

# Experimental Comparison between Induction and Synchronous Reluctance Motor-Drives

M. Villani, M. Tursini, M. Popescu, G. Fabri, A. Credo, L. Di Leonardo.

**Abstract** -- Induction motor and synchronous reluctance motor are promising solutions in different variable speed applications requiring high performance at low cost. Indeed these motor technologies are not based on rare earth Permanent Magnets saving the associated costs and supplying concerns.

This paper presents a comparative analysis of these two motor solutions supported by experimental results: the motors are fed by a variable speed drive executing suitable control algorithms to maximize torque and motor efficiency. The comparative analysis considers the same stator for the two motor technologies and different rotors. Simulation analyses are performed by mean of a Finite Element Tool and supported by experimental tests.

**Index Terms** -- Induction Motor, Synchronous Reluctance Motor, Copper Rotor, Barrier Rotor, High Efficiency, Optimal Motor Control, Rare Earth Free, Maximum Efficiency Per Torque.

## I. INTRODUCTION

The adoption of Rare Earth (RE) in electric motors could represent a bottleneck for mass production due to issues on the materials availability, costs, market dynamics and environmental impact [1].

After many years where the development of electric motors was focused on Permanent Magnet (PM) machines the Induction Motors (IM) and the Synchronous Reluctance Motors (SynRMs) are being investigated with a renovated interest because they both represent motor technologies without rare earth (RE) [2].

Both IM and SynRM are promising solutions for mass production in different fields as industry and automotive applications, they exhibit good performance associated with low cost materials and eliminate the supply risks associated with high performance RE PMs [3].

Nowadays IM is referred as a mature technology, but the adoption of advanced design strategies coupled with innovative manufacturing techniques (flat wires, rotor copper die-cast or automatized processes for fabricated rotors) and cooling methods, seems to open new possibilities for design improvements. Usually adopted in industry applications, IM is becoming interesting also for traction in electric vehicles [3].

SynRM is a more recent motor solution with interesting

advantages such as the low rotor inertia, the high power-to-weight ratio, the good acceleration performance, the flux weakening operation, the low material costs and the easy of manufacturing [1]. SynRM rotor performance is heavily affected by the number and the shape of the rotor barriers and many variables have to be considered at design stage to achieve performance in the specific application.

From the efficiency point of view, the adoption of the copper rotor cage in IM reduces the cage losses with respect to the aluminum one, while the SynRM is affected by the only iron losses at rotor level.

The main drawbacks of the SynRMs with respect to the IMs are the lower torque density, the torque ripple and the power factor, nevertheless suitable design techniques [4] and specific control strategies [5] can overcome these points.

The stator of IM and SynRM can be, in the matter of fact, the same and follows similar design guidelines.

This paper presents a study the authors carried out on the performance of the IM and SynRM technologies fed by a Variable Speed Drive. The purpose of the study is to refine the knowledge on the behavior of motor solutions and related controls to extract design guidelines for the design of variable speed drive for automotive applications based on such motor technologies.

In particular two different control algorithms have been compared by mean of experimental tests: the Maximum Torque Per Ampere (MTPA) and the Maximum Efficiency Per Torque (MEPT) [6].

To facilitate the study a 3kW TEFC reference target motor has been considered and IM and SynRM solutions have been evaluated and compared at rotor level considering the same rotor volume (and the same stator). Two different rotors have been tested: one featuring a die-cast copper rotor cage and one featuring a four barriers reluctance rotor.

The paper is organized as follows: in Section II design principles and data of the two different motor solutions are provided while in section III Finite Element Analysis is described and adopted to compute the efficiency maps of the motors. Section IV addresses the description of the control strategies adopted to exploit the performance of the motors in terms of efficiency at low load while in section V reports experimental results.

## II. DESIGN PRINCIPLES OF THE IM AND SYNRM MOTOR SOLUTIONS

The design of the motors started from the same stator, for the sake of rapid and low cost prototyping the stator of an induction motor TEFC available in the laboratory has been used. The stator section and main data are reported respectively in Fig. 1. and Table I.

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The adoption of a reference and fixed stator introduces specific design constraints nevertheless the authors aim to focus on the rotor design to investigate pros and cons of each different rotor technology with the same available volume. In particular, to the same air-gap diameter adopted for the IM and the SynRM could limit the design effectiveness of the two motor technologies and hence affect the comparison. Anyway, this additional constraint does not prevent a preliminary evaluation of the main performance, pros, and cons of the two motor technologies.

