RESEARCHES IN THE FIELD OF VARIABLE RELUCTANCE ELECTRICAL MACHINES IN TECHNICAL UNIVERSITY OF CLUJ

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Abstract. The variable reluctance electrical machines had an essential role in the changes in electric machine technology during the last 30 years, when digital and power electronics and computerized design methods suddenly started to expand. As new boundaries are set up in both power electronic devices and digital control, the researchers reacted with new inventions and adaptations of electrical machines, generally along the classical lines. But also new machine (in many cases variable reluctance) structures were invented during this period. In all the cases the development of novel control strategies has been the motivating force.
The variable reluctance machines are rather simple, but require control system and in many cases also speed or position sensors. As electronics progresses still further, the opportunities for successful application of variable reluctance machines will still increase [1].
Researchers from Electrical machines Department, Technical University Cluj, Romania, were involved during the last 20 years in several developments in this field. A part of their research works and results are presented in this paper. The author should like to highlight that it was impossible to mention all the results in this field and the selection of those presented in the paper maybe it was subjective.

1. INTRODUCTION

Variable reluctance machines (both rotating and linear) have attracted renewed interest most recently, especially as variable speed motors or generators. The modern variable reluctance motors are driven from an electronically controlled power converter. Hence they do not require rotor windings or cage of any type, for starting or operating purposes. Consequently, the rotor is usually simple, having no MMF source, but permanent magnets in some special cases.
The variable reluctance machines have two types of configurations:

- i.) simple salient type
- ii.) double salient type

In both variants, the variable reluctance machines may have distributed, concentrated or homopolar windings and permanent magnets placed in the stator or in the rotor [2].
There are many types of variable reluctance machines, here only some, the most representatives considered by the author are mentioned:

- i.) Variable reluctance synchronous machines
- ii.) Switched reluctance machines
- iii.) Stepper motors
- iv.) Double salient permanent magnet machines
- v.) Claw-pole machines
- vi.) Transverse flux machines
- vii.) Variable reluctance linear, planar and spherical machines

Researches at the Electrical machines Department (Technical University of Cluj) in the field of variable reluctance machines cover a significant part of these machine variants.
In the paper due to lack of space only a part of these variable reluctance electrical machines are presented. Unfortunately the selection of the machines to be included could be subjective, for which the author asks to apologise to his colleagues.

2. EARLY RESEARCHES

The first research interests in the field of variable reluctance machines were focused on two topics: stepper motors and their controls and the development of an intelligent x-y plotter driven also by stepper motors. These early researches were mainly co-ordinated by prof. Árpád Kelemen and asoc.prof. Mircea Crivii.[3], [4].

A series of reactive stepper motors were designed and prototyped in the 70s (see Fig. 1). Also their control system (DIPAS equipment) was designed in Technical University of Cluj (at that time named Polytechnic Institute). Both the motors and their control units were also manufactured in the Practical Training Workshop of the University mainly during the practical training of the students.

Fig. 1 Reactive stepper motor manufactured in TU Cluj [5]

It should be mentioned that these researches were innovative at that time not only in Romania, but also at international level. Several patents were obtained and it was a huge interest of the industry for these researches.

The stepper motor based electrical drive systems were integrated by the researchers of the University in diverse industrial applications requiring precise positioning. One of the main achievements in this field was the DIGIPAS equipment designed for precise two axis positioning.

The most significant success of the research team was the development of an x-y plotter that could be connected to the first personal computers on the market at the beginning of the 80s. The pen of the plotter was driven by a special dual axis linear stepper motor combination. The platen of one motor was fixed on the moveable armature of the other one. Each motor assured the displacement of the pen on one of the two axis.

The researches in the field of variable reluctance machines were continued also after the political changes in 1989. Several new Ph.D. students begun their research activities, and also new opportunities to collaborate with foreign universities were opened.

The topics covered by the researches were widely extended as well.

3. MAIN RESULTS

The most researches in this field were carried out by the members of the new formed Electrical Machines Department.

3.1 The Hybrid Linear and Surface Stepper Motor

The researches in the field of linear stepper motors were continued with studying the hybrid linear stepper motor.

The basic structure of this variable reluctance permanent magnet linear motor type is given in Fig. 2.

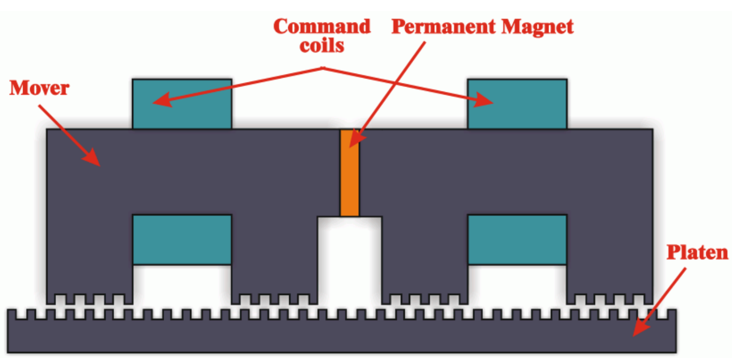
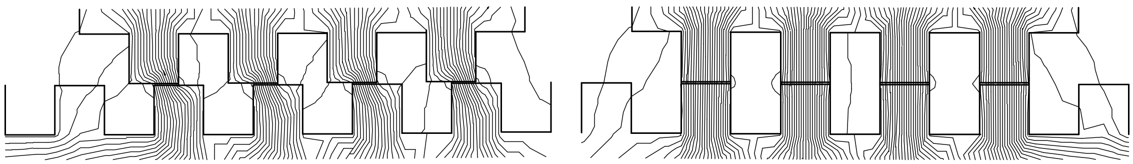


Fig. 2 The basic structure of the hybrid linear stepper motor

The motor consists of a mover suspended over the equidistant toothed platen.

