Wisconsin Electric Machines and Power Electronics Consortium

RESEARCH REPORT
91-1

Novel Reluctance Machine Concepts for Variable Speed Drives

T. A. Lipo
Dept. of Elec. and Comp. Engr.
University of Wisconsin-Madison
1415 Johnson Drive
Madison, WI 53706-1691

WEMPEC

Department of Electrical and Computer Engineering
1415 Johnson Drive
Madison, Wisconsin 53706

Novel Reluctance Machine Concepts for Variable Speed Drives

T.A. Lipo
University of Wisconsin-Madison
1415 Johnson Drive
Madison, WI 53706, U.S.A.

Abstract Although design of the variable reluctance (switched reluctance) type of synchronous machine has experienced intense activity in recent years, relatively little effort has been expended on improving the torque capability of other types of synchronous reluctance machines for potential use in motor drives. Based on preliminary work, it appears that substantial improvements can be made in the design of such motor drives resulting in performance characteristics which could match or, indeed, even exceed that of the induction or variable reluctance machines. Six new innovative variable speed reluctance machine drive configurations which show considerable promise are set forth to demonstrate the attractive possibilities.

Introduction

In the past several decades remarkable progress has been made in the development of induction motor drives using both hard switched dc link and resonant-link schemes which utilize high speed switching devices such as fast recovery bi-polar junction transistors, insulated gate bipolar transistors (IGBTs) and GTOs. These new resonant converters not only have high power density but also possess very low switching losses since switching of the devices are made at zero-voltage instants and thus enable the total system to operate at very high frequency. Switching losses of hard switched converters (dc voltage link converters) have also improved dramatically due to the substantially reduced turn off time of third generation IGBTs.

While the development of solid state power converters has proceeded at a rapid pace, the corresponding development of electric machines, specifically designed to take advantage of these new, high performance power converters has been disappointingly slow. For example, induction machines are presently designed for inverter supplies in a manner nearly identical to design for conventional sinusoidal supplies. That is, the machine is wound with sinusoidally distributed three phase stator windings and the rotor is constructed with a cast aluminum cage (squirrel cage). The only adjustment for operation from an inverter supply is to eliminate the double cage or deep bar rotor which is commonly used to improve the starting torque for fixed frequency operation. This feature is not required from modern inverter drives since the frequency of the converter can be smoothly varied to provide the necessary starting torque.

One of the few significant new development in electric machinery for variable speed operation is the resurgence of interest in the variable reluctance motor [1-4]. This machine, which was invented in the last century, traditionally found use in small positioning type actuators such as tape drives, disc drives, plotting heads and the like. A schematic plot of this type of machine is shown in Fig. 1. In these machines, both the stator and the rotor are equipped with saliencies. Because of this feature, the number of stator poles much be different from the number of rotor poles in order to prevent locking torques at zero speed. While any number of unequal stator/rotor pole combinations are possible requirements for minimizing the solid-state switching elements generally lead to an even number of stator poles which, in turn, leads to an even number of rotor poles in order to optimize torque production. The motor was operated open loop by simply applying voltage sequentially to the windings concentrically wound around the projecting stator poles. If the load is predictable and if the frequency of switching (slewing rate) is not too great, the rotor of the machine follows the excited stator poles in a synchronous fashion without position feedback.

It was recognized by Lawrenson, that if the current flow into the stator windings is carefully controlled with respect to the instantaneous rotor position, a substantial increase in torque production can be realized [1]. While such current regulation schemes were common in induction motor drives at the time, the concept was considered innovative when applied to variable reluctance motors so that the resulting converter/motor combination was christened the switched reluctance motor [1]. This motor created immediate interest due to the fact that the construction of the rotor as well as the stator was exceedingly simple and that unidirectional torque could be produced by unidirectional current in the phases, thereby necessitating only a half bridge (chopper) for each phase. Since the power density and efficiency of this machine approached or even exceeded conventional induction motor drives, Ref. 1 initiated an intense period of research attempting to alleviate the remaining disadvantages of this motor, namely high torque ripple, acoustic noise and need for a position sensor. Unfortunately, after some 15 years of development, significant progress has only been made on the position sensor issue [5-7]. In particular, it now appears that the noise and torque pulsation issues can only be solved by increasing the air gap which, in turn, effectively eliminates the power density and efficiency advantages of this machine.

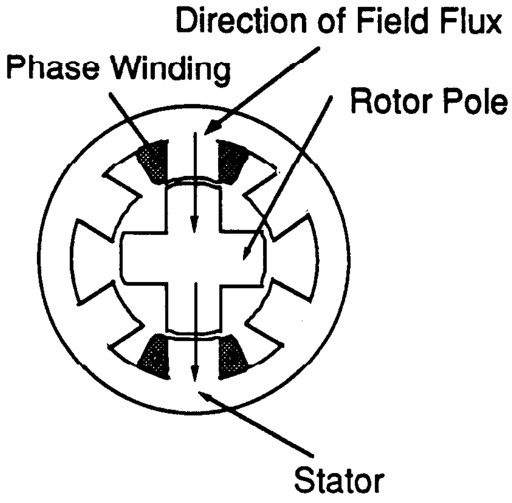

Fig. 1 Constructional Features of Variable Reluctance Motor.

The second remaining recent development in variable speed electric machinery is the strides made in permanent magnet technology which, in turn, has allowed an increase in the power density and efficiency of permanent magnet machines [8]. These new machines constructed of Neodymium-Iron-Boron magnets have the highest efficiency of any motor yet developed. Major obstacles remain, however, including low Curie temperature and high manufacturing cost both for the magnets and the machine itself. While the author believes that such machines will eventually become dominant at nearly all power levels in the future when oil supplies dwindle, they will remain suitable only for specialized applications in which cost has a low priority over the next decade.

Another class of machine, which appears to have been relatively overlooked, is the synchronous reluctance machine. This machine differs from the variable reluctance motor in that the stator is constructed from a cylindrical structure in identical fashion to an induction motor and only the rotor has salient poles. Hence, the stator of both machines can be constructed on the same assembly line, a distinct advantage over the switched reluctance machine. The synchronous reluctance motor also has a long history [9]. Interest in this machine for variable speed applications peaked in the 1960s when fiber spinning plant for synthetic fibers were expanding rapidly. Since the synchronous reluctance motor operates in exact synchronism with the stator frequency, a higher grade of fiber could be produced compared to speed regulated dc motors or induction motors. In these applications, the synchronous reluctance motor was operated in open loop fashion in much the same manner as the early variable reluctance motor drives. In this case the inverter voltage and frequency was set independent of the rotor speed or position and the rotor of the machine followed along synchronously if the load torque and slew rate were not too large. When operated in such fashion, the motor exhibited poor damping so that speed response was very sluggish. Also, with the saliency (X_d/X_q) ratios achievable at that time, the motor operated with a poor power factor and lower efficiency than a comparable induction machine.

