brite euram project BREU-CT92-0572

"Economical Electrical Drive for Highly Dynamic Applications
in the Textile Industry,
the Valve Actuator Industry
and the Vacuum Pump Industry"

Synthesis report
for publication

Project coordinator : **inverto**
Partners : **groschopp**
lne-rug
emi-tub
alcatel
limitorque

Starting date : 1 /5/92
Duration : 42 months
Date of issue of the report : 03/03/96

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	contractnumber:	**BRE2-CT92-0572**
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Synthesis Report for publication

1. Table of contents

‘ 2.’ Summary

2.1. Five keywords on the content of the project

- Switched reluctance motor
- Power converter for switched reluctance motor
- Low cost high efficient dynamic electric motor
- . electric motor

2.2. Abstract of the results and benefits of the project

Within this project :

- a switched Reluctance Motor is designed,
- a power converter for SRM is designed,
- a control strategy is designed and implemented,
- prototypes are built to verify the design and to evaluate practical applications,
- design rules are made in order to easy design other power ranges or other applications,
- the design rules are checked towards the prototypes.

The following end user applications were evaluated in order to evaluate the performance (efficiency and dynamics) of the SRM:

O textile drive application : high dynamics
O valve actuator application : very high stalling torque, high dynamics, torque control
O vacuum pump application, very high speed with low rotor losses (rotor efficiency)
O general purpose drive : high torque, torque control, very dynamic, in order to be used for positioning control drives.

The prototypes realized, are within the 750W -3kWpk power range and operate in the speed range from 1500-20.000 RPM.

Although not evident, the design of the magnetic part of the motor has converged with the practical realisation and measurements. Several optimisations in winding distribution were found. Also the power electronic development has met no particular difficulties.
Concerning the control strategy and control board realisation, a compromise had to be found between soft-and hardware flexibility to enable control technique optimisations (software for overlap of phases,...) and hardware complexity.
Different approaches (microprocessor based, DSP based and programmable logic FPGA based) were evaluated and two different strategies were implemented.

When comparing the SRM to classical motors, following advantages / disadvantages can be found :

- advantages :
  - principally, and when produced is the SRM a low cost motor (cheaper than induction motor)
  - excellent dynamic behaviour is confirmed
  - very high starting torque
  - low rotor losses, good efficiency
  - low rotor inertion
  - basic principle of SRM converter is simple

- disadvantages :
  - up to now no sensorless operation is demonstrated
  - noise is inherent to the motor principle and is higher than an AC servo drive
  - a 'new' **motor technology** which means that high investments are needed (cfr. Grosschop)
  - control technology for high dynamic application is not cheap for the moment because no specific IC's exist.

Today, it's up to the application (torque, volume, production volume) to evaluate *if* the necessary investments in production tools and electronic startup can be profitable.

3. The consortium

3.1 Names and addresses of the partner organisations

3.1.1 Partner 1: INVERTO (power electronics manufacturer)

INVERTO N.V.
Mr. J. De Temmerman, Director
Begoniastraat 15
B-981 O Eke-Nazareth, Belgium
Tel +32.9.385.84.55
Fax +32.9.385.84.72

3.1.2 Partner 2: GROSCHOPP (motor manufacturer)

GROSCHOPP & CO Gmbh
Mr. J. Groschopp, Manager
Greefsallee 49
D-4060 Viersen, Germany
Tel +49.21 62.374.102
Fax +49.21 62.37*.1 09

3.1.3 Partner 3: RUG-ELMAPE (formerly named LNE -RUG) (university)

Laboratory for Electrical Machines and Power E ectronics
University of Gent
Prof. Dr. Ir. J. Melkebeek
Sint-Pietersnieuwstraat 41
B-9000 Gent, Belgium
Tel +32.9.264.34.18
Fax +32.9.264.35.82

3.1.4 Partner 4: EM I-TUB (university)

Elektrische Maschinen & Antriebe - Neue Technologieen
T.U. Berlin
Prof. R. Hanitsch
Einsteinufer 13-15
D-'1OOO Berlin 10, Germany
Tel +49.30.314.22111
Fax +49.30.314.21 133

3.1.5 Partner 5: ALCATEL (vacuum pump manufacturer)

ALCATEL Division Vide
Mr. E. Taberlet, Research & Development
98, Avenue de Brogny - BP 69
F-74009 Annecy Cedex, France
Tel +33.50.65.77.94
Fax +33.50.65.75.76

3.1.6 Partner 6: LIMITORQUE (valve actuator manufacturer)

LIMITORQUE INT.
Mr. P. Bond, Sales and Service Manager
Bone Lane, Newbury, Berkshire
RE 14 5EH Newbury, Great-Brittain
Tel +44.1635.42297
Fax +44.1 635.36034

3.2 Consortium description

3.2.1 Partner 1: INVERTO

INVERTO is a young and innovative small company (special award), specialised in problems on power electronics (design and manufacturing of power electronic converters).
INVERTO is the general coordinator of the project. Moreover, INVERTO **supports the development of** the power electronic converter. Finally, INVERTO exploits the results of the project through the production of the power converter and its basic control, and has applications of the SRM as textile machinery drive and as general purpose drive.