The mover consists of two

electromagnets having command coils and a permanent magnet between them, which serves as an excitation bias source and also separates the electromagnets. Each electromagnet has two poles. All the poles have the same number of teeth. The toothed structure in both parts (mover and platen) has the same very fine tooth pitch [6].
In absence of the command current, the flux produced by the magnet flows through both poles of one electromagnet. When a command coil is excited the flux is concentrated into one pole of the corresponding electromagnet. The flux density in that pole becomes maximum, while the flux density in the other pole is reduced to a negligible value. By commuting this way the permanent magnet flux a tangential force is developed. It tends to align the teeth of the pole where the flux density is maximum with the platen teeth, minimizing the air-gap magnetic reluctance (see Fig. 3).



a) un-aligned b) aligned

Fig. 3 The flux lines in the hybrid linear stepper motor under the poles

The design and control of this linear motor was intensely studied.
An adequate mathematical model was set up for this machine which was further used also for studying other variable reluctance machines. The model is a coupled one, consisting of three parts, circuit, field and mechanical submodels. Its block diagram is given in Fig. 4.

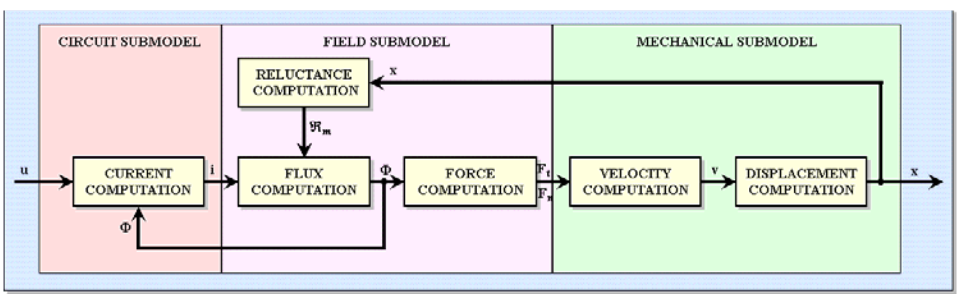


Fig. 4 The block scheme of the coupled circuit-field model

In the circuit submodel the currents of the coils are computed upon the input voltage and taking into account the changes of the magnetic fluxes thru the coils. The field submodel is the most important part of the model. Here the magnetic fluxes in the motor are computed taking into account also the air-gap's reluctances varying with the mover's position. In the mechanical submodel the speed and displacement of the motor are calculated upon the forces computed in the previous mentioned submodel.
Studying this motor variant some drawbacks was observed. In any position of the mover one of the poles is producing a significant breaking force that reduces the motor efficiency.
Beside this the magnetic flux passing thru the air-gap generates a very strong normal force.
These disadvantages were eliminated by reducing significantly the flux passing through the passive poles.
The solution was an innovative construction of the mover with independent modules, as that shown in Fig. 5.
If the command coil on the module is not energised, the flux generated by the permanent magnet passes through the core

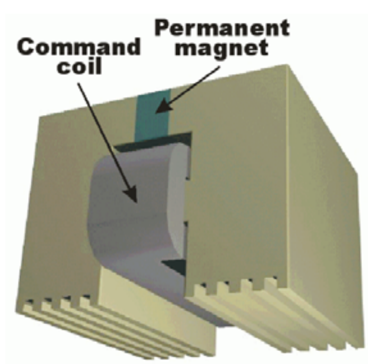
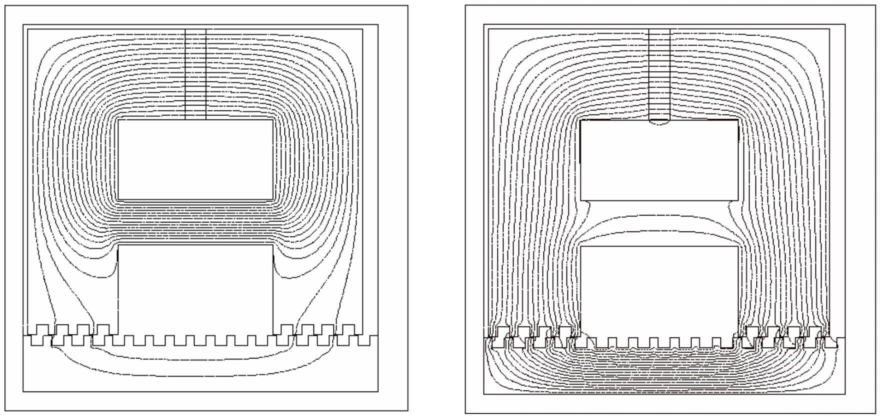


Fig. 5 The mover module

branch parallel to the magnet due to its smaller magnetic resistance (see Fig. 6a). In this case there is no significant force produced. If the coil is energised, the command flux produced by it directs the flux of the permanent magnet to pass through the air-gap (Fig. 6b) and to produce significant forces. Due to the tangential component of the force the moveable armature moves one step minimising the air-gap magnetic energy.



a) passive module b) active module (coil energised)

Fig. 6 The flux lines in a mover module of the linear machine

Using such modules several linear motors can be built up of diverse forces and step length (by varying the number of modules and the distance between them). For example in Fig. 7 a three phased variant of the modular linear motor is given.