With the emergence of induction motor drives with speed control accuracy to a fraction of a per cent, interest in these machines seems to have diminished. However, development of improved rotor structures and stator winding configurations have markedly improved the potential of this machine. In particular, in the sixties, the rotor configuration most often employed was a lamination with punchings or slits oriented so as to create a saliency effect as shown in Fig. 2 [10]. Because of the need for rotor bridges, this type of rotor, however, was only capable of a saliency ratio of two to three. Near the end of this decade, the saliency ratio had improved to values in the region of four to five by utilizing discrete poles mounted on a non magnetic shaft as shown in Fig. 3 [11]. Frame sizes comparable to the equivalent induction motor were claimed [11].

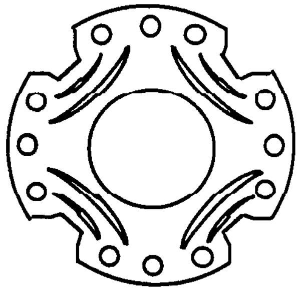

Fig. 2 Illustrating Rotor Punching of Laminated Type Synchronous Reluctance Motor.

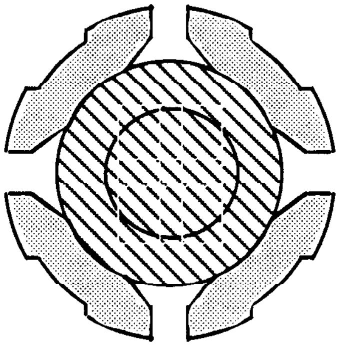

Fig. 3 Showing Rotor Poles of Discrete Pole Synchronous Reluctance Motor.

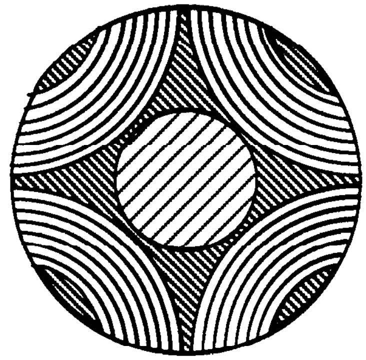

Fig. 4 Axially Laminated Rotor Structure.

While also maintaining a long history [12,13,14], the benefits of a rotor with axially aligned magnetic laminations have only recently been recognized [15,16]. In this case magnetic laminations are bent to produce paths of minimum reluctance in the direction of the laminations and maximum reluctance in the path normal to the laminations as shown in Fig. 4. Saliency ratios reaching 7-8 have been reported with such a construction [16]. With such high saliency ratios, difficulties associated with relatively low efficiency and power factor have essentially been eliminated. In addition, the benefits associated with careful current control of the armature currents, so effectively utilized on switched reluctance motors, are only beginning to be quantified [15]. In particular, it can be shown that with the principle of current regulation, the synchronous reluctance motor can also achieve power densities and efficiencies which, perhaps, exceed the induction machine [17]. Also, it has recently been demonstrated that many of the same advantages of the switched reluctance machine are common to the synchronous reluctance machine as well. For example, the stator of the switched reluctance motor need be fed only with unidirectional currents (two quadrant chopper) in much the same manner as a switched reluctance motor. Also, any number of phases can be considered including two phases, a number which can be achieved only with great difficulty in a switched reluctance motor. In this case the number of solid state switches (transistors) can be reduced to only two; a distinct advantage over a three phase induction motor drive [15,18]. In addition, the torque pulsation and acoustic noise problems, so intractable in switched reluctance motors, can essentially be eliminated in a synchronous reluctance machine.

It should now be apparent that advances in the design and control of synchronous reluctance machines could open up new areas of research in this field. The purpose of this paper is to propose new synchronous reluctance and kindred switched reluctance motor topologies which exploit the capabilities of switched reluctance and synchronous reluctance motor principles. In particular, the advantages of current regulation of synchronous reluctance motors, a concept so far not exploited in such machines, will be given emphasis. Six types of new geometry will be discussed. Application of such machines to typical application families needs be investigated in areas such as 1) low cost consumer applications, 2) high response servo type applications, 3) large industrial drives and 4) traction motor drives. It is believed that several of these machines are radical departures from conventional design and warrant serious consideration.

Novel Synchronous Reluctance Motor Drive Configurations

Multiphase Concentrated Winding Synchronous Reluctance Motor Drive

As previously noted, saliencies exceeding 7.0 can now be realized with modern axially aligned synchronous reluctance motors [14-16]. However, little has been done regarding optimizing the motor for operation with modern, pulse width modulated inverters. In particular, most machines of this type are still operated from six step inverters by simply impressing a voltage on the motor of a prescribed amplitude and frequency. In this case the motor poles are synchronized to the motor voltage by creating an emf which lags the applied voltage by an angle δ. Well known problems of poor transient response, poor power factor, and even instability occur in such a mode of operation [19].

On the contrary, when current regulation is utilized in conjunction with a pulse width modulated inverter, the motor poles are synchronized to the stator mmf (stator current) which lags the interpolar (quadrature) axis by an angle ε (see Fig. 5). Problems associated with transient response, stability and power factor can essentially be eliminated. Torque can now be controlled as shown in Eq. 18, resulting in a continuous maximum efficiency operation for any load. As yet, however, little has been done to take advantage of this option nor, furthermore, to optimize the motor itself to this new operating condition. In particular, significant benefits can potentially be realized if the current is optimized to produce maximum torque rather than to produce a sinusoidal flux density in the air gap. It has recently been shown that injection of a third harmonic in the inverter current can increase the torque output by at least 10% without increasing the copper losses of the machine [20]. Such a third harmonic can be injected into the motor by adopting a 5 phase inverter as shown in Fig. 6. The winding diagram for the corresponding 5 phase, full pitch, concentrated winding, synchronous reluctance motor is shown in Fig. 7. It should be noted that it does not appear that injection of a 3rd harmonic is limited to 5 phase machines and could be used on higher order phase machines as well. For example, with a 7 phase machine, both 3rd and 5th harmonics could be injected to further improve the power density of the machine. However, economics could possibly limit implementation to only machines having 5 phases.

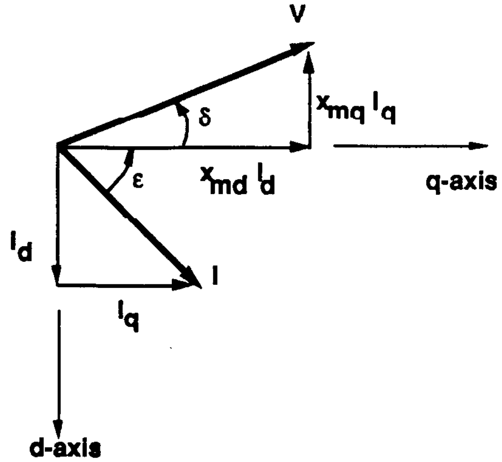

Fig. 5 Vector Diagram for Synchronous Reluctance Motor.

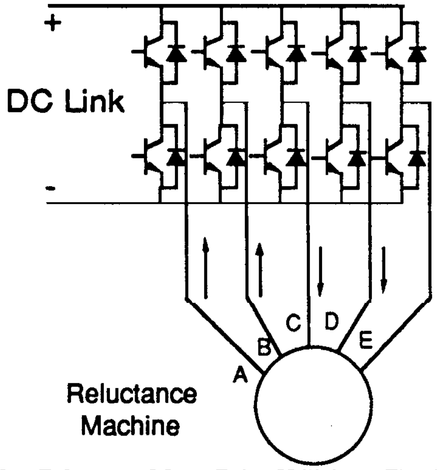

Fig. 6 Reluctance Motor Drive Utilizing a Five Phase Inverter.

