VARIABLE RELUCTANCE PM SYNCHRONOUS MOTORS: A SHORT HISTORY AND NEW DEVELOPMENTS

Loránd SZABÓ[1], **András LELKES**[2]
[1)] Technical University of Cluj, Department of Electrical Machines
3400 CLUJ, P.O. Box 358, Romania
Phone: +40-264-195-699 / Fax: +40-264-192-055
e-mail: Lorand.Szabo@mae.utcluj.ro
[2)] ebm Werke GmbH & Co. KG
Bachmühle 2, D-74673 Mulfingen, Germany
Phone: + 49(0)7938-81-590/ Fax: +49(0)7938-81-9590
e-mail: lelkes@ieee.org

ABSTRACT

In a relatively short period, between 1729 and 1831, all the basic electrical and magnetic principles were discovered. After the magnetic effects of electrical currents and the magnetic properties of iron had become known, the first electrical machines were invented in the 1830's. Since then a myriad of improvements have been notified in this domain. In this paper, some representative patents in the field of small permanent magnet synchronous motors are presented in order to illustrate the developments made in time. From among the numerous recent developments made in the field of small electric motors, anenergy saving mains-fed permanent magnet synchronous motor with its electronic starting circuitry will be presented to illustrate the new trends in this rapidly growing area of modern industry.

1. INTRODUCTION

The electricity has an over 2500 years history. It is well known thatthe Greek mathematician and philosopher Thales was the first who postulated the idea of electricity during the period 625–546 BC.The word "electricity" comes from the Latin term *electricus*, meaning to "produce from amber by friction". This term has its roots in the Greek term *elektor*, which means beaming sun.

Modern milestones in the discovery and harnessing of electricity began in 1729 with Stephen Gray’s discovery of the conduction of electricity. In relatively short period after this, momentous discoveries followed. In 1745, Georg Von Kleist discovered the so-called "Leyden Jar". In 1747, Benjamin Franklin suggested the existence of an electrical fluid that could possibly be composed of particles. After only three years he discovered that lightning was the same as electrical discharges. In 1799 Alessandro Volta invented the first electric battery, the first continuous and controlled source of electricity.

In the next century, in 1820, Hans Christian Oersted discovered the magnetic effects of a current, by observing that electrical currents affected the needle on a compass. A few weeks later, Marie Ampere discovered that a coil of wires acts like a magnet when a current is passed thorough it. These discoveries were the basement of the electrical machine’s theory.

In 1827 Joseph Henry began a series of electromagnetic experiments and discovered the concept of electrical inductance. In the same year, Georg Simon Ohm discovered the conduction law. In 1831 Michael Faraday discovered electromagnetic induction [1].

As it can be seen in only about 100 years all the basic electrical and magnetic concepts were discovered. It is evident that the practical applications of these theories must follow.

The first electrical motors were invented in the 1830's. Christie and Pixii built up a motor, which used the repulsion and attraction between electromagnetic poles switched by a commutator. In the 1840's, attempts to make these motors more powerful and larger failed completely because the magnetic forces do not scale proportionally to distance.

More success was encountered in making generators, usually by moving permanent magnets with respect to coils of wire wound around iron cores, to generate alternating currents. It must be remarked that already over 150 years ago there existed permanent magnet electrical machines!

In 1863, Antonio Pacinotti produced a dynamo with a ring wound armature that was able to produce electricity and also run as a motor. Werner von Siemens and Zenobe Theophile Gramme solved the problem of the motor’s efficiency by introducing magnetic circuits that did not change as the armature rotated. Their machines had smooth armatures with conductors on their surfaces. It was still thought that the conductors actually had to be immersed in the magnetic field to produce forces. Soon it was discovered that the conductors must be put into slots in the armature surface. This was far superior mechanically and also made a smaller air gap possible [2].

The first electric carbon arc lamp was invented in 1876. This was the shot in the arm the electrical industry needed. New orders for larger dynamos caused Gramme, Siemens and many others to find cheaper and more efficient ways to generate electricity.

Already in 1879 Siemens realized the first electrical locomotive and one year later the first elevator. The first public electric tramway was built also by Siemens.