3.2.2 Partner 2: GROSCHOPP

GROSCHOPP is a medium size company and manufacturer of electric motors.
GROSCHOPP has wide engineering experience to allow for flexible, customer oriented design.
GROSCHOPP manufactures the motor prototypes for the project, and exploits the results of the project through the production of these motors. A textile machine application is demonstrated in the project.

3.2.3 Partner 3: RUG-ELMAPE (formerly named LNE-RUG)

The Laboratory for Electrical Machines and Power Electronics (formerly named Laboratory for Industrial Electricity) of the University of Gent has **a** "profound experience in the design of electrical drives, as well as in the support of their production and in the testing of these drives.
RUG-ELMAPE develops the necessary design rules for the motors and the power converters, and participates in the design of the hard- and software for SRM control.
RUG-ELMAPE benefits from the project through the establishment of a profound knowledge on this novel kind of drives.

3.2.4 Partner 4: EMI-TUB

The Electric Machine Institute of the Department of Electrical Engineering of the Technische Universitat Berlin has established a solid reputation in the field of the control of electrical machines, especially small and highly dynamically machines.
EM I-TUB concentrates on the general 'control of the SRM drive. EM I-TUB benefits from the project through the establishment of the fundamental design rules concerning the global control of a SRM drive.

3.2.5 Partner 5: ALCATEL

ALCATEL is a medium size company with a considerable impact on the market of vacuum pump drives.
As an end-user, ALCATEL's role is in the characterisation and support of a global control system for SRM drives. ALCATEL benefits from the, project through the envisaged increased impact on the vacuum pump market.

3.2,6 Partner 6: LIMITORQUE

LIMITORQUE is a small company, part of a multinational company, controlling a substantial share of the valve-actuator market world-wide.
As an end-user, LIMITORQUE's role is in the specification and development of a global control system for SRM drives. LIMITORQUE valorises the results of the project as a producer of valve actuators.

4. Description of the achievements

The research aimed at in the framework of this project is the developm ent of a methodology for the determination of the design parameters optimizing the SRM drives with respect to energetic and volumetric efficiency (compactness) as well as the controllability of torque and speed, for a wide range of drive problems. Within this wide range, this project optimises the SRM drive with respect to the following applications:

- valve actuator industry (partner Limitorque)
- textile industry (partner Groschopp)
- vacuum pump industry (partner Alcatel)
- general purpose highly dynamic drive (partner Inverto)

4.1 Achievements of the different work packages

Most achievements result from extensive calculations and discussions. A summary is provided in the following paragraphs.

4.1.1 Motors

Detailed technics! specifications have been set up (deliverable? of WPI of this project). The following table summarises the specifications and the results cf the prototypes from the first dimensioning of the motors (deliverable of WPII):

application	WP I requested specifications NB (rpm)	PB (W)	TS (Nm)	WP II obtained specs after WPII (dimension) NB (rpm)	PB (W)	TS (Nm)
1a. ALCATEL-roots	3000	2100		2200	2000	12.4
1 b. ALCATEL-molec.	42000	440	0.1	discontinued		
2. L] MITORQUE-text.	156-3250	1000	11.5	2100	3000	19.3
3. GROSCHOPP-text.	15000	200-600	0.6	7700	2700	4.2
4. INVERTO-text.	1500	1200	22	1400	1200	11.4

Note that initially, two different approaches were presented for the vacuum pump industry. The molecular pump drive (lb)' was discontinued, due to priority reasons and practical technical difficulties.

The final specifications have been updated (deliverable of WPIII), and final prototypes have been built and tested (deliverables of WPIV and WPVI). The results are summarised in the following table:

application	WP III requested specs after modifications NB (rpm)	PB (W)	TS (Nm)	WP Iv-vi obtained specs after prototyping NB (rpm)	PB (W)	TS (Nm)
1a. ALCATEL-roots	3000	2000	8.0	(see remark)		
2. LIMITORQUE-text.	2100	3000	19.3	first prototype satisfies end-user		
3. GROSCHOPP-text.	400	25	1.2	400	20.5	0.74
4. INVERTO-text.	1400	1200	11.4	first prototype satisfies end-user		

<u>Conclusion:</u>
- first prototypes 2 and 4 deliver a performance which satisfies the end-user. Inverto had asked a higher torque which is not realised in the Inverto prototype. But the feasibility of this higher torque has been shown in the similar Limitorque prototype.
 second prototype 1 a was designed to be mounted on the ALCATEL roots pump. Unfortunately, the mounting of the rotor was subject to technical problems, causing the rotor to touch the stator for speeds of 500 rpm and up. More research is necessary to overcome these mounting problems, who have destroyed up to twice the prototypes.
- second prototype 3 has completely new specifications, due tc a very practical and specific applications found by Groschopp. .

