. brush type, D.C. shunt and stepping motors to a limited degree.

This product can be best described as a Brushless DC Motor without Permanent Magnets. The drive is nearly the same as any other brushless D.C. drive.

III. Definitions

There are several names for these types of brushless motors. The Europeans use the term SR or the Switched Reluctance. In the USA the term VR Brushless is used because of the similarities in the technology as recognized in the USA from the wide spread use of VR stepping motors used in printers and early floppy disc read/write actuators.

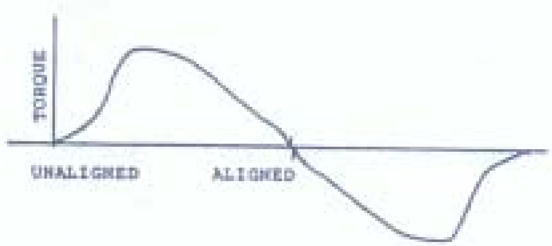
My opinion is that since the drive does not switch the reluctance as the magnetic circuit reluctance is dependent upon motor rotor position, then the term switched reluctance is not appropriate. Furthermore, since the reluctance is truly variable as a function of rotor position the terms Variable Reluctance or VR seem appropriate. So as to distinguish this motor from a stepping motor which is an open loop prime mover, the VR prefix should precede the term D.C. brushless. It is generally accepted that D.C. brushless implies a motor with no windings on the rotor, no brushes or commutator but with wound phases in the stator or stationary part. These stator phases are energized with D.C. current pulses (not timed pulses like a stepping motor) but electronically commutated from some type of shaft angle position sensor.

The VR Brushless D.C. motor operates within that description. Although I don't wish to argue A.C. induction or stepping topologies, even though it is clear they have no brushes or commutators, the stepping motor is commutated by clock pulses. (Not shaft position pulses.) The induction motor is not commutated at all but has sinusoidal current in all phases all the time. Therefore neither of these are D.C. motors even though they are brushless. Another way of comparing motor types is with the speed vs. torque curves. I promised I wouldn't argue this point so let us define the motor and drive which is the subject of this paper: VARIABLE RELUCTANCE BRUSHLESS D.C. MOTOR WHICH WE WILL ABBREVIATE WITH VRBLDC.

III. VRBLDC Historical Background

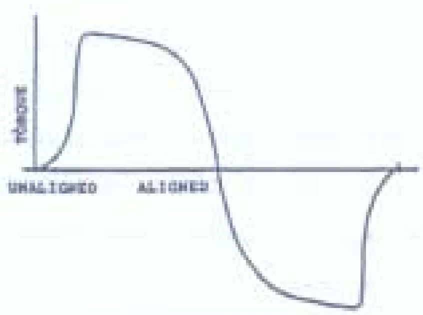
An American patent was issued in behalf of Taylor in 1938 which described what we now call a VRBLDC motor. In those days in England and the U.S. they were referred to as Electromagnetic engines. Due to a variety of problems with materials and structural limitations this technology was dropped in favor of other technologies and remained somewhat dormant for a long time.

With the development of semiconductors and an understanding of magnetic saturation characteristics of ferris materials, the VR technology was reintroduced in the USA in the form of stepping motors due to the step like torque characteristics when switching phase to phase which corresponded to step to step performance. In Europe the reintroduction of the VR type motor took the form of variable speed or continuous speed type motors which were commutated like a brushless D.C. (from shaft rotor locations rather than timed pulses). The torque production was not smooth which resulted in torque ripple.



TORQUE VS ROTOR ANGLE
TYPICAL VR STEPPING MOTOR

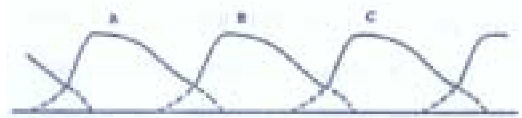
FIG. 1A



TORQUE VS ROTOR ANGLE
TYPICAL VR BRUSHLESS MOTOR

FIG. 1B

Fig. 1A shows the typical torque per step of a VR stepping motor and Fig. 1B shows the torque curve of a single "stroke" of a somewhat typical VR brushless motor. (Both examples have one phase energized per step or per stroke.)



TORQUE VARIATION WITH COMMUTATION ROTATION
FIG. 2A

PHASE COMMUTATION RESULTS IN TORQUE RIPPLE

TORQUE RIPPLE WITH PHASE COMMUTATION
TYPICAL VR BRUSHLESS MOTOR

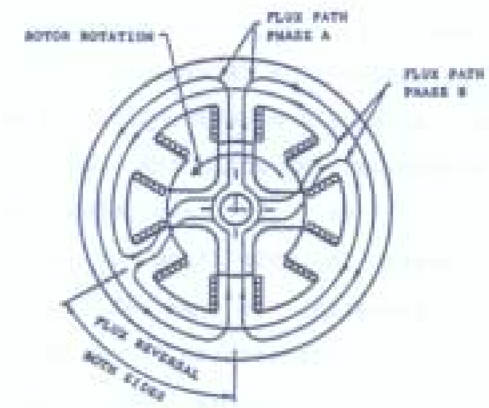
FIG. 2B

Fig. 2A and 2B show the torque production with subsequent phases energized. The torque ripple is clearly evident. Note that this phenomenon is a motor characteristic not a control trait. Furthermore the torque ripple can be significantly altered with the control of current in each phase. (See Fig. A in Appendix)

The design of a VR brushless motor is very difficult because there are so many variables. Up until the last ten years or so the evolution or improvements in this type of motor magnetic geometry was somewhat limited by trial and error methods. (With all due respect to those VR stepper designer of the last two decades.) However since the availability of computers and associated software, the "MAGETITION" of the 80's is impowered with the ability to model the VR motor very rapidly and with surprising accuracy thereby saving man-years of trial and error. The result has been quite impressive if we look around the world at recent developments.