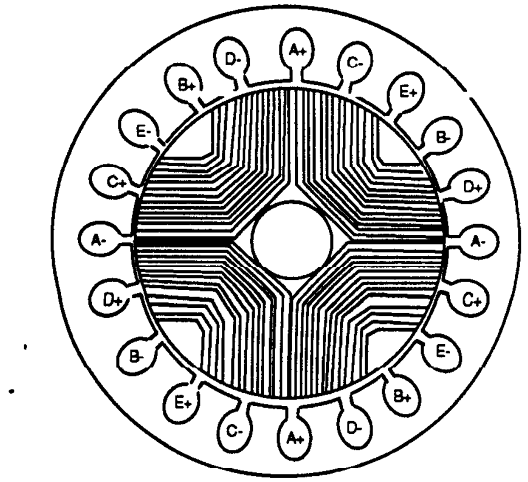

Fig. 7 Winding Configuration for Five Phase Synchronous Reluctance Motor.

Another possibility for exciting such a 5 phase machine is to produce square wave currents as illustrated in Fig. 8. In this case the period of conduction of one inverter leg can be increased from 120° to 144° thereby increasing the torque production of the machine and utilization of the devices accordingly. While such a mode of operation creates extra losses as well, it has been shown that this mode produces a net increase in the torque production when copper losses are held constant [21,22].

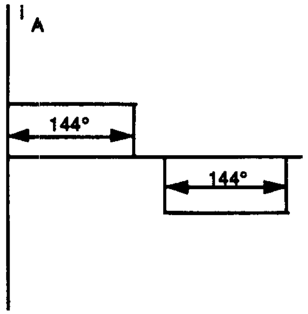

Fig. 8 Square Wave Current Waveform for 5-Phase Reluctance Machine.

Field Regulated Reluctance Machine

Another scheme for control of this machine is illustrated by Fig. 9 [23]. In this case each of the 5 phase currents are controlled to take on a stepped waveform with two amplitudes I_A and I_F. The value I_A is supplied when the coil side of this particular phase is located along the pole face of the rotor. The current I_F is supplied when the coil side is positioned in the interpolar space.

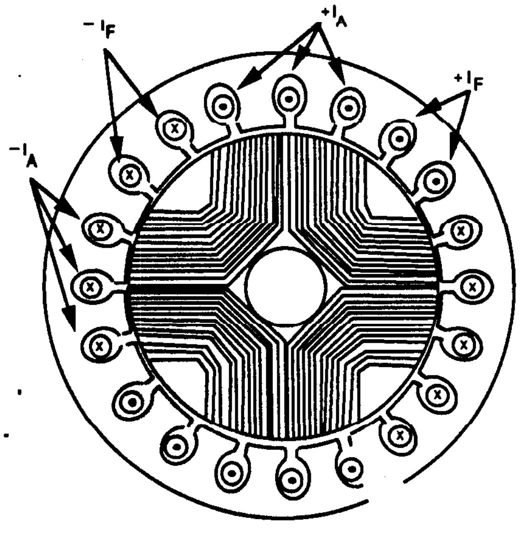

Fig. 9 Excitation of Synchronous Reluctance Motor Using Field Regulation Principle.

Figure 10 shows an idealized plot of the counter EMF and current in one of the five phases. Note that a typical phase current takes on one of two amplitudes, I_A and I_F. For 3/5 of the time the amplitude is I_A while the pole is sweeping by the slot which contains this phase. For 2/5 of the time the amplitude is I_F which corresponds to the time when the interpolar region is occupying the region beneath the slot. Note that when the pole sweeps by the phase, the flux linking the winding is changing (or flux is said to be "cut") and the EMF E is induced. The power transmitted to the shaft is clearly

$$P_{ag} = 5\cdot\left(\frac{3}{5} E\, I_A\right) = 3\, E I_A. \tag{1}$$

The developed electromagnetic torque is therefore

$$T_e = P_{ag} / \omega_{r(mech)} \tag{2}$$

Since

$$E = \frac{P}{2}\, \omega_{r(mech)}\, L_{md} I_F \tag{3}$$

Equation 2 can be written

$$T_e = 3\, \frac{P}{2} L_{md}\, I_A I_F \tag{4}$$

Hence, the torque can be controlled in identical fashion to a dc machine, namely to keep I_F constant in which case the torque T_e is then proportional to the "armature current" I_A. Compared to a conventionally wound three phase machine, the presence of a "3" term rather than the usual "3/2" term in the torque expression can be noted.

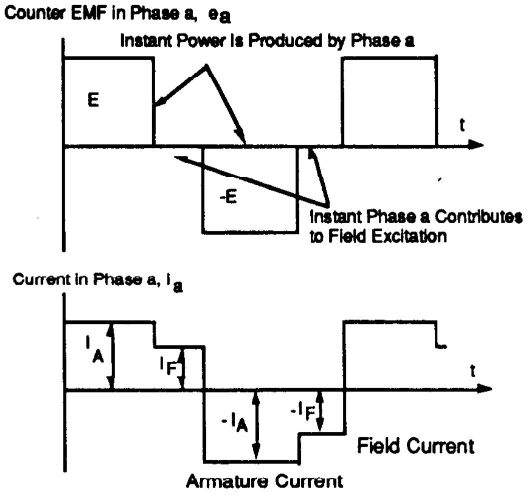

Fig. 10 Current and Voltage Waveforms of One Phase of Synchronous Reluctance Motor Employing Independent Control of Armature and Field MMF.

Two Phase Concentrated Winding Synchronous Reluctance Motor

When cost is of primary concern, that is in consumer applications, synchronous reluctance motors also shows considerable promise. In this case, the essential feature is to keep the number of solid state switches to a minimum. Probably the minimum number of switches possible to produce bi-directional rotation is the value of two. Figure 11 shows an idealized diagram of such a synchronous-reluctance machine while Fig. 12 shows details of the winding configuration [24]. In this case, only unidirectional currents are supplied to the two phases as shown in Fig. 13 and the current is injected into the machine only when the inductance of a given phase is increasing. In effect, the machine operates in much the same manner as a variable reluctance machine. However, since the inductances vary nearly linearly, and since the torque varies as $(1/2)\, I^2\, (dL/d\theta)$, the torque for each "stroke" or current pulse is nearly constant as shown in Fig. 14. Hence, the torque pulsations, normally associated with such machines can essentially be eliminated. Figure 15 shows a plot of the power loss per unit torque versus the torque itself for a synchronous reluctance and a variable reluctance machine of exactly the same air gap diameter and stack length. Since both power loss and torque vary as the square of the current when the machine is not saturated, one would expect a nearly horizontal line for both machines. However, since the variable reluctance machine saturates at a much lower current (i.e. flux linkage) the torque of the variable reluctance motor changes at a rate less than the square of the current (approximately linearly). In this case the power loss per unit torque increases rapidly. However, the curve remains much more horizontal for the two phase synchronous reluctance motor indicating that this type of machine is a much better torque producer. It is apparent that design of such machines is rich in possibilities and the choice of phase number, current waveform, rotor construction will vary with each application and forms a very interesting body of future work.