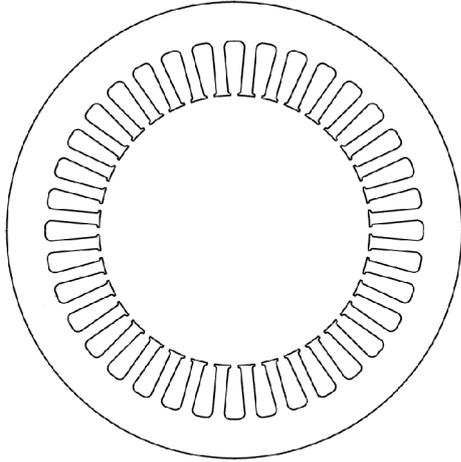


Fig. 1. Reference stator adopted for the design of the rotors.

TABLE I  
MAIN DATA OF THE REFERENCE STATOR

Rated Power	(kW)	3
Phase voltage (rms)	(V)	240
Phase current (rms)	(A)	7.7
Number of poles	(-)	4
Stack length	(mm)	130
Outer stator diameter	(mm)	152
Inner stator diameter	(mm)	90
Wire Size	(mm <sup>2</sup> )	0.94
Number of turns per phase	(-)	198
Number of Slots	(-)	36

In the following, some highlights related to the design strategies for the two rotor are reported along with the cross section of the designed rotors. The same industrial grade electrical steel of the stator will be used for the manufacturing of the rotors.

#### A. Induction motor

The technology selected for the induction copper rotor is the die-casting, a low cost rotor cage manufacturing process. For these reason, die-casting is common manufacturing method for aluminum rotor cage for IM while copper is mainly used the for the largest frame motors. Copper die-cast rotor construction does not differ significantly from the aluminum one and, in essence, the manufacturing details are identical. The additional manufacturing challenges are increased temperatures and pressures required to die-cast copper. The primary reason copper die-cast rotors are not commonplace yet is because it requires specialized equipment (investment) and know how in this field.

The use of die-cast copper rotor requires reviewing the motor design criteria on industrial motors. Particular attention has to be paid for the design of the rotor shape in order to exploit the advantages of the copper cage, without affecting the motor performance.

The authors have investigated the use of copper rotor and have developed a design guideline to optimize the efficiency in three-phase low voltage induction motors [6],[8],[9].

The design procedure takes into account the Manufacturers suggestions related to existing tooling equipment to reduce the cost of the prototype. Fig.2 shows the rotor cross section of the optimized design.

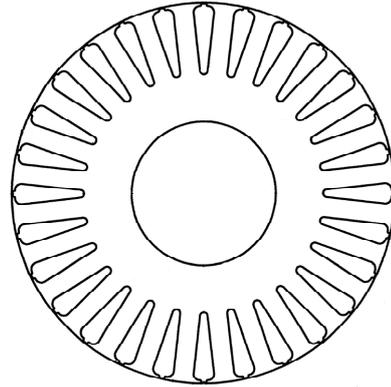


Fig. 2. Cross Section of die-cast Copper Rotor.

#### B. Synchronous reluctance motor

The design of the SynRM has been carried out by a sizing procedure that allows determining all the geometrical data by adopting simplified relationships between geometrical and physical motor data in order to meet the motor specifications.

The number and the shape of the flux barriers affect heavily the saliency ratio and hence the performance of the machine. Also the torque ripple has to be verified at design stage as it can be relevant in these kind of machines. Moreover the dimensions of the ribs and bridges in the rotor geometry affect both the performances and the mechanical strength of the rotor and need a careful evaluation.

The design flow for high performance at low torque ripple is carried out by mean of an iterative process based on Finite Element Analysis and a custom optimization algorithm adapted to SynRM [10].

The cross section of the optimized rotor is reported in Fig. 3; one can notice the different shapes of each one of the barriers computed by the optimization process.

The costs of the manufacturing process are manly related to the punching and shaft insertion where the main challenges are related to the mechanical strength of the rotor. It follows that the SynRM allows to save the costs related to the whole amount of the rotor copper and the die-casting process with respect to the IM.

### III. PERFORMANCE EVALUATION BY MEAN OF FINITE ELEMENT ANALYSIS

To refine the design of the two rotor solutions and estimate the performances over the speed range a Finite Element (FE) model has been developed.