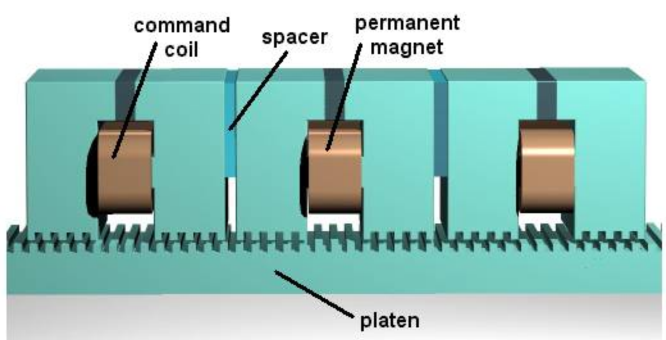
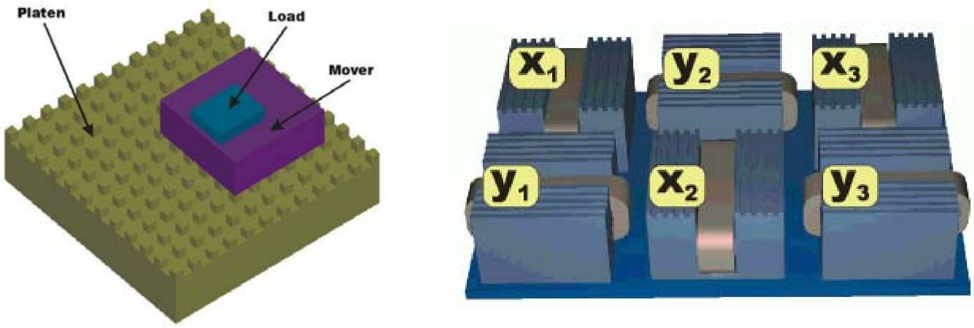


Fig. 7 The three-phase modular variable reluctance linear motor

The design, simulation and control of such modular linear machines were intensely studied by the researchers from Technical University of Cluj [7], [8], [9].

The researchers took into study also the surface (planar) motor variants of the modular machines. Surface motors assure two degrees of freedom movement in the plane. They have a lot of benefits, as simplicity, efficiency and positioning accuracy, due to the lack of rotary-to-linear conversion mechanisms, mechanically complex assemblies that require regular maintenance and develop inaccuracies over time. In a typical application of the surface motors, the flexible manufacturing system, they carry the product subassemblies from one overhead manufacturing device to another and precisely position the subassembly so that the overhead devices can perform their required actions.

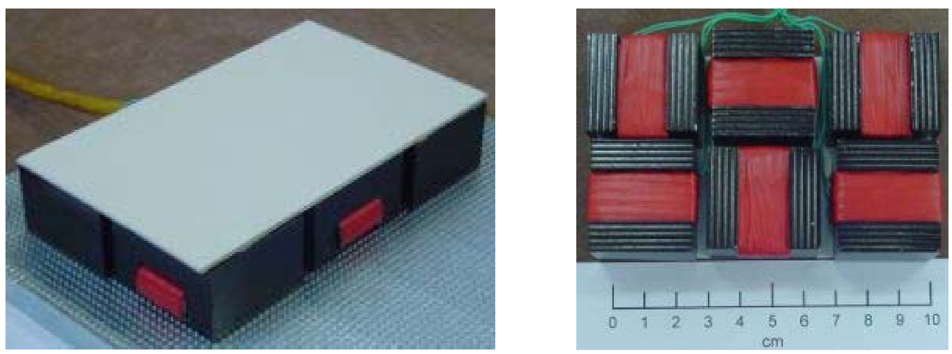
A three phase modular surface motor was studied by the researchers (see Fig. 8a) [10]. Basically its mover is composed of two modular linear motors (such as that shown in Fig. 7), each ensuring the movement in one of the two orthogonal directions (*x* and *y*), as shown in Fig. 8b.



a) the motor structure b) the disposal of the modules in the mover

Fig. 8 The variable reluctance surface motor

A laboratory model of the motor was also built up and tested in the laboratories of the Electrical Machines Department (see Fig. 9).



a) the motor b) the mover

Fig. 9 The laboratory model of the variable reluctance surface motor

3.2. The Switched Reluctance Machine

The switched reluctance machine (SRM) is one of the most frequently used variable reluctance machines. The machine's rotor and stator both have salient poles. The stator winding consists of coils placed on the stator poles, usually one coil on each pole. An excitation phase comprises two pole's coils connected in series, usually two opposite poles. Each phase is independent and the excitation represents a sequence of voltage/current pulses applied to each phase in turn. The rotor is simple, being made of conventional or axial laminations without any kind of winding, excitation, squirrel-cage, or permanent magnet.

Several switched reluctance motors were designed in the Electrical Machines Department of Technical University of Cluj by the researchers led by prof. I.A. Viorel and prof. Viorel Trifa [11], [12]. All the designed motors were analysed by means of numeric field computations.

Next only results from a single SRM variant will be presented. The cross section of the designed machine is given in Fig. 10.

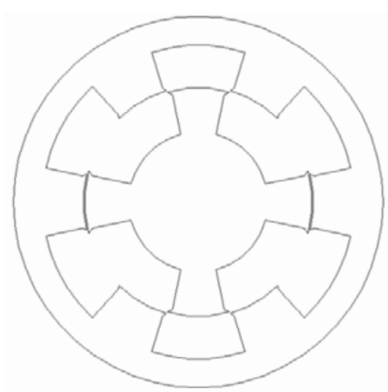
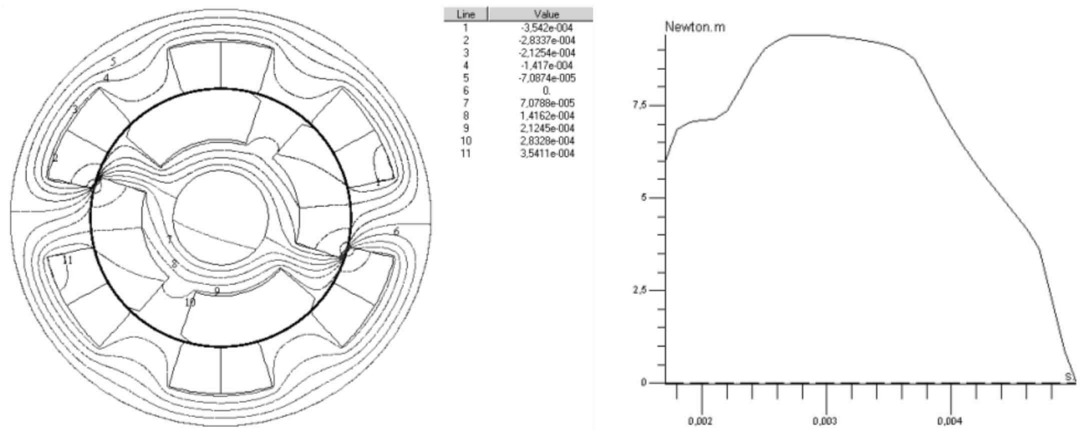


Fig. 10 The mover module

A part of the results of the numeric field computations can be seen in Fig. 11. The flux plot in the motor and the torque vs. rotor position characteristics all emphasize the correct sizing of the motor.



a) flux lines b) torque vs. rotor position

Fig. 11 Results of the switched reluctance machine's numeric field analysis

Also a laboratory model of this switched reluctance machine was built up.