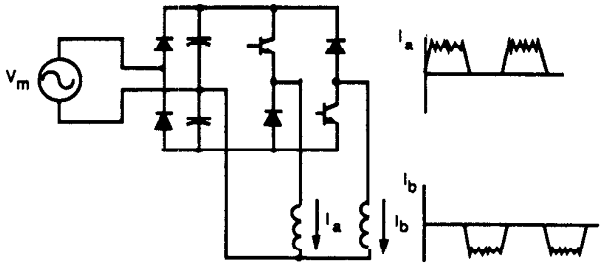

Fig. 11 Converter Configuration for Two Phase Synchronous Reluctance Motor Utilizing Unidirectional Current Pulses.

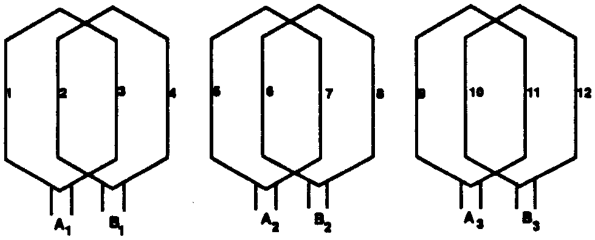

Fig. 12 Winding Diagram for Two Phase, Six Pole Synchronous Reluctance Motor.

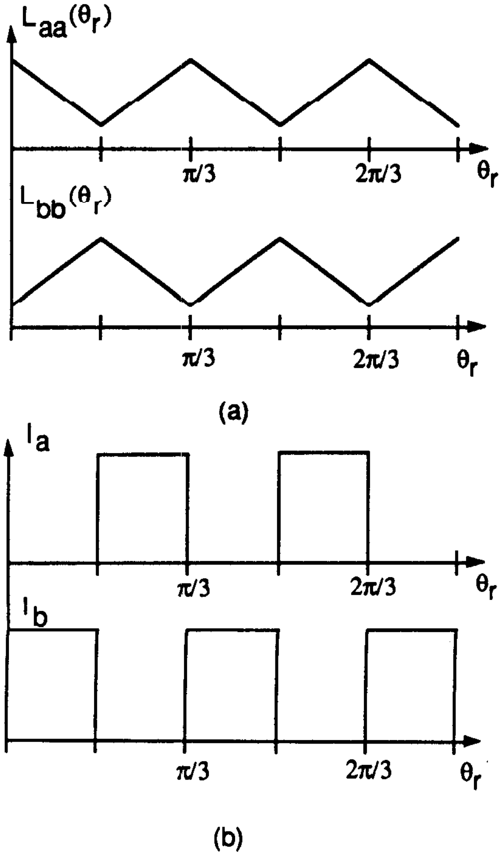

Fig. 13 (a) Variation of Self Inductances and (b) Current Waveforms of the Two Stator Phases as a Function of Rotor Position.

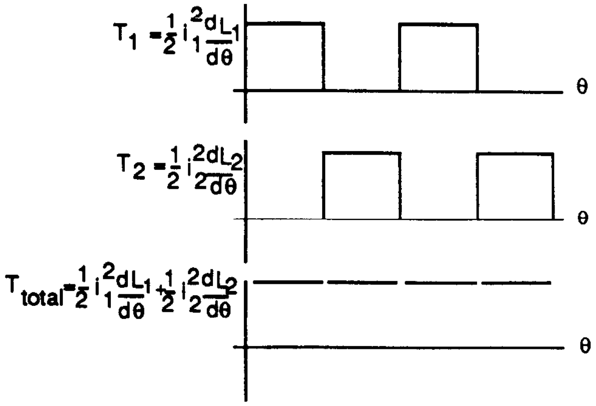

Fig. 14 Waveforms Illustrating Torque Production in Two Phase Synchronous Reluctance Motor.

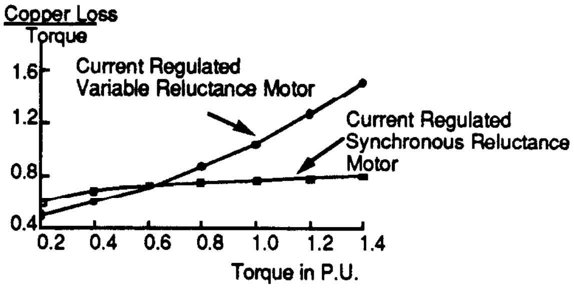

Fig. 15 Ratio of Torque to Copper Loss versus Torque Curves for 7.5 HP Variable Reluctance and Two Phase Synchronous Reluctance Motor.

Homopolar Variable Reluctance Motor Drive

Recently, interest in the use of variable reluctance for motor drives has experienced a surge of interest [1-4]. These machines, when combined with a solid state converter to realize a variable speed drive, has been christened a switched reluctance motor (SRM) [1]. The mechanism of torque production by the doubly-salient saturated variable reluctance action has been well-explored [24-27]. In addition to its simple and rugged construction, the SRM has well-known advantages in terms of the converter supply. The power converter feeding an SRM is simple and reliable because of its unipolar current conduction peculiarity. However, the SRM is not without its shortcomings. One can easily identify the following drawbacks: 1) Relatively poor energy ratio (normally 80% at best), a factor equivalent to power factor for conventional ac machines. As a result, the associated power converter is generally derated. 2) Very complicated torque production because of the highly saturated magnetic flux path and the complexity of the current waveform over a wide range of speed. Therefore, accurate torque control is very difficult, and torque ripple and accompanying acoustic noise is always significant in such machines. 3) Manufacturing tolerances limit the minimal airgap length which is critical to the performance of the motor, especially for motors of smaller size. Therefore, like induction motors, small motors suffer from an "excitation penalty" unless very stringent manufacturing tolerances are maintained. It should be noted that these drawbacks are inherent in the operating principle of the SRM, in which the stator current serves as both field current and torque current and the phases are individually pulsed.

On the other hand, the homopolar type of inductor machine, have been widely used as high speed AC alternators [28-30], and only recently have their application to adjustable speed motor drives been considered [31]. These machines also possess the unipolar current conduction property if operated in switched reluctance mode, as for stepping motors. As shown in Fig. 16, the construction of a typical homopolar type variable reluctance motor [32], consists essentially of two SRM's stacked together except that the homopolar machine has an additional DC excitation providing the main flux, which adds to its structural complexity. Because of the existence of the DC excitation, this construction has been considered to be of lower power density and has only found applications in high speed cases [30]. However, as revealed by a preliminary study of this configuration, this drawback can be offset by the higher energy ratio made possible when operating in a switched mode which heretofore has apparently never been exploited. This analysis suggests the possible emergence of a new type of brushless dc motor, the homopolar variable reluctance motor (HVRM), with performance superior to that of SRMs while preserving all the merits of SRMs.