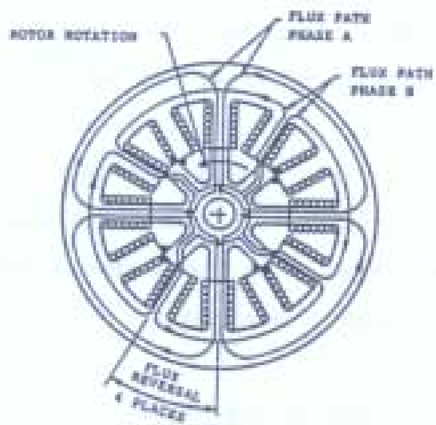
IV. <u>VRBLDC DESCRIPTION</u>

The term Variable Reluctance Brushless D.C. motor (or Switched Reluctance motors) relates to a motor which has two sets of salient poles, one set is in the stator which has phase coils around th epoles and another set of poles on the rotor. There are no permanent magnets required to produce a torque moment. The coils in the stator must be arranged in sets or phases of one or more which must be energized individually or together to facilitate shaft rotation which produces torque.



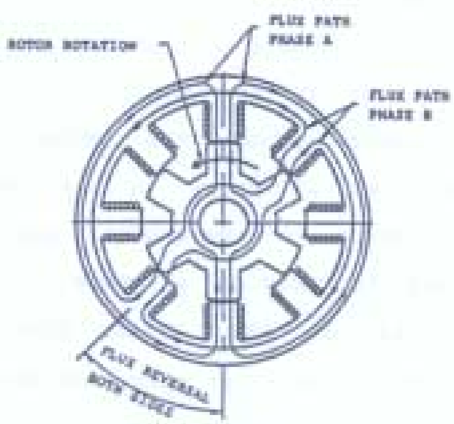
6 POLES STATOR
4 POLE ROTOR
3 PHASE

FIG. 3A



12 POLE STATOR
8 POLE ROTOR
3 PHASE

FIG. 3B



8 POLE STATOR
6 POLE ROTOR
4 PHASE

FIG. 3C

Fig. 3A and 3B show the magnetic circuits of two simple 3 phase VR motors with the phases and magnetic flux paths. Fig. 3C shows a simple 4 phase VR motor. Notice the magnetic flux paths as well as the aligned and unaligned concept of the salient rotor poles to the salient stator poles.

When a phase is energized, the nearest rotor poles are attracted to the stator poles of the phase energized. The phase switch is closed when the rotor to stator air gap is largest (i.e. circuit reluctance highest and phase inductance the lowest). When the rotor rotates and when the rotor poles are almost aligned with the stator poles which are energized, the phase switch is opened and the next phase switch is closed because the air gap to that next phase pole is the largest. The process is repeated with torque and continuous rotation resulting.

V. ANALYSIS OF VRBLDC MOTOR TORQUE

As we can see from the preceding description of the VRBLDC motor the torque produced is by a rotor “stroke” (VR stepping motors used the term steps).

With one phase or two phases energized, a stroke is defined as the angle the rotor rotates from the unaligned torque equilibrium rotor to stator position to the aligned torque equilibrium rotor to stator position. If we consider the electrical energy converted to mechanical energy through one stroke of the rotor (unaligned poles to aligned poles) we can write an equation for the average electromagnetic torque produced.

$$Ta = Ns \frac{W}{2\pi} \text{ (in Newton Meters)} \tag{1}$$

Ns is Number of strokes/rev

W is Energy converted/stroke

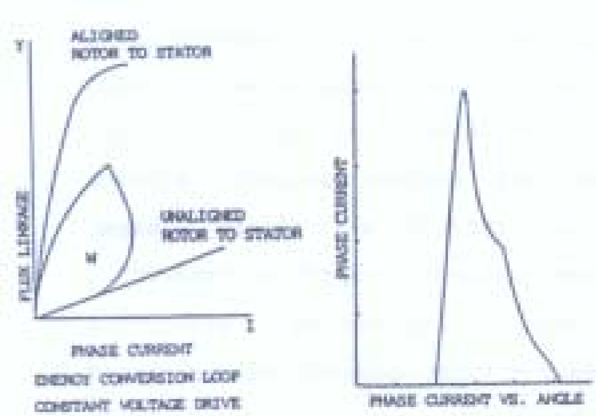


FIG. 4A FIG. 4B

Fig. 4A shows a plot of the flux linkages of a single phase of a VR motor vs. the phase current. The area enclosed equals the energy W converted for one stroke. When the rotor rotates from the unaligned rotor to stator position (phase switched on) to the aligned rotor to stator position (phase switched off) the shape of the loop during the stroke is similar to a shape caused by a constant voltage drive with phase current waveforms shown in Fig. 4B.

If a constant current drive is used the corresponding energy loop and phase current waveforms are shown in Fig. 5A and 5B correspondingly. Notice that the current is limited by the drive and a much larger energy loop is depicted. This is not all that significant but only the result of these two examples. The actual choice between constant voltage or constant current is quite another topic.