The stator core was obtained from the sheets of a commercial available induction machine (see Fig. 12).

Several applications of the switched reluctance machines had been studied. Among them the switched reluctance generator, the integrated starter-generator and the SRM for hybrid electrical vehicle should be mentioned here [13].

Recently also some fault tolerant variants of the switched reluctance machines and also their power converters are widely taken into study [14], [15].

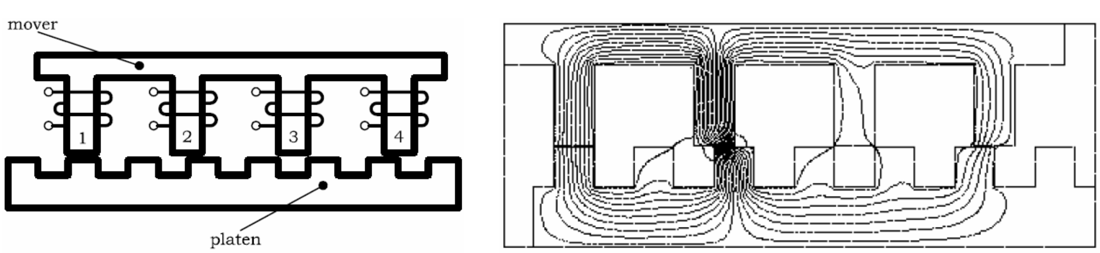
Fig. 12 The built up SRM

As the researchers involved in switched reluctance machines had also experience in linear machines their researches were extended also in the field of linear switched reluctance machines.

These machines despite their relatively high demand for reactive power are an attractive alternative for linear drive systems due to their three important advantages: constructive simplicity, fault tolerance and the possibility to construct them modularly.

The one sided linear switched reluctance machine was studied at the beginning of 90's [16].

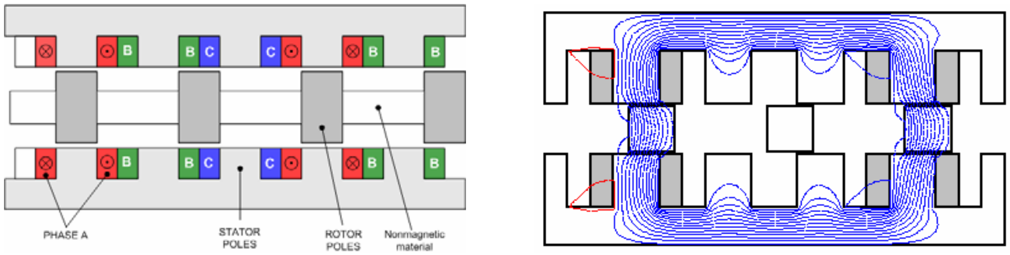
Results of the machine's numeric field analysis are given in Fig. 13.



a) the motor structure b) the flux lines obtained by FEM analysis

Fig. 13 The one sided linear switched reluctance motor

More recently the double sided linear switched reluctance motor (see Fig. 14) and its control capabilities were studied [17].



a) the cross section of the motor b) the flux lines obtained by FEM analysis

Fig. 14 The double sided linear switched reluctance motor

The main advantage of such a double sided linear motor construction is that attracting normal forces acting between the mover and the two stator armatures are compensated, hence practically useful tangential forces are acting on the mover.

3.3. The double salient permanent magnet machines

The double salient permanent magnet machine combines the advantages of the permanent magnet excitation and the simplicity of the variable reluctance structure. Theoretically, they can offer higher performance expectation over all existing machines in terms of efficiency, torque density, torque / current ratio, torque / inertia ratio. They usually assume the advantages of torque production from both the variable reluctance structure and the permanent magnet excitation, but it also inherits the current commutation problems from the reluctance machine and the difficulties in the field control from the PM excited machine.

The double salient permanent magnet machines may have the permanent magnets placed on the rotor or on the stator. They can have different numbers of phases or poles. They may also have a special winding to control the excitation field [2].

Diverse double salient permanent magnet machines were studied by the researchers from T.U. Cluj led by prof. Ioan-Adrian Viorel. The most promising variant was the radial-flux machine with the permanent magnets placed on the stator poles given in Fig. 15 [18].

A comprehensive electromagnetic design/estimation procedure for this motor was developed. The designed variants were checked out via a 2D-FEM analysis and found within acceptable error range. The main characteristics of a designed sample motor are given in Fig. 16