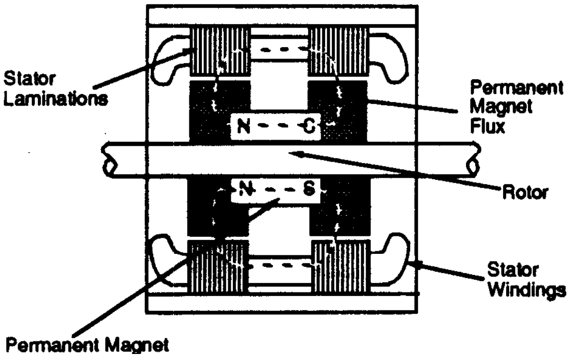

Fig. 16 Side View of Homopolar Variable Reluctance Motor

The principle of operation of the homopolar variable reluctance motor is illustrated in Fig. 17 which shows the punchings and a stator winding of a 3-phase, 6/4-pole HVRM. The DC excitation can be provided by either a permanent magnet or a stationary solenoid, as shown in Fig.16. In either case, the main flux path is designed such that, for any rotational position, its reluctance is ideally a constant for the DC excitation, and infinite for any additional MMF in the path. This requires that:

(i) the total overlapped pole area be kept constant at any instant. Thus the reluctance of the airgap part, which forms the majority of the total reluctance of the main flux path, is invariant of the rotor position. It is clear that the 6/4-pole structure with $\beta_s = \beta_r = \pi/6$, as shown in Fig. 17, will meet this requirement.

(ii) the magnetization characteristic of the main flux path must be an approximation of that of common electrical steel, or as shown an approximation of that of high residual flux density PM material, like Alnico-V. The nearly flat-topped characteristic constitutes a very high reluctance path for the stator MMF.

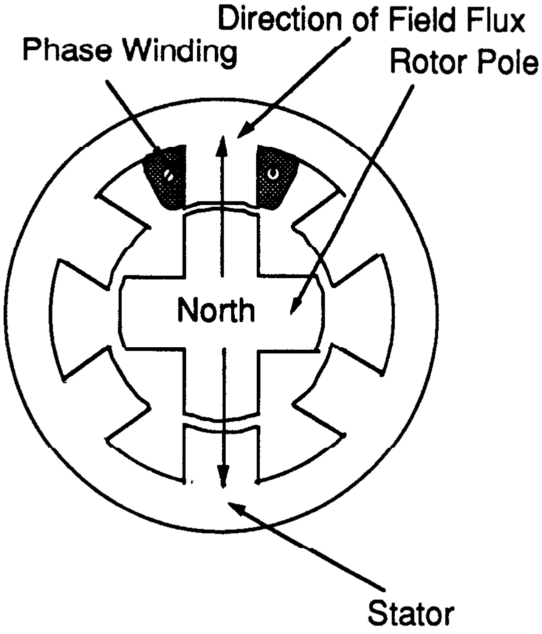

Fig. 17 Axial View of Homopolar Variable Reluctance Motor. Winding of Only One of the Three Phases is Shown.

Once these characteristics are ensured, the MMF in the working stator winding will produce only stator leakage flux which is forced to circulate within the lamination plane. However, the main flux linkage in the stator winding produced by the permanent magnet, which is little affected by the existence of the stator leakage flux and thus almost proportional to the overlapped area of the active stator pole and rotor pole, will change linearly with the rotor angle. This concept of decoupling of the stator flux forms a new operating principle for the homopolar variable reluctance motor. The concept can be further explained by reference to Figs. 20 and 21 which show typical flux linkage versus current curves for a switched reluctance motor and for a homopolar variable reluctance motor respectively. In the case of the switched reluctance motor, Fig. 18, a particular "stroke" of the motor results in a current/flux linkage trajectory which rotates on this plane in the counterclockwise direction.

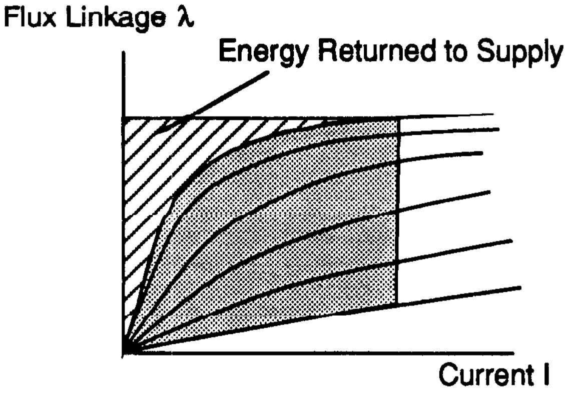

Fig. 18 Typical Flux Linkage vs. Current Curves for Variable Reluctance Motor.

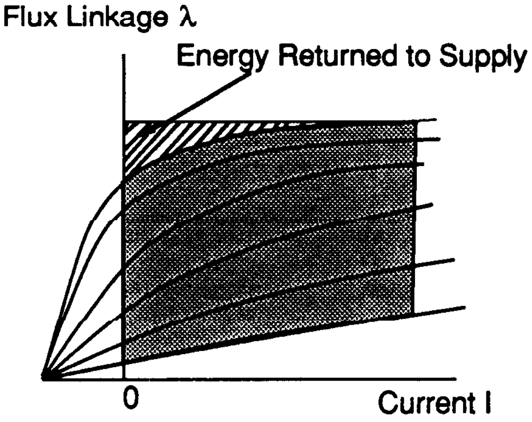

Fig. 19 Typical Flux Linkage vs. Current Curves for Homopolar Variable Reluctance Motor.

The motion encloses an area shown in the figure as the darkened region which corresponds to the energy conversion. During the period of the cycle where the current is again decreasing to zero, energy is returned to the supply as denoted by the dashed region, During this time the inductance increases rapidly making the process of forcing the current to zero very difficult. In practice, a current "tail" is often produced which could even result in production of a negative torque component. The size of the current tail can only be reduced by a substantial increase in the KVA rating of the power converter relative to the rating of the machine. In Fig. 19 a similar "stroke" for a homopolar variable reluctance motor is shown. In this case the presence of the dc magnet MMF results in a shift of the lambda/current curves. That is, flux in the pole under consideration is produced even when the stator current is zero. Hence, the magnet is now acting as the excitation winding as in a normal permanent magnet machine and the excitation energy need not come from the power converter during each stroke. The energy returned to the supply is clearly much smaller indicating a more efficient energy conversion process. Also, note that the pole remains saturated during the entire process so that the problems with the "current tail", discussed above for the switched reluctance motor have been eliminated suggesting the possibility of using a power converter of much smaller rating than for the switched reluctance motor.

In order to achieve good flux decoupling, it is apparent that special considerations are to be given at the design stage to reducing the stator leakage inductance, especially the mutual leakage. A larger airgap, while a critically adverse factor for SRM's, helps to reduce the leakage inductance of this type of machine, although a trade-off must be made between the reduction of the leakage inductance and the inevitable increase of the DC excitation MMF.