4.1.2 Power converter and control hard- and software

As a deliverable for WPII, the first dimensioning of the power converters has been executed. The proposed converter has the following characteristics:

- IGBT technology 220/380 V drive, prototypes built:
  - ⇒ 24 V_{DC},200W
  - ⇒ 220V_{AC}, 1.1 kW
  - ⇒ 220V_{AC}, 2.2kW
  - ⇒ 220V_{AC}, 3.0kW

  switching frequencies > 25kHz are possible, motor speeds limited by commutator logic (tested till 12.000 RPM)
- microcontroller control, including program and data memory and permanent parameter memory
- conditioning of analogue measurements from power stage, for sampling by the microcontroller
- position encoder interfacing
- keyboard and LCD display on front panel, providing access to all process parameters
- electrical user interface (galvanically isolated):
  * NPN inputs 24V/10mA
  * NPN open collector outputs
  * O... 10V and 0(4)...20mA inputs
  * **0...1 Ov** outputs
  * RS232, preferable RS422 or RS485
- software for control and user interface:
  * commutator, including phase selection and switching instant control
  * current (torque) control loop
  * speed control loop
  * general protection
  * industry standard 1/0, including speed-frequency-torque input, run-stop input, rotation sense input, run and error relay outputs ,
  * user I/O, to be configured depending on the applications and needs

* serial channels, to allow the drive to be configured by an other serial device

The design has been carried out as a deliverable of WPIII, and includes all of the component ratings and the detailed schematics of both power converter and control card.
The construction has been done as a deliverable **of** WPIV. Most of the above specifications have been fulfilled, except for:

- 0(4)...20mA input not implemented
- galvanic isolation for analogue 10 not implemented
- some industry standard 10 not implemented, but may easily 'be inserted into the existing control software structure
- serial channel 10 software not implemented

Since **a lot** of **fast logical tasks** have to be performed by the control board, a discussion was made about the implementation :

a) on a programmable hardware lever **(FPGA)**
b) on a programmable microprocessor lever (microcontroller or DSP)

Tests have been executed using the constructed drives (deliverable of WPVI) showing the excellent dynamic behaviour of the SRM. For the machine prototype nr. **2,** e.g., having a inertia of 0.00109 kg m^2, speed is reversed from full speed 2140RPM clockwise to full speed counter clockwise and at rated current in about 30 ms, showing an average torque during reversal of 14.9 Nm. The speed changes almost linearly in time.

4.1.3 **Design tools and resulting design rules for** SRM

As deliverables of **WPV** and WPVI, the design rules of the electromagnetic design of SRM and CAD software for the design of SRM are established.

The static performance of the SRM depends on two criteria:

- average torque as a function of the phase current
- instantaneous torque as a function of the rotor position

Numerical field computations are necessary for accurate evaluation of the above criteria. For these computations, finite element software has been adapted specifically for static field and torque computations of SRM. These calculations yield the following design rules:

- a practical rule for the critical overlap angle
- optimal opening angles for stator and rotor teeth
- optimal yoke factor

The dynamical performance of the SRM depends on two criteria:

- base speed, above which constant power is developed
- form of the torque-speed characteristic

A simplified analytical machine model is proposed, featuring a minimal number of parameters, allowing for rapid prototyping. These calculations yield the following design rules:

- below base **speed** torque is roughly equal to the static torque. This is the constant torque region.
- above base speed, up to 2...4 times base speed, the torque drops inversely proportional to the speed. This is the constant power region.
- the form of the torque-speed characteristic does not depend on the 'number of windings.
- the simplified machine model yields the torque-speed characteristic analytically, from only two parameters, which can be measured directly.
- the base speed of the machine is chosen by specifying the number of windings.

4.1.4 Design 'rules for drive and global control circuit

As a deliverable of WPV, the design rules for the drive and the global control circuit have been established and characterised.
Many calculations and simulations have been executed to derive the optimal control strategy for SRM.
The main conclusions are:

- cascaded controllers are sufficient to control the SRM drives.
- the inductance of the motor phase windings and the motor phase back- emf influence the phase current build-up. The switch-on and switch-off angles therefore have to be changed with motor speed to optimise the shaft torque over a wide speed range.
- dynamics of speed measurement are important for the dynamics of the speed control loop. This depends on position encoder resolution, sampling speed, measurement accuracy and measurement range.
- optimal control may require many calculations. Calculation time should be limited for dynamically purposes. Good dynamically behav our has been achieved' with prototype drives, using only a fast processor to perform most of the control tasks.