In 1882 John Hopkinson patented the three-wire (three-phase) system for electricity generation and distribution. He also defined the principle of the synchronous motor. In 1885 Galileo Ferraris demonstrated in public that he had produced polyphase alternating current using a rotary magnetic device.

Nikola Tesla issued a patent in 1888 on a motor with four or six poles connected to four or six slip rings on the output shaft of a generator. The connection is arranged so the poles in the motor are progressively shifted as the generator rotates. This was the base for the induction motor. The history of the synchronous machines began in 1891, when Sigmund Schuckert from the Brown & Boveri Company demonstrated his alternating current synchronous electric motor [3].

Since then the field of electrical machines and drives has been in permanent ascension. Several motor types were elaborated in the last 100 years. Next we shall present a few significant milestones in the history of small permanent magnet synchronous motors.

2. REPRESENTATIVE PATENTS IN THE FIELD OF SMALL PERMANENT MAGNET SYNCHRONOUS MOTORS

Next from the myriad of patents in the field of small permanent magnet synchronous motors two representative ones will be presented. It must be recognized, that the selection is somewhat subjective, but both are representative for the estimation of their development in time.

In 1948 H.D. Brailsford patented a self-starting motor which was adapted to be operated by the currents from a low voltage source (battery or dry cell) [4]. The cross section of the motor is shown in Fig. 1.

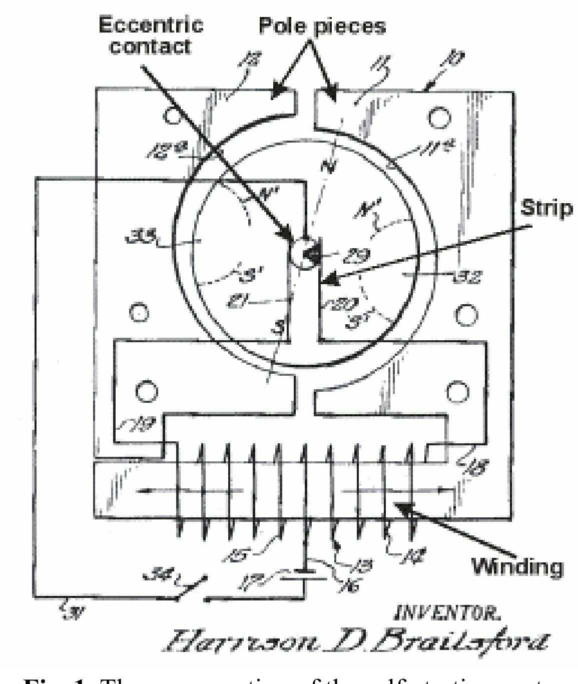

Fig. 1. The cross-section of the self-starting motor patented in 1948

The proposed motor has a permanently magnetized disc rotor, which provides a pair of diametrically opposite poles. The stator of laminated core has also two pole pieces and a common winding. The winding effectively forms two field coils having a common center tap for connection to a source of dc. The other ends of the coils are connected by conductors to flexible conductive contact strips or brushes.

The conducting shaft is provided with an eccentric contact portion formed as by removing a portion of the shaft. The contact members isolated from each other are supported on a plate and they are spaced apart that the eccentric makes contact with said members alternately during the rotation of the rotor.

It is interesting to observe that the motor has an unsymmetrical air-gap in order to force the rotor to come to rest with the axis of the permanently magnetized poles in a position where the maximum starting torque can be exerted upon re-energizing of the field coils. Therefore the rotor operates always in one direction.

This construction solution can be found until nowadays in several types of permanent magnet motors. In Fig. 2 the cross section of a modern brushless dc motor is presented in order to highlight the resemblance between the pole face designs of the two motors.

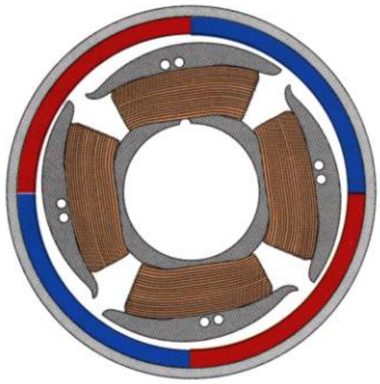

Fig. 2. The cross-section of a contemporary brushless dc motor

In order to fulfill the requirements of the market (e.g. to provide small, cheap, robust, long life running motors that have a few components and can be easily controlled) several new motor types were invented.