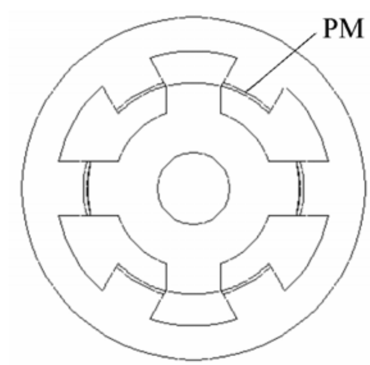
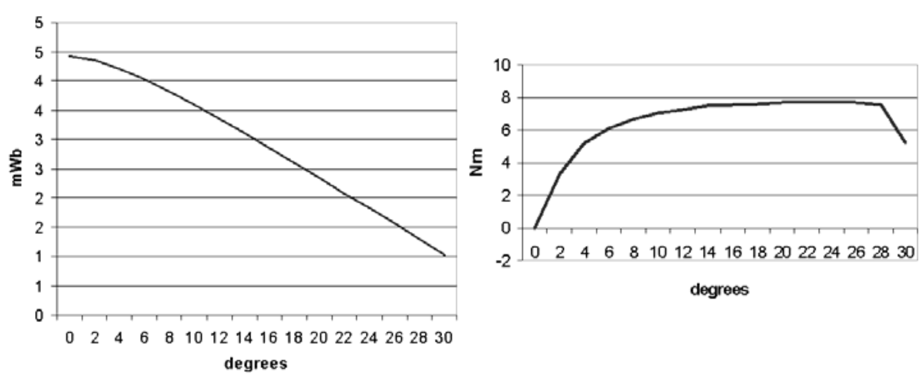


Fig. 15 The double salient permanent magnet machine



a) air-gap flux plot b) torque plot

Fig. 16 The air-gap flux and torque vs. rotor position at phase current I = 23 A

Also another variant of the double salient permanent magnet machines was designed and built up in the Department of Electrical machines of the T.U. Cluj.
The radial flux machine with permanent magnets in the rotor is in fact a hybrid switched reluctance motor, as it can be seen in Fig. [19]. Basically it operates in the same way as a stepper motor with permanent magnets in the rotor.
These machines could be a competitor of the switched reluctance motor.

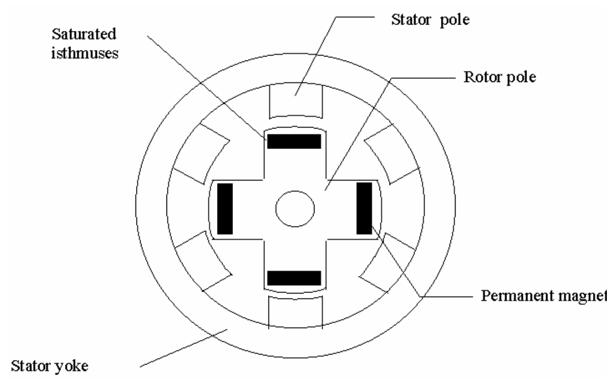


Fig. 17 The radial flux machine with permanent magnets in the rotor

3.4. Claw-pole machines
Claw-pole is a special homopolar type of stator or rotor topology used in different electrical machines. These machines have a very simple construction, only a winding being used for all the poles. The current that flows through this winding is a dc current. Therefore, the winding can be substituted by a permanent magnet [2].
Based on this idea two claw-pole machines were developed in technical University of Cluj.
The first one was built up under prof. Ioan-Adrian Viorel's supervision in the beginnings of the 90's. It was a low power dc brushless motor with claw-pole type armature. It had an unsymmetrical claw-pole armature and a ring-type sintered rotor made of ferrite. Its longitudinal cross section is given in Fig. 18 (1 stator yoke, 2 stator homopolar coil, 3 claw-poles, 4 permanent magnet rotor ring, supply and control device room) [20].

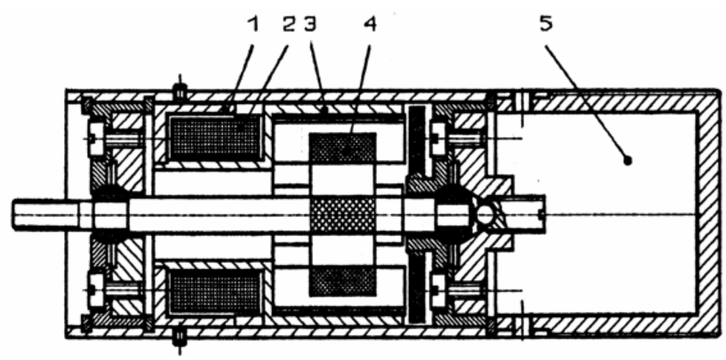
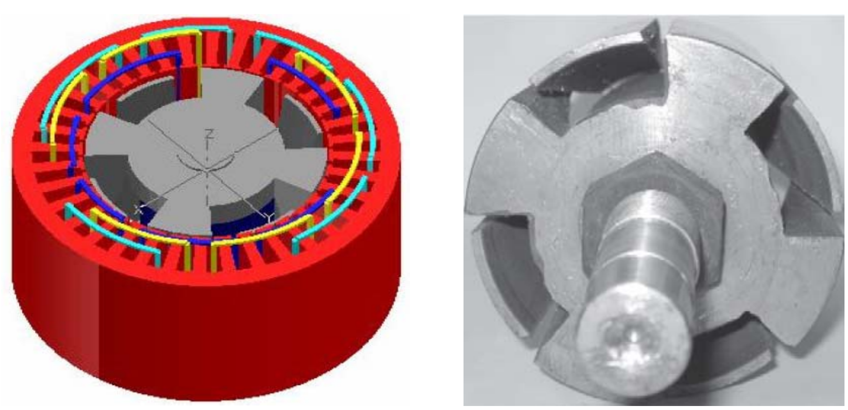


Fig. 18 Cross-section of the claw-pole dc brushless motor

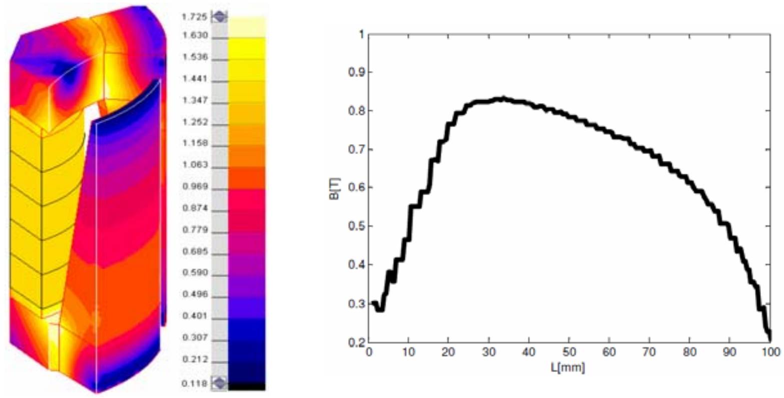
More recently a research group led by prof Biró Károly Ágoston developed a claw-pole permanent magnet synchronous generator for small direct-driven wind power applications. The construction of the generator is given in Fig. 19.