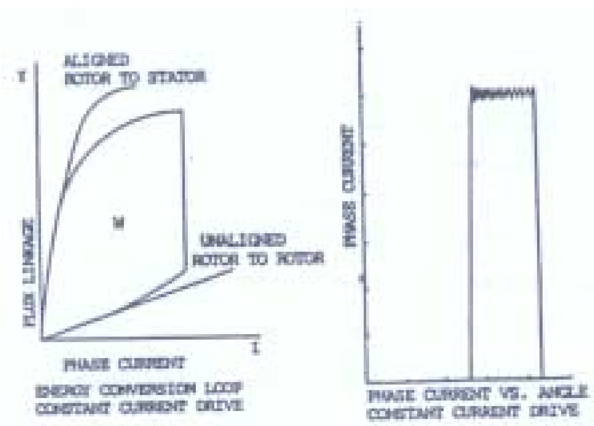


FIG. 5A FIG. 5B

The main differences to remember about VR Brushless DC motor torque production compared to other motors are these:

Average torque proportional to number of strokes per revolution. Average torque proportional to the inductance ratio (aligned to unaligned).

The inductance ratio of a given motor is reduced when the number of stator and rotor poles are increased because for a given diameter and length motor the greater the number of poles, the shorter the air path in the unaligned rotor position and the smaller the iron area for the aligned position inductance. See Table 1 for a comparison of these parameters.

TABLE 1

Inductance Ratios vs. Poles and Phases for 4 3/4” diameter VRBLDC motors and 4.0” long stacks.

Table 1

Number of Poles Stator/Rotor	Phases	Inductance Ratio Aligned/Unaligned
4/2	4	25.6
8/6	4	8.4
16/12	4	6.1
6/4	3	10.4
12/8	3	6.7
18/12	3	4.5

In actual motor operation the average output torques of VR motors has been greatly increased back in the 1970’s when the importance of high magnetic saturation was appreciated. This is particularly effective at relatively low speeds when high current can be forced into the phases with a constant current drive.

A large air gap between the rotor and stator requires considerable ampere turns to produce the mmf across the stator to rotor. If a very small air gap is used (limited by mechanical constraints, cost and audible noise) there is sufficient ampere turns to magnetically saturate the rotor/stator tooth tips thereby greatly increasing the output torque.

At very high rotating speeds it is impossible to drive high currents into the phases due to electrical time constraints being larger than the “phase on” pulse width (commutation phase advance helps).

This subject of saturation and torque related to the properties of the rotor and stator has been treated in many papers over the past few years. It is so critical to the development and optimization of VR brushless motors that it is guaranteed that much current and future analysis is expected using various computer modeling methods such as the University of Glasgow “PCSRD” solver and various magnetic solvers such as Infolytica’s finite element package called “MAGNET” or “MAG-PC”.

Integrated Engineering offers a boundary element magnetic solver called MAGNETO.

VI. SPEED CAPABILITY

The VR brushless DC motor exhibits no back EMF from permanent magnets which would limit its no load speed to the value where th eback EMF equals the buss voltage (commutation advance reduces this problem with all brushless motors). The VR motor has pulses of back EMF but it is not continuous. With commutation advance the back EMF can be positive to the buss (same polarity) so that very high no load speeds are possible. This same commutation advance allows larger average currents per stroke at all speeds to enable much higher torques to be developed.

As we all know it is difficult to design and produce high speed permanent magnet brushless D.C. motors due to the back EMF and magnet retention problems. The VR brushless motor is at a great advantage on both points as it contains neither permanent magnets nor magnet retention schemes.

The other choices for high speed motors are two types, namely series wound brush type AC motors or AC induction motors which require high frequency for high speed.

NOTE: A low speed (RPM) motor with a high pole count is electrically a high speed motor as well as a low pole count high RPM motor.

VII. MOTOR LOSSES

If we consider average to low speed motors with antifriction bearings, the main source of motor losses are I^2R or copper losses. However, when we increase the speed (electrical rotation X number of poles) the copper losses are very small compared to the hysteresis and eddy current losses or iron losses.

Table II shows the copper and iron losses of a motor at 3000, 10,000 and 20,000. The ratios of copper to iron losses of the three speeds are 9.8 to 1 at 3000, 0.63 to 1 at 10,000 and 0.16 to 1 at 20,000 RPM.

TABLE II

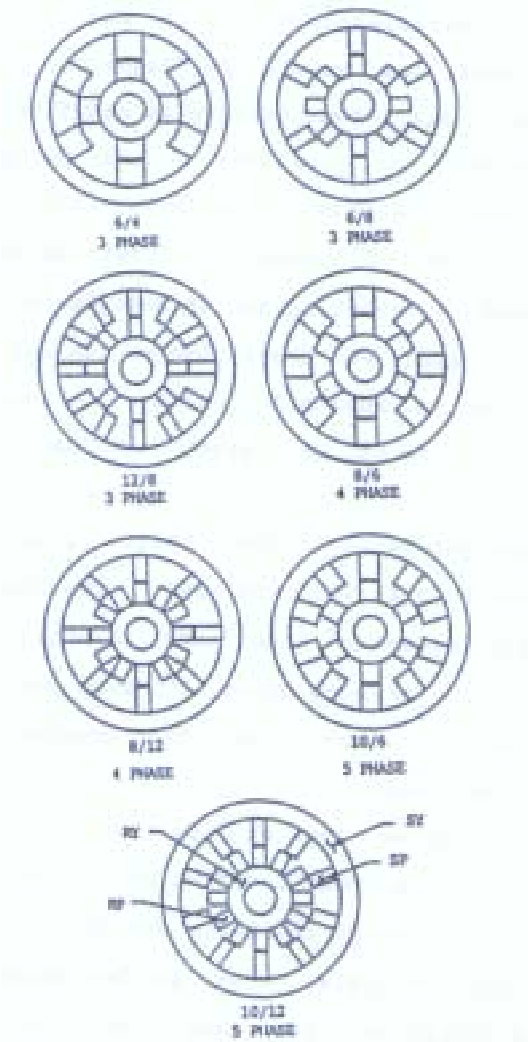
Loss comparisons of VRBLDC 4.5” diameter motor with 2.5” long stack 160 VDC 3 phase.