A new type of motor, called later the brushless dc motor having a very great future success was evidenced first in 1962, when T.G. Wilson and P.H. Trickey patented the so-called "dc machine with solid state commutation". It was subsequently developed as a high torque, high response drive for specialty applications such as tape and disk drives for computers, robotics and positioning systems, and in aircraft where brush wear was intolerable due to low humidity [5].

The brushless dc motor's early versions (also called "collectorless dc motors") had four separately controlled windings, which generated the rotating field inside the motor. Thecollectorless operation was possible by using two Hall generators and at least four power transistors.

A simpler motor structure was proposed and patented by Rolf Müller (Papst Motoren) in 1975. This patented motor was very simple, required few electronic components and which a simple control circuit could easily control. The simplicity of the motor was a very important criterion, because these motors were used in a very great number in various applications.

The schematic cross-section of Müller's motor is shown in its starting/stopping position in Fig. 3. Basically it is a two-pole external rotor motor having auxiliary electronic circuit [6].

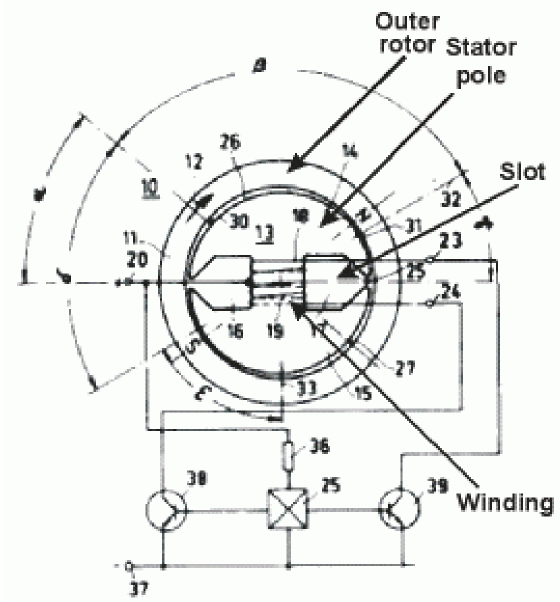

Fig. 3. The cross-section of the collector-less motor patented in 1975

The motor has an outer permanent magnetic two-pole rotor, which is magnetized to have an approximately sinusoidal or trapeze-shaped magnetic field distribution the motor rotates in clockwise direction. The stator has a salient double-T armature having an upper and o lower pole. The armature is formed with two slots in which a single winding is placed formed of two winding halves having a center tap. Two Hall generators are located at the edge of the slots.

The air-gap is made variable, shaped in a specific manner. Upon the rotation of the motor the magnetic energy is first stored and this magnetic energy is then released during interruption of current through the stator winding, so that further driving torque is obtained from the motor.

This type of motor combined with adequate control circuits can provide variable speed operation. In this case, the currents through the coils must be precisely controlled and to be applied exactly at time when the voltage induced in the windings by the permanent magnet rotor have a maximum (when stator and rotor poles are displaced by rough 90electrical degrees.

To improve efficiency and to obtain smooth operation and vibration-free running, current should be supplied to the windings preferably only in that time range, when there is a displacement of 90 electrical degrees between stator and rotor poles. This means that current will flow only during a relatively short period of time at any rotor revolution. Thus the ripples in the torque derived from the power applied to the motor are substantial. However, the torque ripples of the motor are relatively uniform at any speed.

The above-presented patents are only two of the myriad of tries made by engineers to improve several types of motor, to make them more competitive on the market. Next a newer development in this field will be presented, were the specialists were focused on a single type of application of the small permanent magnet synchronous motors.

3. A RECENT DEVELOPMENT IN THE FIELD OF SMALL PERMANENT MAGNET SYNCHRONOUS MOTORS

It is obvious that it is impossible to sort the tremendous number of motor types and variants, to decide that a single type could be the best. All motor types have several advantages and disadvantages. Therefore for any specific applications the most suitable solution must be adopted, taking into account all the circumstances.