a) the 3D structure b) the rotor armature

Fig. 19 The claw-pole synchronous generator

The 3D FEM based field computations proved the correct design of the generator. A part of its main results are given in Fig. 20. Also the harmonic content of the generated voltage under different working conditions were taken into study [21].



a) Magnetic flux density map b) Flux density along the rotor pole

Fig. 20 Results of the 3D FEM based field computations

3.5. Variable Reluctance Synchronous Machines

Variable reluctance synchronous machines are very attractive for both line-start and variable speed electric drives. Their torque density, power factor and efficiency are competitive with other machine types only if the saliency ratio ($k = M_d/M_q$, the ratio of the *d*-axis and *q*-axis magnetising inductances) is high [2]. The machine's rotor is the most important key factor in obtaining the high saliency, and therefore a lot of efforts were put in improving the rotor topology. As a result several rotor constructions emerged world wide and numerous ones were also studied under prof. I.A. Viorel at the Technical University of Cluj.

The first variable reluctance synchronous machine taken into study had a very simple construction. Its rotor was built up using conventional lamination and had concentrated anisotropy. The cross section of one half motor is given in Fig. 21. The main target of the studies was to find the best non-magnetic material thickness of the magnetic barrier of the rotor [22]. The analysis was performed via numeric field computations. The *d*-axis and *q*-axis flux plots for the best machine variant are given in Fig. 22.

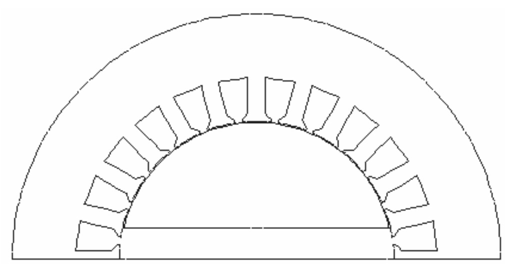
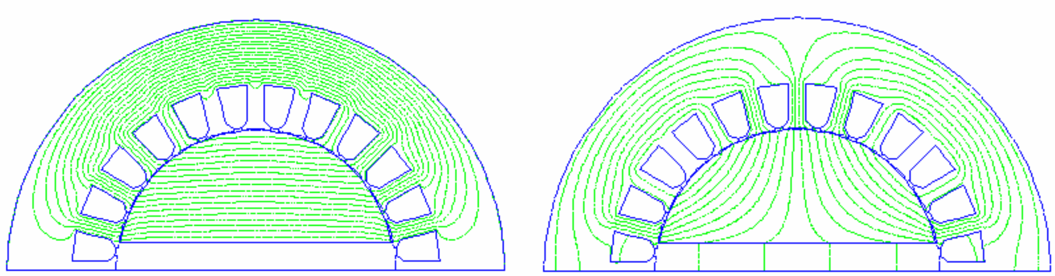


Fig. 21 The rotor of the variable reluctance synchronous machine



a) *d*-axis flux plot b) *q*-axis flux plot

Fig. 22 The flux plots of the variable reluctance synchronous machine

The best saliency ratio (13.2) and unfortunately the worst efficiency (0.771) were obtained for a 12 mm thick flux barrier.

Later another variable reluctance synchronous machine was taken in study by the same research group. This was designed and built up using the case and the stator sheets of a commercial available induction machine.

The rotor core was made of crude induction machine magnetic sheets and had a concentrated nonmagnetic material on the rotor *d*-axis. There were no core bridges between the rotor segments. The cross section of the machine can be seen in Fig. 23.

It was also studied by means of finite elements method based numeric field computations. The *d*-axis and *q*-axis flux plots obtained by simulation are given in Fig. 24 [23].

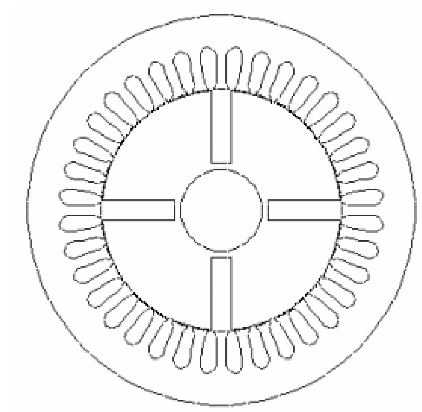
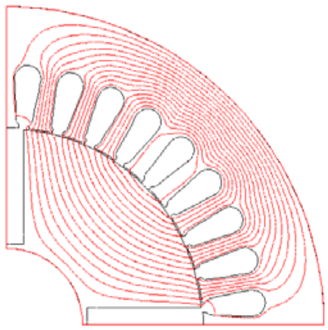
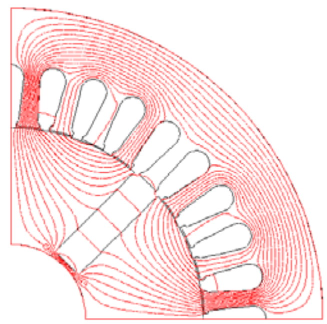


Fig. 23 Cross section of the machine



a) *d*-axis flux plot



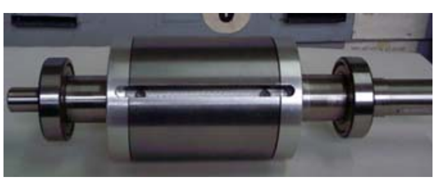
b) *q*-axis flux plot

Fig. 24 The flux plots on the two quadrature axis of the machine

The obtained saliency ratio of 3.77 was quite good for such a simple structure.