Losses (Watts	3,000	10,000	20,000
Copper	587	30	7.6
Iron	60	48	46
Efficiency	77.5%	89.7%	85.8%
Torque (NM)	7.0	0.64	0.15

Hysteresis losses in an electromagnetic are caused by magnetic flux reversals (from positive to negative or negative to positive). Eddy current losses are caused simultaneously by the time rate of change of current (dI/dt). When a motor phase is switched on or off both of these losses can and do occur in most all motors. The losses of a particular grade of magnetic lamination material is tested and guaranteed by the steel mill in Watts/lb at 10KG an d15KG. The longer the magnetic iron path through the motor, the ore poles, the more phases, the higher the speed, the greater the iron losses.

If we look at Fig. 3A, 3B, and 3C we notice that the flux paths for each phase through the motor are the longest paths possible. When another phase is switched on, the same iron from the switched off phase is used for the switched on phase. However in some portions the flux is reversed and in others the flux decreases and then increases. This iron loss action is similar in a stepping motor, permanent magnet brushless DC, AC induction, wound D.C. and in permanent magnet D.C.

The exact analysis would yield different results for each motor type. Since the subject of this analysis is Variable Reluctance Brushless DC motors we will restrict our study to this type of motor.



VR BRUSHLESS POLE & PHASE ARRANGEMENT

FIG. 6

If we study Fig. 6 we see an arrangement of several pole and phase selections of VR motors. The rotor and stator laminations are divided up into regions so that an analysis of the switching frequencies can be studied and calculated. TABLE III identifies these regions and the corresponding switching loss frequency formulas for each region as the motor rotates.

TABLE III

REGION	DESCRIPTION	LOSS FREQUENCY
SY	Stator Yoke	$F_{SY} = \frac{RPM}{60} x N_R N_{PH}$
SP	Stator Pole	$F_{SP} = \frac{RPM}{60} x N_R$
RY	Rotor Yoke	$F_{RY} = \frac{RPM}{60} x N_R N_{PH}$
RP	Rotor Pole	$F_{RP} = \frac{RPM}{60} x N_S$

Communication $F_C = \dfrac{RPM}{60}$ x N

N_R = NUMBER OF ROTOR POLES

N_{PH} = NUMBER PHASES

Table IV shows the calculated switching loss frequencies in the four regions for several types of VR motors per 100 REV/SEC.

TABLE IV

PHASES	3	3	3	4	4	5	5
N_R /N_R	6/4	6/8	12/8	8/6	8/12	10/6	10/12
F_C	1200	2400	2400	2400	4800	3000	6000
STROKES/REV	12	24	24	24	48	30	60
F_{SY}	1200	2400	2400	2400	4800	3000	6000
F_{SP}	400	800	800	600	1200	600	1200
F_{RY}	1200	2400	2400	2400	4800	3000	6000
F_{RP}	600	600	1200	800	800	1000	1000

When the optimized VR motor lamination geometry is determined for a given requirement and the number of poles and phases are selected, one can determine the volume and weight of each region of the design. Then using a loss curve of watts/lb plotted against frequency for either 10KG or 15KG magnetic induction, on can calculate the magnetic core losses of a given motor design. At best it would only be an approximation because as we have said before, the loss data is only provided at 10KG and 15KG. In actual operation of the VR motor, the flux saturation values in regions and portions of regions (like tooth tips) plus the effects of flux reversals in some regions makes it nearly impossible to predict the conditions under which to calculate the losses. One of the best ways to analyze the various flux densities in the regions is to use a Finite Element or a

Boundary Element Magnetic solver. (Examples given in Appendix.)

The eddy current losses of each region can also be calculated by multiplying the volume of each region times the eddy current loss per unit volume in watts per cubic inch.

$$P_{EC} = \frac{4}{3P} K_f^2 F^2 B_m^2 T^2 \tag{2}$$

where Bm is the max value (Δ Bm/2) of the cyclic loop density in webers/in^2, t is the lamination thickness in inches and P is the resistivity of the lamination material in a cubic inch. The frequency is f and k_e is a constant which varies with flux density Bm. Here again the calculated values would be only approximations due to the variable state of each region of the magnetic circuit. Further identified flux reversals in certain regions are approximations that can be made for the hysteresis losses.

The effects of these causes a reduction of efficiency at high commutation frequencies. As explained previously, the high frequencies occur at either high RPMs or in high pole count designs. The excess heat generated in the laminations reduces bearing life and must be dealt with by using cooling fans and heat sinks, such as found in series wound AC motors and AC induction motors.

VIII. A NEW LOW LOSS MAGNETIC CIRCUIT FOR VR BRUSHLESS PC MOTORS

(Patents Pending)

Since the VR motor is very useful at high speeds because it contains no permanent magnets to produce torque, it would be even more useful if the efficiency at high rotating speeds or high switching speeds could be substantially improved. It turns out that such a design improvement is possible if the pole arrangements are positioned so as to greatly shorten the magnetic flux paths for a given diameter of motor and to provide exclusive lamination iron for the flux of each phase, so as not to be shared by other phases. In regions SY and RY, (depicted in Table III) where the loss frequency equals the commutation frequency in conventional VR motors, this new short and exclusive circuit would reduce the loss frequency in the SY and RY regions by dividing by the number of phases. Furthermore there would be no flux reversals resulting in no full loop hysteresis losses; (only minor loop losses). The loss frequency in the SP region is the same as the conventional VR design while the loss frequency in the RP region is slightly lower. In each case the commutaiton frequency is slightly higher than a conventional motor which somewhat offsets some of the gains. However the average torque is higher with the low loss design because the number of strokes per revolution is greater.