Engineers from the German ebm Werke Company, a major manufacturer of motors and fans in a rated output power range from 5 W to 1.5 kW were focused on fan applications, especially those for refrigeration technologies, where fans often have to work around the clock without interruption.

For fan applications, mainly shaded-pole motors, permanent split capacitor type induction motors and electronically commutated motors have been used. Low cost positioned and robust single-phase induction motors have a low efficiency (under 60%). The electronically commutated motors have some important technical advantages over single-phase sub-fractional horsepower induction motors: wide speed range, easy speed controllability and high efficiency. On the other hand, highly efficient electronically commutated motors cannot be used in many applications because of their higher price. The cost of a commutating electronics for small electronically commutated motors rises excessively, if the motor is supplied directly by mains. This commutating electronics becomes unnecessary if the motor is operated line-commutated. However, in case of fan applications, direct-on-line starting is not applicable because of the high impeller inertia. The starting problem must be solved electronically in an inexpensive way.

The proposed energy saving, mains-fed, permanent magnet synchronous motor presents a reasonably priced, highly efficient alternative both to single phase induction motors and to electronically commutated motors.

The most important aim of the research was to find the motor, which consumes the less power at the same mechanical loading. This is a very important issue because these motors for fans are operated almost 24 hours a day and 365 days a year. It is much more important than the motor's purchase price. In [7] the costs (purchase price vs. energy cost) of a 10 W shaded-pole motor during its typical lifetime of 30,000 operation hours are presented. The purchase price is only about 4% of the total costs!

This is because the shaded-pole motor has a very low efficiency. For example, a 4-pole shaded-pole motor with 5 W nominal shaft power has a maximum efficiency of only 16% and a power factor cos φ = 0.69. An electrical power consumption of 31 W is required for a mechanical output power of 5 W due to the poor efficiency. The difference (26 W) is very great and is converted into heat. Motors are frequently used at operating points other than the optimum, so that the efficiency is reduced even further. For example, with a mechanical load of 2.5 W, the efficiency of the same motor is less than 10%!

The efficiency comparison of the shaded-pole and the proposed synchronous motors is shown in Fig. 4.

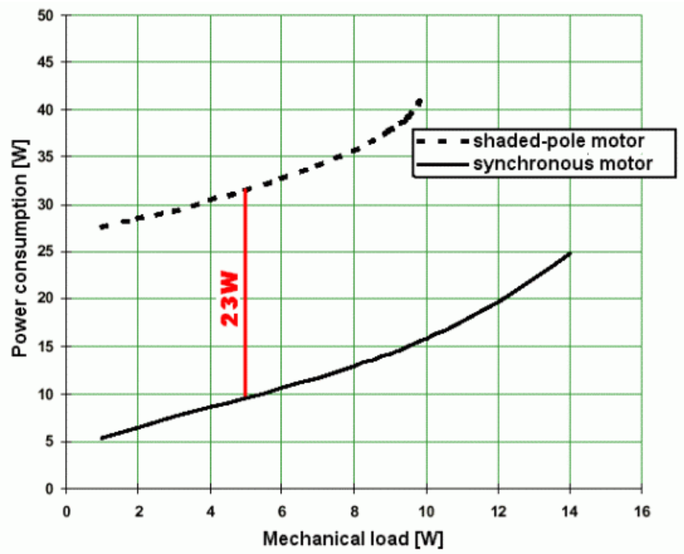

Fig. 4. Efficiency comparison of the shaded-pole and the proposed synchronous motors

Apart from the large amount of energy wasted and the high energy costs, another disadvantage of the shaded-pole motor is that it heats its environment, which is a very great disadvantage in case of using the fan in refrigerators. The high operating temperature also shortens its life expectancy. Therefore, these motors have to be replaced at specific intervals with significant additional costs, especially in applications, where the motors are running continuously.

That means that the shaded-pole motor is inexpensive to buy, but its energy and maintenance costs over the years are tremendous. Therefore from the economic point of view it is much more economic to purchase a more expensive motor with greater efficiency.

Taking all these into account the ebm Werke's engineers worked out a small single-phase permanent magnet synchronous motor integrated with its starting electronic circuits for a specific area, that of driving fans and coolers [8].