The prototype of the designed machine (given in Fig. 25) was built up in 2003 and was equipped with an incremental position transducer to ensure the actual position signal necessary for the control system.

The machine was built together with a general-purpose power converter (of SIMOVERT MASTERDRIVES type) to form a compact variable speed drive unit (see Fig. 25b) [24].



a) The rotor of the machine

b) Built in the compact variable speed drive system

Fig. 25 The variable reluctance synchronous machine

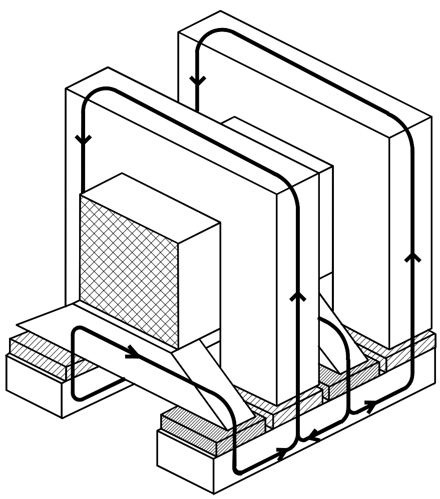
3.6. The Transverse Flux Machines

The transverse flux machines (TFM) are relatively new topologies of electrical machines. Several variants have been designed since the 80's, but no mass production has been reported yet. It is expected that they will occupy an important segment of the low-speed, high-torque, variable-speed drive market.

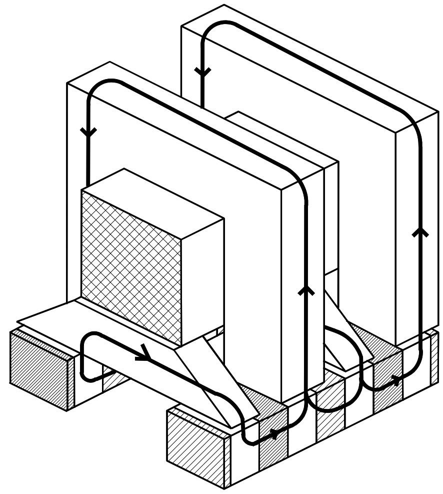
The basic principle is the same for all variants. A stator phase winding having a circular form produces a homopolar MMF distribution in the air-gap. This MMF is modulated by a pattern of stator poles or teeth to interact with a heteropolar pattern of permanent magnets placed on the rotor. The number of stator poles is usually half of the number of rotor permanent magnets, but much greater than for the conventional machines with heteroplar topology [2].

May be this is the one where the most significant theoretical results were obtained by the researchers working under the supervision of prof. Ioan-Adrian Viorel. Dozens of papers, several research grants dealt with this topic in the past 10 years. A very close international collaboration was set up on this topic with the Electrical Machines Department, RWTH Aachen (Germany) led at that time by prof. Gerhard Henneberger. And last but not least it should be mentioned that prof. Ioan-Adrian Viorel is the first author of the single book ever published in this field [25].

The researches were focused on the single sided transverse flux machines. They can be with surface mounted permanent magnets or with magnets inserted in the rotor. Both variants have a special return flux I-shaped on the stator. The two basic structures of such machines are given in Fig. 26.



a) with surface mounted permanent magnets



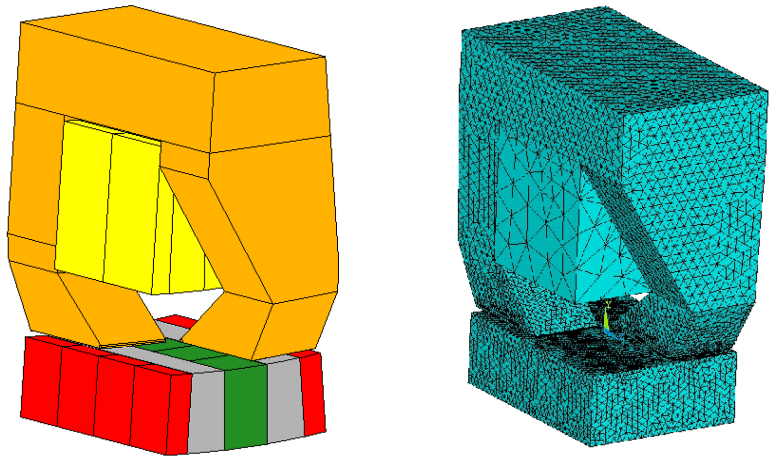
b) permanent magnets inserted in the rotor with flux concentrating poles

Fig. 26 The single-sided TFM machine structures

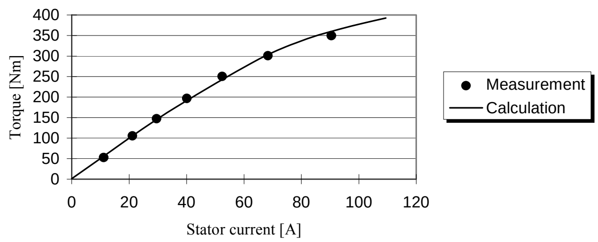
For all the variants detailed design algorithms were worked out. Having these as starting point almost all the TFM variants can be designed.

The designed motor structures were checked by means of FEM based numeric field computations. Only 3D-FEM analysis could be used due to the complexity of the flux paths topology and the true 3D flux configuration of the machines in study.