In summary, the homopolar variable reluctance motor is a new type of brushless dc motor featuring:

1. A unipolar, soft-switching power converter with reduced current ratings compared to SRMs, having no additional current stress and much lower voltage stress as compared to SRMs for the main switches. As is also true for SRMs, there is no 'shoot-through' fault path making this machine much easier to protect that conventional ac induction or permanent magnet motors.
2. A high power density which certainly comparable to or even in excess of SRM's or even induction motors.
3. A linear torque control characteristic so that precise torque control is possible in a servomotor application.
4. A new principle of operation which, in contrast to the SRM, allows the machine to have a nearly smooth torque with low mechanical noise.

Doubly Fed AC Excited Reluctance Motor Drive

In practice there are numerous situations, such as pump and compressor applications, where the speed of the drive does not need to change over a wide range. The fact that the power to be controlled in the speed adjusting process is only a small part of the the machine rating and implies that the converter rating can be reduced to a great extent for such drive systems. One of the means to reduce the converter rating is to use a solid state converter to control the slip power into the rotor terminals of a doubly-fed wound rotor induction motor. In such applications, a bidirectional power converter rated approximately at 15% of the machine rating can provide a + - 15% power transfer from the rotor to cover a 30% speed range at constant torque [33-35].

Although a doubly-fed wound rotor machine provides a means to reduce the converter rating, the complication of the rotor and the slip ring limit the application of such machines. To eliminate the complicated rotor and slip arrangement, the so-called self cascaded induction machine has been proposed [36-38] and recently resurrected [39]. A self cascaded machine normally consists of a specially wound rotor and a stator with windings as shown in Fig. 20. The stator winding sets up a pole pair number of a multiple of three with respect to the main terminals A, B and C, and a non-triplen pole pair number with respect to the star points a,b and c. One of the two windings is connected to the utility supply while the other is connected to a frequency converter for the purpose of speed control. Unfortunately, with the need for a special shorted windings on the rotor, this class of machine has suffered severely from the point of view of efficiency.

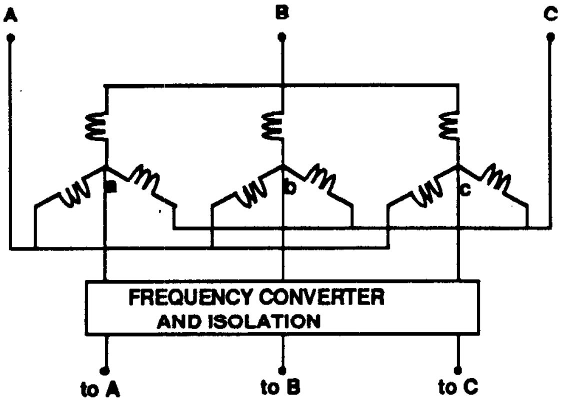

Fig. 20 Stator Connection of Doubly Excited Reluctance Motor.

The efficiency problem concerned with the doubly-fed induction machine can be substantially solved by replacing the doubly wound rotor with a simple reluctance type rotor. Such a machine was first proposed in a synchronous machine realization having a dc field excitation by Broadway [40-44]. This machine was later constructed by Heyne and El-Antalby [45]. In this case the stator is outfitted with a pair of three phase windings and a dc voltage is applied between the two neutral terminals. While such a machine shows promise for fixed speed, sinusoidal operation it requires a full rated converter for variable speed.

While much more suitable for variable speed operation, it appears that a doubly-excited three phase arrangement of a reluctance type machine, operating in a doubly fed, variable speed mode has never been previously even been proposed, much less investigated. In this case the stator is wound in the double three phase winding arrangement similar to the self cascaded induction machine and the rotor consists of simple saliencies without an additional rotor winding (Fig. 20). The cage rotor of the normal self-cascaded machine is replaced by a low cost, readily manufactured salient rotor equipped without a cage winding. Since this type of machine has no rotor copper loss and the stator windings serve a dual purpose of carrying the normal fixed frequency current as well as the variable "slip frequency" current this structure clearly offers the possibility of high efficiency. The low machine manufacturing cost and maintenance cost due to the simple rotor structure, low converter cost due to the rating reduction and promise of high efficiency makes such a machine very attractive as a potential means of economical variable speed drives, particularly for pump, fan, and compressor applications.

The principle of operation of this machine can be explained briefly by reference to Fig. 22 which shows how the p pole stator MMF interacts with the rotor saliencies having (p+q)/2 poles to form a q pole flux and MMF component. Since the second stator winding is also wound with q poles, the two q pole MMF waves interact to produce an electromagnetic torque. More details of the analysis of this machine can be found in Ref. 46.

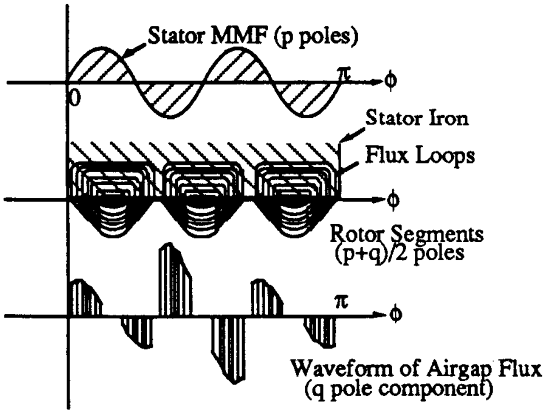

Fig. 22 Principle of Operation of Doubly AC Excited Reluctance Motor

Permanent Magnet Assisted Synchronous Reluctance Motor

While it is possible to increase the torque of the synchronous reluctance motor to a value in excess of the induction motor this is accomplished at the expense of increasing the stator current in the synchronous reluctance machine by a factor of $\sqrt{2}$ higher than the induction motor [17]. While this creates the same losses in this machine as the induction motor, the increased current clearly imposes a penalty on the converter since the switch ratings must be increases by $\sqrt{2}$ compared to an induction motor. In effect, the synchronous reluctance motor runs at a poorer power factor than the induction motor.

This problem can alleviated by inserting permanent magnets between rotor laminations such that the permanent magnets "assist" the torque production. The principle can be illustrated by expressing the torque in term of d-q variables. That is,

$$T_{pmr} = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \tag{5}$$

When permanent magnet are included in the q-axis flux path the flux linkage expressions become

$$\lambda_{ds} = L_{ds}\, i_{ds} \tag{6}$$

$$\lambda_{qs} = L_{qs}\, i_{qs} + \lambda_{mq(pm)} \tag{7}$$

where L_{ds} and L_{qs} are the d- and q-axes inductances and, since $L_{ds} \neq L_{qs}$.Eq. 5 can also be written as

$$T_{pmr} = \frac{3}{2}\frac{P}{2}[(L_{ds} - L_{qs}) i_{qs} i_{ds} - \lambda_{mq(pm)} i_{ds}]$$