Fig. 7 shows a few examples of the new low loss VR Brushless D.C. motor.

Fig. 7A depicts a 6/5 3-phase arrangement which would be equivalent to a conventional 6/4 3-phase but with only 41% of the iron losses. Fig. 7B shows a 12/10 3-phase which would replace a conventional 12/8. The improved 12/10 3-phase arrangement exhibits about the same iron losses as the conventional 6/4 even though the commutation frequency is greater than double. This permits a lower ripple higher torque VR motor in the same package with the same losses. Fig. 8 shows the flux paths of one phase as calculated and plotted using MAGNETO, a boundary element magnetic solver. Fig. 9 show the flux paths of two conventional VR motors using a finite element magnetic solver by Infolytica.

The key to the pole arrangements centers around the requirement that the wound poles of all phases must be arranged in pairs of opposite polarity to achieve the adjacent pole paths of short lengths. This permits exclusivity of iron to the phases in the stator yoke and almost exclusive in the rotor yoke.

The relationship or rules of this particular VR exclusive flux path design are given as follows:

1. Rotor poles are equally spaced.
2. Wound stator pole pairs/phases have the identical angle spacing of any two rotor pole angles.
3. Adjacent poles in a stator phase pair must be wound to yield opposite magnetic polarity to assure the flux path shown in Fig. 8.
4. If there is more than one pole pair per phase the adjacent poles from pair to pair a phase must be wound so that the phase currents produce like magnet polarities to prevent more flux paths.