From the numerous results here only those for a single TFM variant are given. The motor structure in study has one stator core, a spatially shifted U-shaped core and a corresponding rotor part, consisting of two permanent magnets and two rotor flux concentrating poles (as seen in Fig. 27a) [26]. The 3D mesh generated, shown in Fig. 27b, is impressive: it has over 200,000 tetrahedral elements. Based on the simulated results the torque versus armature current characteristics (given in Fig. 27c) were plotted and compared with those obtained by measurements.



a) the TFM structure in study b) the 3D FEM mesh



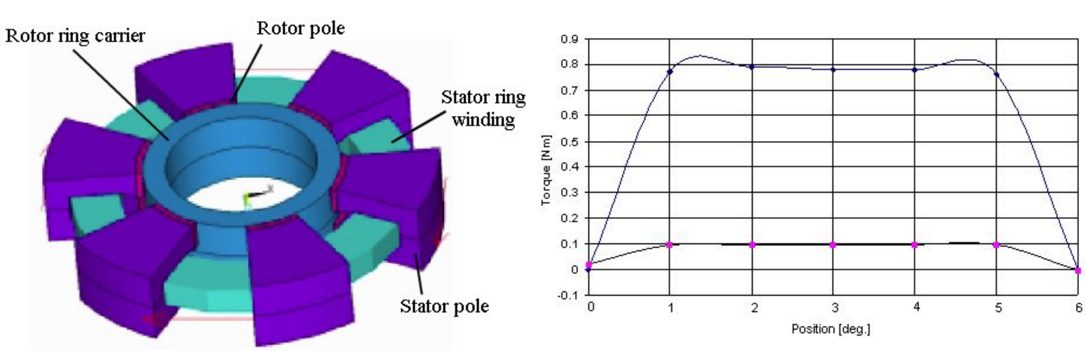
c) torque vs. armature current characteristics at low speed

Fig. 27 The results of simulation for the TFM in study

At the department of Electrical machines of Technical University of Cluj also the reluctance variant of the transverse flux machine was taken into study.

The transverse flux reluctance machine is a TFM variant with passive rotor. It has a ring winding with salient poles on the stator and only salient poles on the rotor. It behaves like a switched reluctance machine, the main difference consisting on the homopolar stator winding. Each phase of it is an independent module, as shown in Fig. 28a. The TFRM must have three or more than three phases in order to avoid the start-up difficulties and to obtain continuous rotation [27].

The static characteristics obtained via FEM computations are given in Fig. 28b.



a) the structure of the machine b) the static torque versus rotor position characteristics

Fig. 28 The transverse flux reluctance machine

An other research team led by prof. Vasile Iancu was working in the field of linear transverse flux reluctance machines.

These were developed on the basis of the modular linear motors, such as shown in Fig. 7. The three phased linear transverse flux reluctance machine's structure is given in Fig. 29.

Its working principle is identical to the modular linear motors mentioned in section 3.1, but the sense of the displacement differs (it is perpendicular to the direction of the magnetic flux).

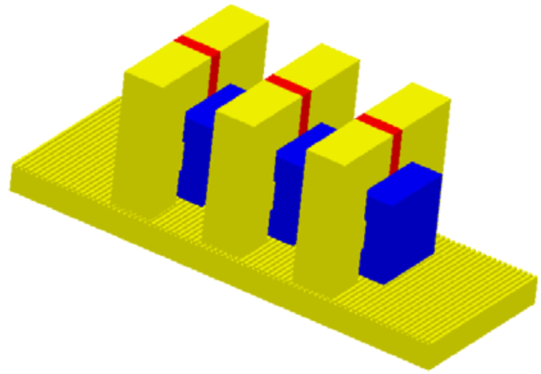
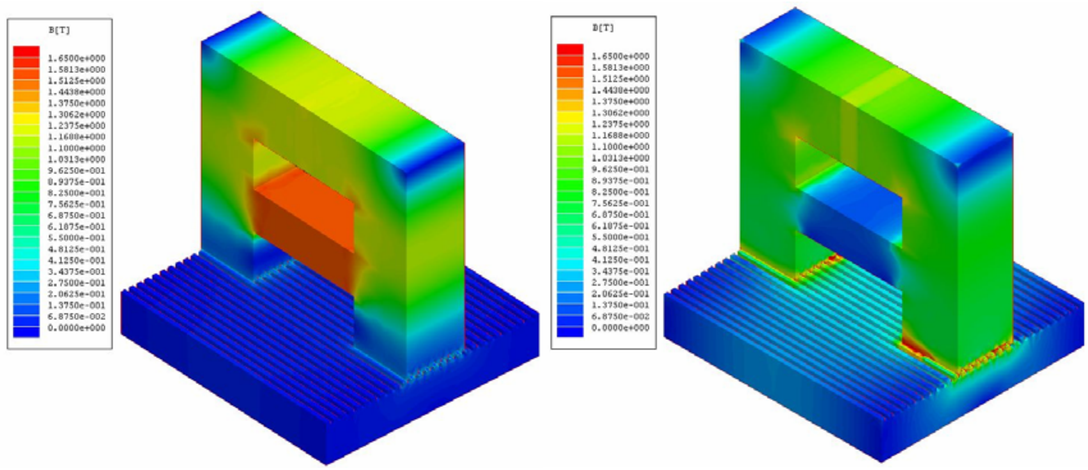


Fig. 29 The linear transverse flux machine

This structure could be analysed also only by means of 3D FEM computations. Some of its results are given in Fig. 30 [28].



a) passive module b) active module

Fig. 30 The results of the field computations of a linear transverse flux machine

Also the double sided version of this machine was investigated [29].

4. WORKSHOP ORGANISED

On 17th September 2002 the Electrical Machine Department of Technical University of Cluj organised a successful scientific meeting entitled *Workshop on Variable Reluctance Electrical Machines*. The papers presented in this workshop covered the theory, design, control, respectively modelling and simulation of all the types of variable reluctance machines. The papers were published in a printed proceeding and they are also available on-line at URL: http://users.utcluj.ro/~szabol/Organized_Conferences/Variable%20Reluctance%20Machines%202002/Workshop_on_VR_machines_2002.htm.

5. CONCLUSIONS

Members of different research groups working at the Technical University of Cluj have a significant experience in variable reluctance electrical machines. They practice cover conception, design, simulation of the variable reluctance machines together with their control systems and power converters.

The experience gathered in the last 20 years and the motivation and knowledge of the younger researchers who joined these research groups is the key of future works in this rapidly expanding field of electrical engineering.

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