In order to reduce the required calculation time, the use of a faster processor, look-up tables, programmable logic and other dedicated hardware is advised.

4.2 Conclusion of achievements

One of the main objectives of the project was to develop modelling and design tools, and to build up experience "to be able to develop and design SRM drives for different applications".
This objective is achieved with good result, and one can say that the many difficulties and problems, encountered during this project have helped to optimise and fine-tune that design experience:

- magnetic design tools are available
- control algorithm experience is available
- power electronic knowledge is available
- practical motor construction has been realised
- performance is demonstrated

The other objectives of demonstration to the end user application is realised with success in three of the five applications. One demonstration has been abandoned, and one is still under progress due to practical mechanical problems.

When comparing the SRM to classical motors, following advantages I disadvantages can be found :

- advantages :
  - principally; and when produced is the SRM a low cost motor (cheaper than induction motor)
  - excellent dynamic behaviour is confirmed
  - very high starting torque
  - low rotor losses, good efficiency
  - low rotor inertion
  - basic principle of SRM converter is simple
- disadvantages :
  - up to now no sensorless operation is demonstrated
  - noise is inherent to the motor principle and is higher than an AC servo drive
  - a 'new' motor technology which means that high investments are needed (cfr. Grosschop)
  - control technology for high dynamic application is not cheap for the moment because no specific IC's exist.

Today, it's up to the application (torque, volume, production volume) to evaluate if the necessary Investments in production tools and electronic startup can be profit: ble.

5. Exploitation plan "'

5.1 partner 1: INVERTO

Inverto has exploitation plans on the following fields :

- Textile machinery drives: interest is shown by customers for highly dynamic SRM drives. The drives of Inverto can be used for demonstration. Mainly weaving machine manufacturers will be contacted.
- General Purpose drive : the startup of a motor AND power converter production line for the very conservative market of standard drives seems to be very risky. It seems to be vety difficult to beat "standard motors" with "non-standard motors", not even when better.
  For that reason exploitation will be sought towards more specific applications:
  1) automotive applications and electric vehicles
  2) low cost consumer applications, the high volume market makes no problem about non-standard tooling & production facilities (vacuum cleaners, drilling machines,...)
  3) special applications: avionics, robotics.
- with the following timing :
  96 -> textile machinery prospection
  96-97 -> automotive, avionics prospection
  97 -> consumer electronics prospection

5.2 partner 2: Groschopp

Groschopp has the knowledge constructing SRM drives, and will offer this technology in it's product range of "special motors":

- high production volume textile drive, high dynamic
- very high speed vacuum cleaner motor (high production volume)
- maybe low cost drilling machine motor (very high volume)

5.3 partner 3: RUG-ELMAPE

Description of results

- development of extensive SRM design tools:
  - optimisation of torque/angle response
  - optimal distribution of premagnetising and phase windings
  * statical characteristics and optimal control strategy
  - design rules
  * finite element software to verify designs and to estimate iron loss
- design and realisation of hardware for digital SRM control
- design and realisation of control software

As a scientific/research partner, the exploitation of the project results is limited.

The prime exploitation strategy is to act as a designer or as a consultant for designers. Transfer of knowledge is possible, but may only prove satisfactorily towards specialised clients, such as motor manufacturers (for the SRM design tools) and drive manufacturers (for control hard- and software).

5.4 partner 4: EMI-TUB

Experience, built-up in this project will be exploited as a consultant for the design of control algorithms for third parties.

5.5 partner 5: ALCATEL

No exploitation plans are confirmed until mechanical problems and tests are completed on the roots pump.

5.6 partner 6: LIMITORQUE

The duration tests of the SRM drive on the actuators are still uncer evaluation. It seems that the objectives of this application are achieved, and - if cost can be optimised - this solution will be offered to Limitorque valve actuators customers.

6. Collaboration sought

6.1 partner 1 : INVERTO

Collaboration sought towards :

- manufacturers of. electrical vehicles
- manufacturers of high volume, high speed or high torque tools & equipment
- manufacturers of avionic or aerospace servo drive systems

6.2 partner 2: Groschopp

No specific collaboration sought.

6.3 partner 3: RUG-ELMAPE

As stated in the exploitation plan, RUG-ELMAPE prime collaboration goal is to act as a designer or as a consultant for designers. The developped SRM technology is applicable and adaptable for a wide variety of applications. **To** establish contact with end-users, further collaboration with a drive manufacturer is wanted.

6.4 partner 4: EMI-TUB

No specific collaboration sought.

6.5 partner 5: ALCATEL

No specific collaboration sought.

6.6 partner 6: LIMITORQUE

No specific collaboration sought.

7. References

7.1. Publications resulting from the project

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