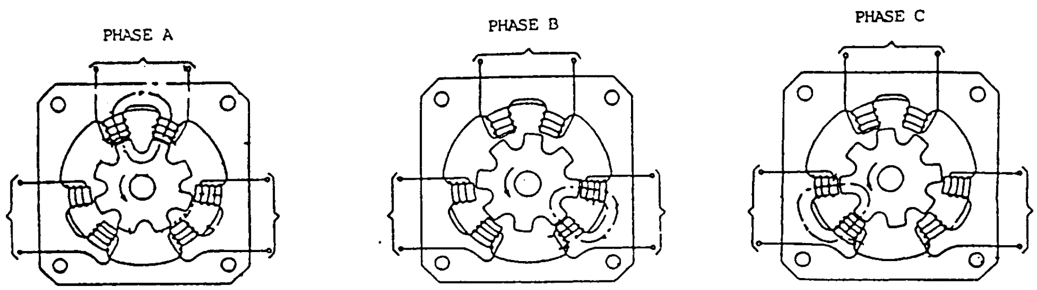


FIG. 7A

6/5 3 PHASE

VR BRUSHLESS POLE ARRANGEMENTS WITH LOW LOSS EXCLUSIVE IRON PATHS

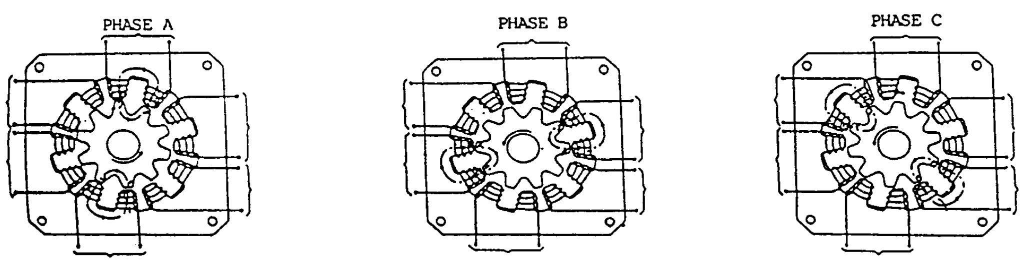


FIG. 7B

12/10 3 PHASE

VR BRUSHLESS POLE ARRANGEMENTS WITH LOW LOSS EXCLUSIVE IRON PATHS

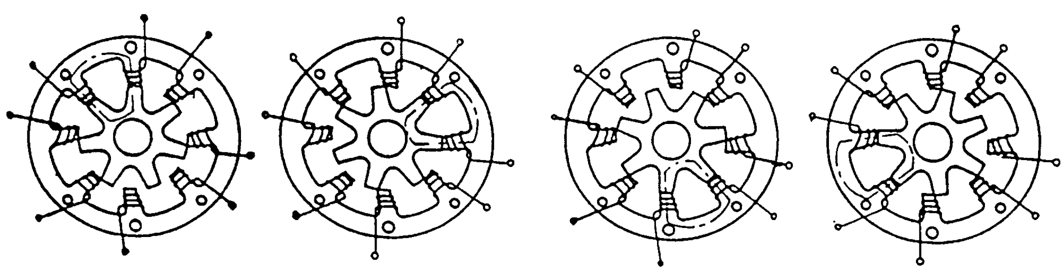


FIG. 7C

8/6 4 PHASE

VR BRUSHLESS POLE ARRANGEMENTS WITH LOW LOSS EXCLUSIVE IRON PATHS

PATENTS PENDING

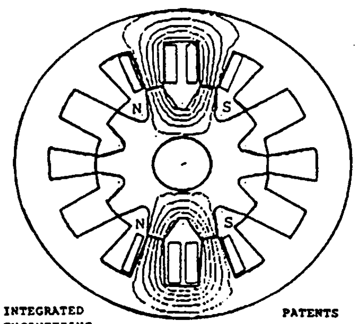


Fig. 8A

NORMAL SATURATION

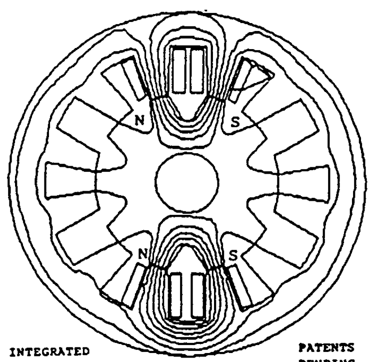


FIG. 8B

HIGH SATURATION

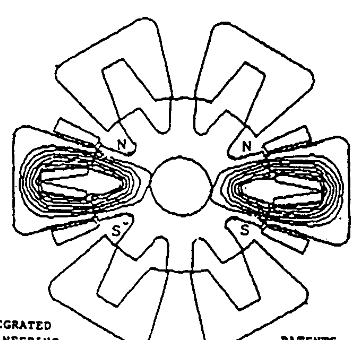


FIG. 8C

INDIVIDUAL LAMINATION SEGMENTS

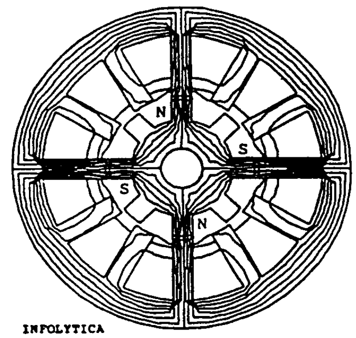


FIG. 9A

CONVENTIONAL VRBLDC

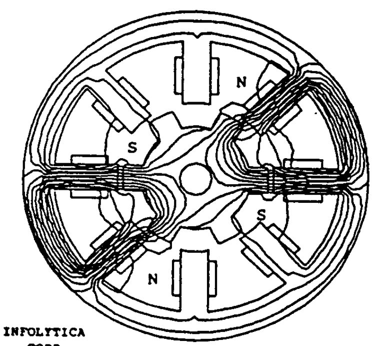


FIG. 9B

CONVENTIONAL VRBLDC

Table V

Number Phases	Strokes / Revolution	N_S/ N_R	Rotor Angle	Stator Angle
2	6	4/3	120°	120°/60°
3	15	6/5	72°	72°/48°
3	30	6/10	36°	36°/84°
3	30	12/0	36°	36°/24°
4	24	8/7	51.43°	51.4°/38.6°
4	48	16/14	25.714°	25.7°/38.6°
5	45	10/9	40°	40°/32°
6	66	12/11	32.7°	32.7°/27.3°

Table V shows a list of some possible pole arrangements for this type of circuit design.

There are many more possibilities and the usefulness of some arrangements would be unique to certain applications.

It is the opinion of this author that the most practical design for (3) phase motors is the 12/10 design shown in Fig. 7B.

If a 4 phase design is preferred, the 8/7 would seem to be useful, although the unbalanced radial magnetic forces would need to be accommodated. The 16/14 (4) phase design has balanced radial forces but it would be RPM limited due to the high commutation frequency. It would however make an excellent servo motor with very low ripple torque.

The actual optimized design of the lamination shapes is best determined using a magnetic solver. All of the designs built and tested so far by Pacific Scientific have been achieved using a boundary element solver called MAGNETO sold by Integrated Engineering Software Inc. of Winnipeg, Manitoba, Canada on an IBM 386 computer.

A solver of some type is the only possibility compared to trial and error methods using expensive prototype hardware.

The actual application oriented calculations are performed by Pacific Scientific using Dr. Tim Miller's PCSRD from the University of Glasgow. This simulation type design software is written in Turbo Pascal and executes a design simulation in just a few seconds. After the optimization of the magnetic circuit for each size motor, PCSRD is used to assist in the motor sizing, and selection of the stack length and windings for a given requirement. The optimum phase advance for any load/speed point is calculated with this software. The losses are outputted along with current waveforms.

Fig. 11 shows an example of some actual speed vs. torque curves of a VR Brushless DC motor with a 3" long stack. The family of curves shows the performance of the motor on a dynamometer with 160V DC and 5 amp current limit at different angles of commutation phase advance.

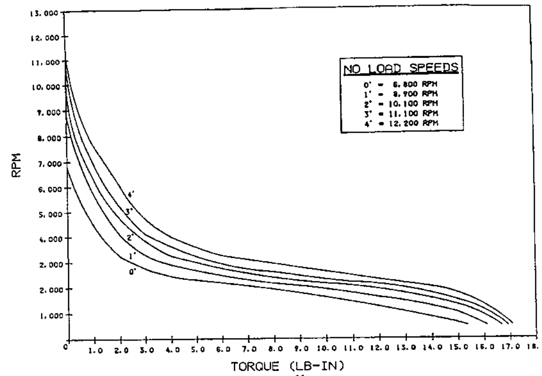


FIG. 11

IX. Summary

The Variable Reluctance Brushless D.C. motor has finally come to this age. Pacific Scientific has developed (Patents pending) a low loss high performance low noise design. The design and development time was greatly shortened by the use of a magnetic solver for the actual magnetic circuit optimization. The specific application design is being done with a performance simulation program.

An appendix is provided which shows some modeled data as well as performance data on some of the VR brushless DC motors which Pacific Scientific has built using this technology.

REFERENCES:

1. CHAI, D.J., Konecuy, K., "Effect of Saturation on Step Motor Tooth Permeance and Face", 1982, IMCSD Symposium, U of I.
2. KUO, B.C., GAO, G.A., "Performance of Saturated Tooth Structure and It's Utiligatiun in Step Motor Design", 1982 Proc. IMCSD Symposium, U of I.
3. ROTERS, H.C., "Electromagnetic Devices", 1961, John Wiley & Sons.
4. MILLER, T.J.E., Various Publications and white papers on "Switched Reluctance Motors & Drives", University of Glasgow.
5. LAWRENSON, P.J., et. el. "Variable-Speed Switched Reluctance Motor", 1980 IEEE Proc. Vol. 127.
6. BYRNE, J.V. & McMULLIN, M.F., "Design of a Reluctance Motor as a 10KW Spindle Drive", 1982 proc. MOTORCON.