If we examine the first term in Eq. 5, i.e. the saliency term we can note that the quantity $L_{ds} i_{qs} i_{ds}$ while the quantity $L_{qs} i_{qs} i_{ds}$ is negative. In effect, the q-axis saliency (q-axis flux) acts to <u>lower</u> the torque production which is primarily coming from the d-axis saliency (d-axis flux) interacting with the q-axis current. We could consider that a theoretical maximum torque for a synchronous reluctance machine can be reached if we were able to make $L_{qs} = 0$. This possibility can be reached by use of the second term of Eq. 5. In particular, assume that the polarity of the magnets are reversed relative the positive direction defined by the q-axis (direction of the stator q-axis MMF). Then, Eq. 5 can be written,

$$T_{pmr} = \frac{3}{2}\frac{P}{2}\{L_{ds}\, i_{qs} i_{ds} - [L_{qs} i_{qs} - \lambda_{mq(pm)}] i_{ds}\} \tag{9}$$

Hence, the second (negative torque producing term can be made as small as necessary by placing magnets in the q-axis of the rotor. In effect, the q-axis inductance can be made to approach zero. Figure 22 shows a phasor diagram including the effects of a permanent magnet in which the quadrature axis current is assumed to be completely cancelled. Note the potential for improved power factor compared to the normal synchronous reluctance motor. It is clear that the power factor can be improved even more by reducing the d-axis component of stator current (which now not need be the same value since the torque has effectively been increased).

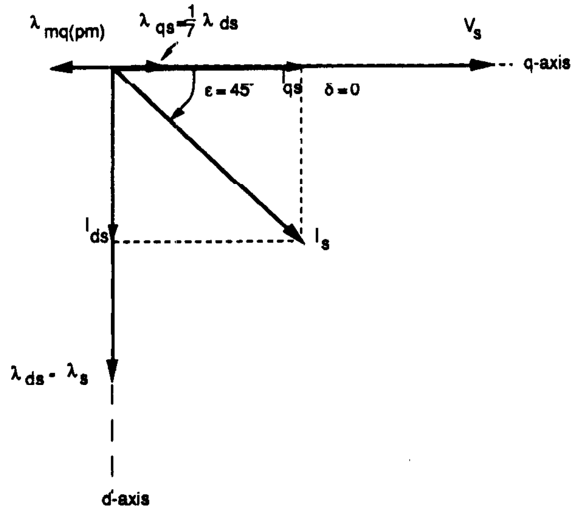

Fig. 22 Phasor Diagram Corresponding to Fig. 5 for Permanent Magnet Assisted Synchronous Reluctance Motor.

A tentative diagram of the rotor geometry for the permanent magnet assisted synchronous reluctance motor is shown in Fig. 23. Note in particular, that simple bar magnets are placed in the sections between lamination groups which make up the salient pole structure. These bar magnet are held in place by simple mechanical pressure produced by bolting the lamination groups. The magnets are magnetized so as to force the permenant magnet flux into the quadrature axis. It is important to mention that the amount of flux which is needed is not large since the machine is basically magnetized by the d-axis component of stator current as in a normal machine. Only a relatively small amount of quadrature axis flux is need to counteract the q-axis armature reaction.

Conclusion

This paper has presented six new types of reluctance motor structures for use in adjustable speed drives. The purpose of this paper is to demonstrate that there appears to be rich research possibilities in the field of adjustable speed reluctance motor drives. It is hoped that the reader will join the author in exploring these exciting new possibilities.

Acknowledgments

The author acknowledges the substantial contributions of his graduate students, including Long Ya Xu, Liang Feng, Yufeng Liao and Hamid Toliyat as well as many others. This research was made possible by the continued support of the WEMPEC (Wisconsin Electric Machines and Power Electronics Consortium) sponsors to whom the author is greatly indebted.

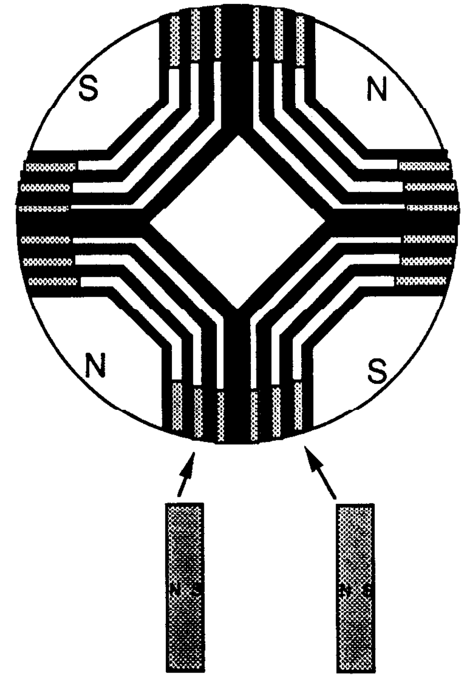

Fig. 23 Illustration of Rotor Configuration for Permanent Magnet Assisted Synchronous Reluctance Motor Drive.

References

[1] P.J. Lawrenson, J.M. Stephenson, P.T. Blenkinsop, J. Corda and N.N. Fulton,"Variable Speed Switched Reluctance Motors" Proc. IEE, pt. B, vol. 127, July 1980, pp. 253-65.
[2] W.F. Ray, R.M. Davis,"Inverter Drive for Doubly-Salient Reluctance Motor: Its Fundamental Behavior, Linear Analysis and Cost Implications", Electrical Power Applications, vol. 2, pp. 185-93, 1979.
[3] W.F. Ray, P.J. Lawrenson, R.M. Davis, J.M. Stephenson, N.N. Fulton, R.J. Blake,"High Performance Switched Reluctance Brushless Drives", IEEE Trans.on Industry Applications, vol. IA-22, No.4 , 1986, pp. 722-30.
[4] M.R. Harris, J.W. Finch, J.A. Malick, T.J.E. Miller,"A Review of the Integral Horsepower Switched Reluctance Drives", IEEE Trans. on Industry Applications, vol. IA-22, No.4, 1986, pp.716-21.
[5] J.T. Bass, T.J.E. Miller, M. Ehsani,"Robust Torque Control of a Switched Reluctance Motor Without a Shaft-Position Sensor", IEEE Trans. on Industrial Electronics, vol. IE-33, pp.212-16.
[6] J.T. Bass et al.,"Simplified Electronics for Torque Control of Sensorless Switched Reluctance Motors", IEEE Trans. on Industrial Electronics, vol. IE-34, pp. 234.
[7] B.K. Bose et al.,"Microprocessor Control of Switched Reluctance Motors", IEEE Trans. on Industrial Applications, vol. IA-22, 1986, pp.708-15.
[8] H. Weh, H. May and M. Shalaby,"Highly Effective Magnetic Circuits for Permanent Magnet Excited Synchronous Machines", International Conference on Electrical Machines, Cambridge Ma, 13-15 August 1990, pp. 1040-1045.
[9] J.K. Kostko,"Polyphase Reaction Synchronous Motor", Journal of A.I.E.E., vol. 42, 1923, pp. 1162-1168.

[10] P.F. Bauer and V.R. Honsinger,"Synchronous Induction Motor Having a Segmented Rotor and Squirrel Cage Winding", U.S. Patent 2733362, Jan 1956.

[11] P.J. Lawrenson and L.A. Agu,"Theory and Performance of Polyphase Reluctance Machines", IEE Proc., vol. 111, No. 8, August 1964, pp. 1435-1445.