The mechanical and magnetic parts of a brushless dc motor have been used. The motor has an external rotor, which rotates around the internal stator. The rotor contains a low-cost plastic-bonded ferrite magnet, which is magnetized with 4 poles. Ferrite magnet was selected for cost reasons. The stator has 4-slots with a single-phase winding. The winding does not produce a rotating field, but a pulsating one. Beside this, the magnetic field is not generating torque in certain rotor positions. If the motor were to stop in any of these positions, it might not be able to produce any starting torque, irrespective of the current flowing through the winding. To avoid this, a specially designed stator core is used, which forms a non-uniform air gap with the rotor. This results in a reluctance torque, which ensures that the motor cannot stop at the critical angle positions when the power supply is switched off. The short end windings and the bearing system, which is integrated inside the stator, result in a compact construction. In Fig. 5 the cross-section of the motor is given.

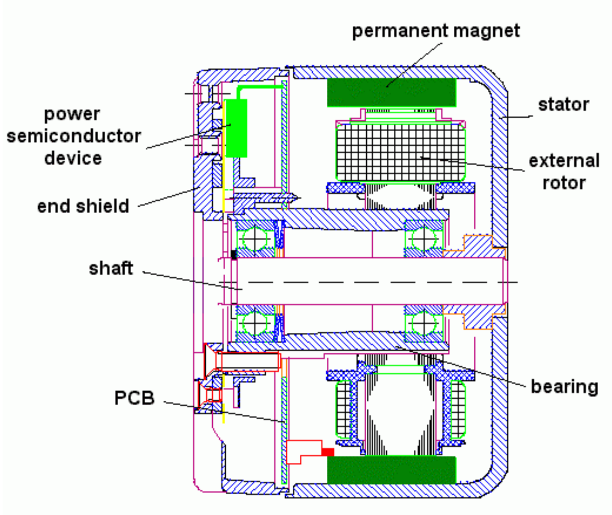

Fig. 5. The cross-section of the proposed motor

The external rotor construction is very advantageous for certain applications, particularly for fans. For radial fans, the motor can be fitted inside the fan impeller itself. For axial fans, the blades can be mounted on the rotor directly. Both versions result in a space-saving fan/motor unit. The firm connection between all rotating parts in a fan also ensures accurate balancing and thus a low load on the bearing allowing a long life time.

Conventional low-power mains-operated synchronous motors generally have low inertia. This allows the rotating parts to accelerate to synchronous speed very rapidly. Motors such as these can thus be started by connecting them directly to the AC mains system, without any additional measures. The external rotor motor presented above has considerable greater inertia, owing to their external rotor and the fan impeller mounted on it. Therefore it needs special starting and synchronization circuits and procedures [9, 10].

During start-up, the main's frequency differs significantly from the motor's rotary frequency. Therefore, a rotor-position-dependent commutation method has to be applied which selectively switches only the appropriate half-wave or half-wave-part of the alternating line voltage on motor windings, in order to gain a maximum accelerating torque without risk of demagnetization of permanent magnets. This seems easily to be achieved by a logical comparison of line voltage polarity to the polarity of the induced voltage. The latter can be derived from a Hall-effect sensor, which is placed in the external rotor's magnetic field [11].

The best and the simplest technical solution found by the engineers from ebm Werke is presented in Fig. 6. The relatively simple electronics has two triacs, the most inexpensive and robust electronic power switches, which are controlled by a low-end-microcontroller. During the run-up phase, triac Tr_2 is active and feeds the start-up winding. With an appropriate control strategy, the rotor can be accelerated up to its synchronous speed, even driving a high-inertia load. The control software is in charge of avoiding demagnetization of the rotor during the time of acceleration and synchronization. Once the rotor is synchronized, the motor is permanently connected to the mains via Tr_1, and it works at constant speed and with high efficiency [12].

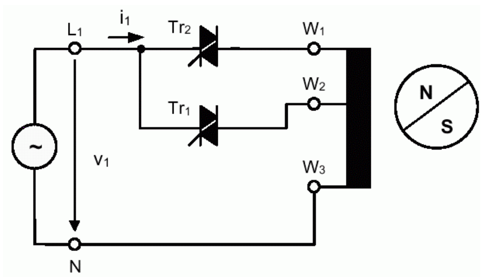

Fig. 6. The starting electronic circuit of the proposed synchronous motor

This solid state starter is not only less expensive than the electronics of an electronically controlled brushless dc motor, but also its size is significantly smaller. So it is possible to integrate the starter circuitry into the motor flange, as shown in Fig. 7. An advantage of a synchronous motor with integrated starter is the simple mains connection similar to that of a shaded-pole motor.