7. BYRNE, J.V., DEVITT, F., "Design and Performance of a Saturable Variable Reluctance Motor", 1985 proc. MOTORCON.

APPENDIX:

Additional background and supportive information is provided in this last section.

ADVANTAGES OF VR SO SR BRUSHLESS MOTORS

- Rugged, simple low cost machine.
- Permanent magnets not used to produce torque.
- Operates without any mechanical brush/cummutator parts.
- Majority of losses contained in stator for ease of cooling.
- Capable of operation over wide temperature range.
- Extremely high speed operation possible.
- Zero torque under shorted conditions.
- High torque low speed gearless designs possible.
- Relatively simple drive topology required.
- Can be used as motor or generator.

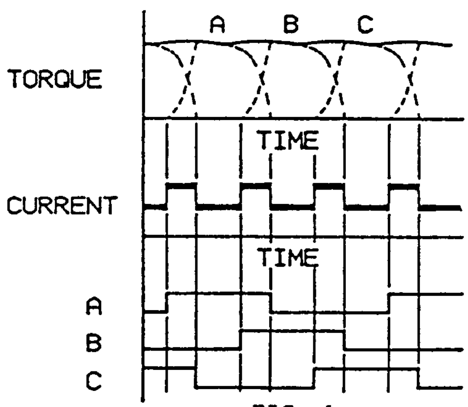


FIG. 1
VR Brushless 3-Phase with phase overlap.

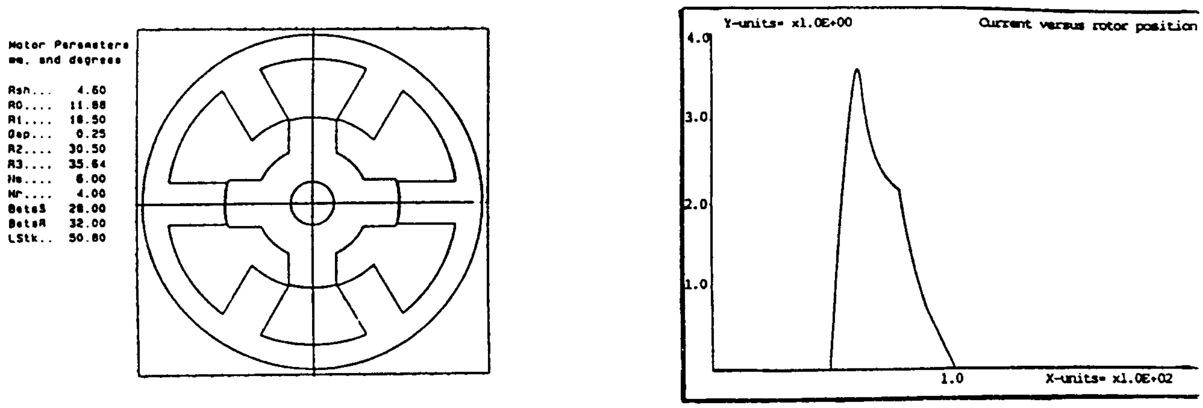
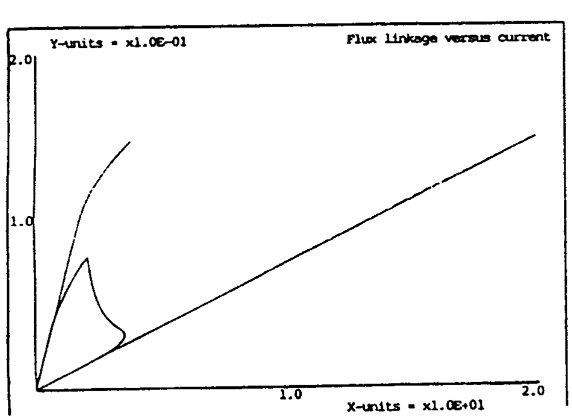
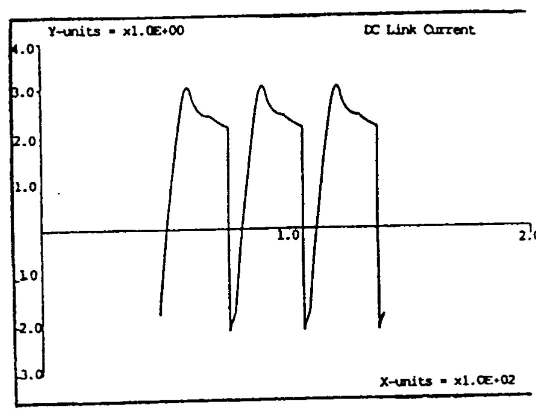


FIG. 2- PCSRD Performance Modler results. (University of Glasgow)