[12] A.J.O. Cruickshank, A.F. Anderson, R.W. Menzies,"Theory and Performance of Reluctance Motors with Axially Laminated Anisotropic Rotors", Proc. IEE, vol. 118, No. 7, July 1871, pp. 887-893.

[13] A.R.W. Broadway,"Cageless Induction Motor", Proc. IEE, vol. 118, 1971, pp. 1593-1600.

[14] S.C. Rao,"AC Synchronous Motor Having an Axially Laminated Rotor", U.S. Patent 4110646, August, 1978.

[15] L.Y. Xu and T.A. Lipo,"Analysis of a Variable Speed Single-Salient Reluctance Motor Utilizing Only Two Transistor Switches" IEEE Trans. on Industry Applications, Vol. 26, No. 2, March/April 1990, pp. 229-236.

[16] A. Fratta, A. Vagati,"A Reluctance Motor Drive for High Dynamic Performance Applications", in Conf. Rec 1987 Ann. Meet. IEEE-IAS, pp. 295-302.

[17] T.A. Lipo,"Comparison of Power Density of Squirrel Cage Induction and Synchronous Reluctance Machines", Conference on Evolution and Modern Aspects of Synchronous Machines", Zurich, Sept. 1991 (to appear).

[18] T.A. Lipo and L. Xu,"Variable Speed Reluctance Machine with High Power Density", Patent Granted (to be issued).

[19] T. A. Lipo and P. C. Krause, "Stability Analysis of a Reluctance-Synchronous Machine", IEEE Trans. on Power Apparatus and Systems, Vol.PAS-86, August 1967, pp. 825-834.

[20] H. Toliyat, L. Xu, and T.A. Lipo, "A Five Phase Reluctance Motor with High Specific Torque", To be presented at the IEEE IAS Annual Meeting, Oct. 1990.

[21] H. Toliyat, T.A. Lipo and J.C. White,"Analysis of a Concentrated Winding Induction Machine for Adjustable Speed Drive Applications, Part 1 (Motor Analysis)". To be presented at the IEEE PES Winter Meeting, Feb. 1991.

[22] H. Toliyat, T.A. Lipo and J.C. White,"Analysis of a Concentrated Winding Induction Machine for Adjustable Speed Drive Applications, Part 2 (Motor Design and Performance)". To be presented at the IEEE PES Winter Meeting, Feb. 1991.

[23] H. Weh,"Zur Weiterentwichlung weshelrichtergespeister Reluktanzmaschinen fur hohe Leistungs-dichten und grosse Lesitrungen" (On the Development of Inverter Fed Reluce Machines for High Power Densities and High Outputs), Electrical Machines Inst., Technical University of Braunschweig, etz Archiv, Bd. 6, 1984, pp. 135-44.

[24] M.R.Harris, A. Hughes, P.J. Lawrenson,"Static Torque Production in Saturated Doubly-Salient Machines", Proc. IEE, pt. B, vol. 122, no.10, 1975, pp.1121-27.

[25] J.M. Stephenson, J. Corda,"Computation of Torque and Current in Doubly-Salient Reluctance Motors from Nonlinear Magnetization Data", Proc. IEE, pt. B, vol. 126, pp. 393-96.

[26] J. Corda, J.M. Stephenson,"Analytical Estimation of the Min. and Max. Inductances of a Doubly-Salient Reluctance Motor", Proc. Int. Conf. on Stepping Motors and Systems, Leeds, U.K., 1979.

[27] J.M.Stephenson, M.A.El-Khazendar,"Saturation in Doubly-Salient Reluctance Motors", Proc. IEE, pt. B, vol. 136, no.1, 1989, pp. 50-58.

[28] J.H. Walter, "The Theory of the Inductor Alternator", AIEE Trans. on PAS, No.1, 1942.

[29] E.F. Fuchs et. al.,"Design of a Homopolar Machine with Nearly Closed Stator Slots", Proc. ICEM'82, Budapest, 1982, pp. 96-99.

[30] W.D. Ouden et. al.,"Efficiency of Small Homopolar Synchronous Motors at High Speeds", Elect. Mach. & Power Syst., 1987, p. 29.

[31] A. Kelemen et. al.,"Vector Control of PM-Hybrid Stepping Motors", EPE'89, Aachen, W.Germany,1989, pp. 283-88.

[32] B.C. Kuo,"Step Motors and Control Systems", SRL Publishing Company, Champain, Illinois, USA.

[33] G.A. Smith,"Static Scherbius System of Induction-Motor Speed Control", Proc. IEE, vol. 124, No. 6, 1977, pp. 557-560.

[34] W. Shepherd and J. Stanway,"Slip Power Recovery in an Induction Motor by the Use of a Thyristor Inverter", IEEE Trans. on Industry and General Applications, vol. IGA-5, No. 1, 1969.

[35] H.W. Weiss,"Adjustable Speed AC Drive Systems for Pump and Compressor Applications", IEEE Trans. on Industry Applications, vol. IA-10, No. 1, Jan/Feb 1974, pp. 162-167.

[36] L.J. Hunt,"The Cascade Induction Motor", J. IEE, vol. 52, 1914, pp. 406-426.

[37] F. Creedy, "Some Developments in Multi-Speed Cascade Induction Motors", J. IEE, vol. 59, 1921, pp. 551-552.

[38] A. Kusko and C.B. Somuah,"Speed Control of a Single-Frame Cascade Induction Motor with Slip-Power Pump Back", IEEE Trans. on Industry Applications, vol. IA-14, March/April 1978, pp. 97-105.

[39] R. Spee, A.K. Wallace and H.K. Lauw,"Performance Simulation of Brushless Doubly-Fed Adjustable Speed Drives", IEEE IAS Annual Meeting Conf. Rec., pp. 738-743.

[40] A.R.W. Broadway and G. Thomas,"Single-Unit PAM Induction Frequency Convertors", Proc. IEE, vol. 114, 1967, pp. 958-964.

[41] A.R.W. Broadway, L. Burbridge,"Self-Cascaded Machine: a Low-Speed Motor or High Frequency Brushless Alternator" Proc. IEE, vol. 117, July 1970, pp. 1277-1290.

[42] A.R.W. Broadway, "Cageless Induction Motor", Proc. IEE, vol. 118, 1971, pp. 1593-1600.

[43] A.R.W. Broadway, "Brushless Stator-Controlled Synchronous-Induction Machine", Proc. IEE, vol. 120, August 1973, pp. 860-866.

[44] A.R.W. Broadway and G. Thomas, "Brushless Cascade Alternator", Proc. IEE, vol. 121, 1974, pp. 1529-1535.

[45] C.J. Heyne and A.M. El-Antably, "Reluctance and Doubly-Excited Reluctance Motors", Final Report, Oak Ridge National Laboratories, Report ORNL/SUB/81-95013/1, 123 pp.

[46] F. Liang, L. Xu and T.A. Lipo,"d-q Analysis of a Variable Speed Doubly AC Excited Reluctance Motor", Proc. 1990 International Conference on Electrical Machines, Boston MA, August 1990, pp. 849-855 (to appear in Electric Machines and Power Systems).