Fig. 8 shows the rotor displacement angle profile, and the motor current envelope curve achieved with this solid state starter circuit.

Fig. 7. The starting electronic circuit integrated into the motor flange

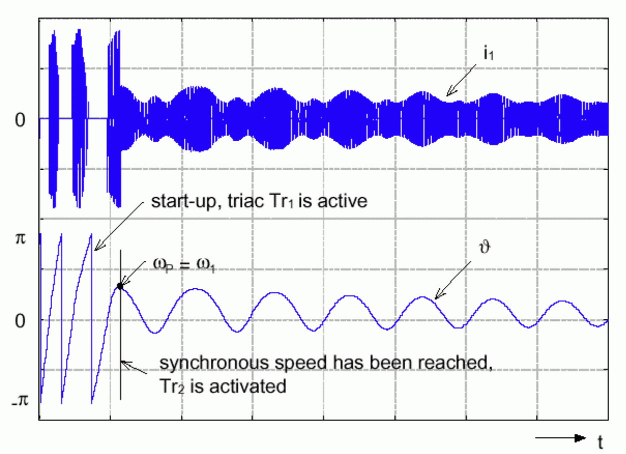

Fig. 8. The displacement angle υ and the envelope curve of the motor current i_1 at synchronization

As it can be seen the start-op period during which the currents are relatively great is short. After coupling all the stator winding to the mains, in a few periods the steady-state regime is reached. With a special PLL control, the oscillation shown in Fig. 8 can avoid almost entirely [11].

All the results presented here confirm the usefulness of the proposed synchronous motors and of the starting electronic from both the technique and economic point of view. The manner in which the engineers from ebm Werke solved the problems regarding a specific application of electrical drives shows the right manner to solve a relatively complex technical challenge.

REFERENCES

[1] *Early History of Electricity*, IEEE. 2001.
URL: http://www.ieee.org/organizations/history_center/early_history_electricity.html

[2] J.B. Calvert: *Electrical Machinery*. URL: http://www.du.edu/~jcalvert/tech/elmotors.htm

[3] J.F. Metcalf: *Electricity to year 1900*. URL: http://www.ioa.com/~micron/002-Electricity.html

[4] H.D. Brailsford ,*Patent 2,457,637*. United States Patent Office. 1948.

[5] E.C. Lee: *Review of Variable Speed Drive Technology*, PowerTec Industrial Motors Inc.
URL: http://www.wireworld.com/seminar/drives/

[6] R. Müller: *Patent 3,873,897*. United States Patent Office. 1975.

[7] A. Lelkes, Th. Bertolini: Energy saving motor to substitute induction motor, *AMD&C Magazine*, 2000, No. 5, pp. 24-27, 2000.

[8] A. Lelkes, J. Krotsch: *Synchronous AC motor,* US Patent & Trademark Office, US 2001/0011877 A1, 2001.

[9] A. Lelkes, J. Krotsch: Energy saving mains-fed PM synchronous motor with integrated solid state starter, in: *Proceedings of the 37th International PCIM' 2000 Conference*, Nürnberg, vol. Intelligent Motion, pp. 257-262.

[10] J. Krotsch, A. Lelkes, Th. Zoller: Low-noise, sensorless commutation of brushless DC motors, in: *Proceedings of the 38th International PCIM' 2001 Conference*, Nürnberg, vol. Intelligent Motion, pp. 151-156

[11] A. Lelkes, J. Krotsch: Single-phase external rotor synchronous motor, in: *Proceedings of the 9th European Conference on Power Electronics and Applications EPE 2001*, Graz, on CD-ROM: PP00079.pdf.

[12] A. Lelkes, L. Szabó.: Power Economic Small Synchronous Motor with Electronic Starter, *ELEKTROTECHNIKA*, vol. 94 (2001), nr. 12, pp. 422-428.