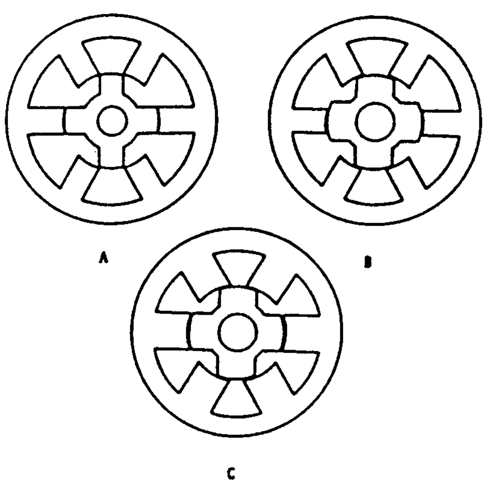
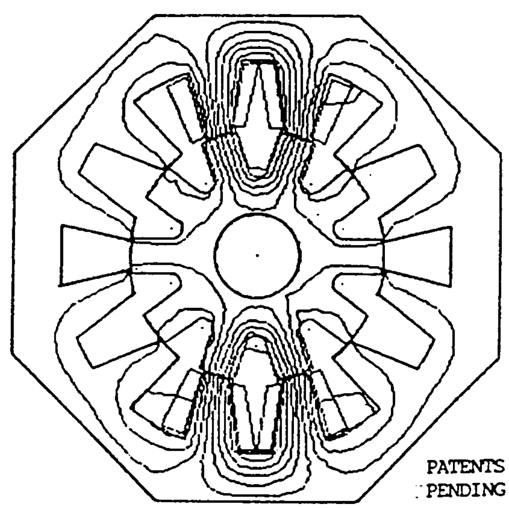


FIG. 3

Various pole angle proportions. Each resulting different torque.



"MAGNETO"

FIG. 4

Flux plot from magnetic solver at very high flux density.

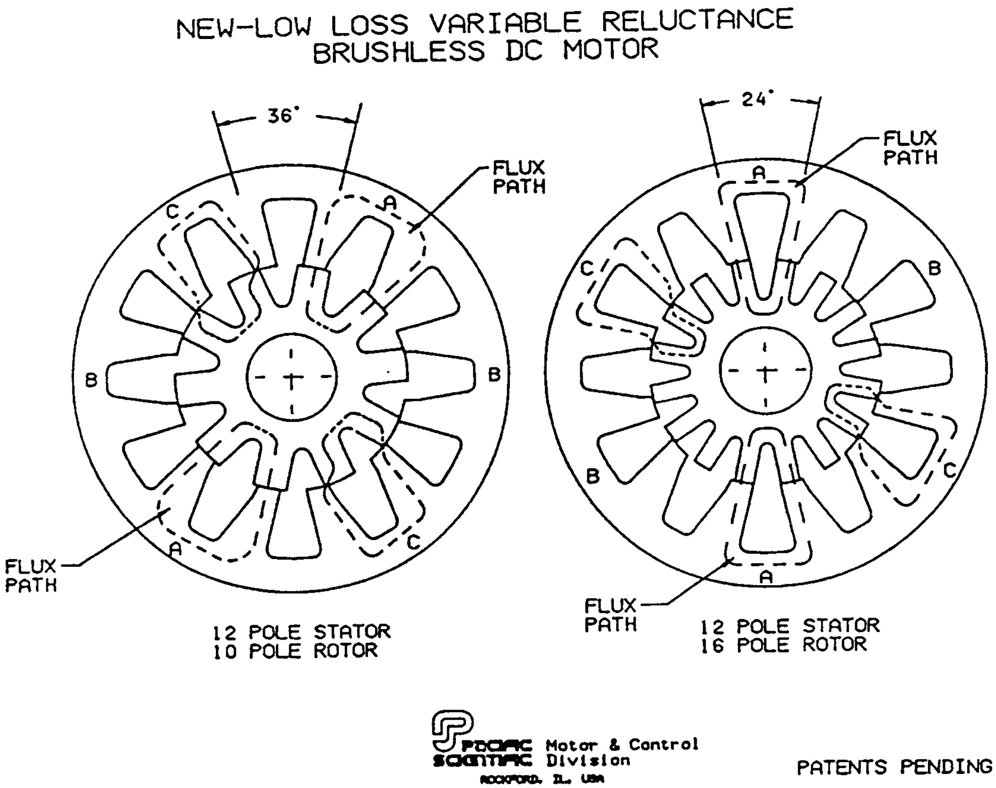


FIG. 5

VRBLDC 3 phase motor, 12 pole stator and either 10 pole rotor or 16 pole rotor.

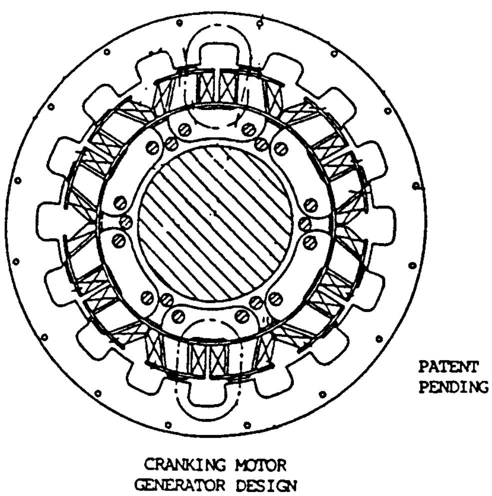


FIG. 6

Special VRBLDC 3-Phase inside out design with
12 pole stator and 16 pole rotor.

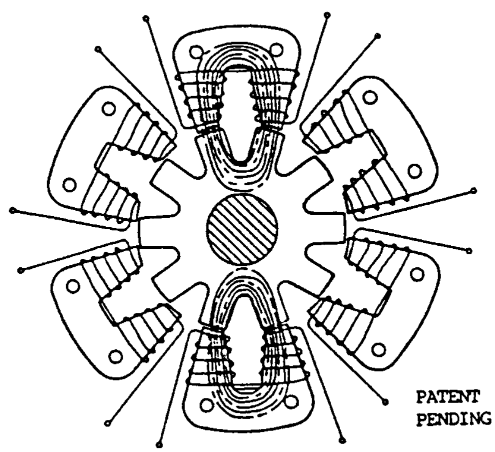


FIG. 7

Special 12/10 3-Phase VRBLDC Motor.