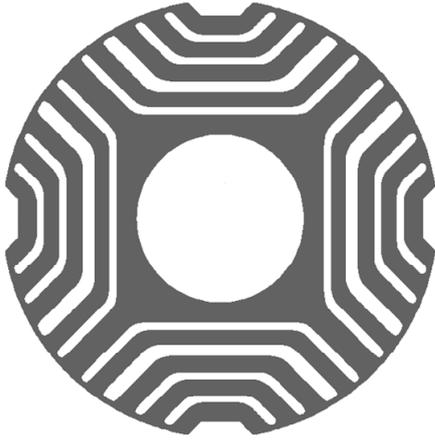


Fig. 3. Cross Section of four barriers SynRM rotor.

The FE Analysis reporting the induction levels and the flux lines at rated performance for the IM and SynRM are reported respectively in Fig. 4 and Fig. 5. One can notice very high induction levels located in part of the teeth of the IM while globally the induction levels are acceptable and compatible with the electrical steel selected.

About the SynRM the highest induction levels are concentrated in the tangential ribs with the purpose to enhance the reluctance of the motor and then the performance.

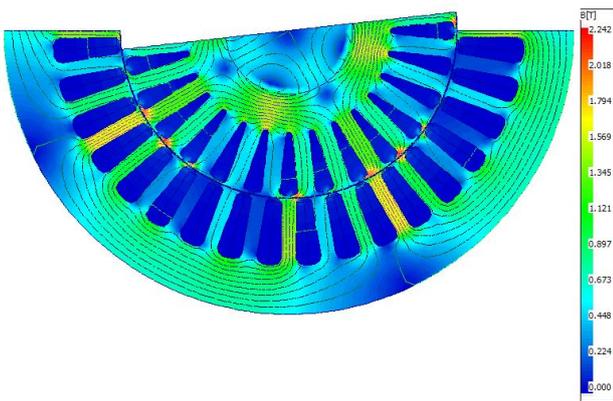


Fig. 4. IM FE Analysis: map of the induction at rated performances

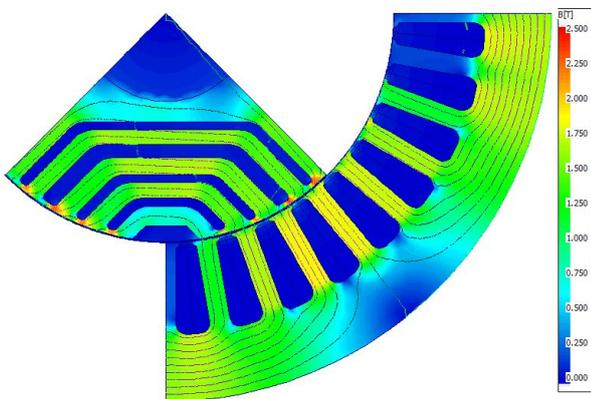


Fig. 5. SynRM FE Analysis: map of the induction at rated performances

Rated computed performance of the two motors are reported in Table II considering the MTPA control strategy. Both the motors are able to reach the output power and

torque; one can confirm the higher efficiency of the SynRM with respect to the IM and the lower power factor.

The FE tool allows computing the efficiency map of the motor by iterative process.

Different commercial tools support the automatic evaluation of the efficiency maps allowing even the selection of the preferred control strategy. Usually the MTPA control strategy is adopted as default while some tools allows the selection of the mapping method considering the absolute maximum efficiency.

The efficiency maps of the IM and SynRM have been computed by mean of the Motor-CAD Software based on MTPA control and reported respectively in Fig. 6 and Fig. 7.

TABLE II  
PERFORMANCE AT RATED POWER, MTPA CONTROL.

		IM	SynRM
Speed	(rpm)	1500	1500
Torque	(Nm)	20.00	20.3
Output Power	(W)	3145	3188.7
Input Power	(W)	3714	3563.9
Phase Current	(Arms)	6.8	7.7
Phase voltage	(Vrms)	233,4	203
Frequency	(Hz)	51.45	50
Power Factor	(-)	0.778	0.76
Efficiency	(-)	0.844	0.871
Dc Bus Voltage	(V)	600	600

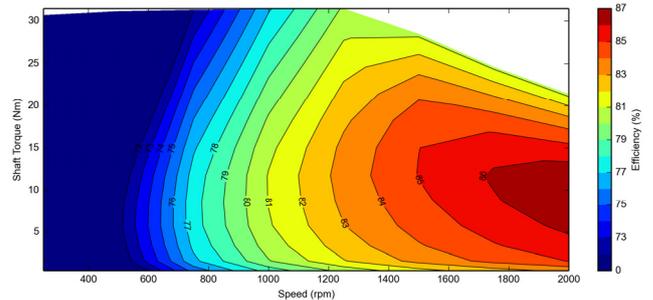


Fig. 6. IM FE Analysis: efficiency map (MTPA Control)

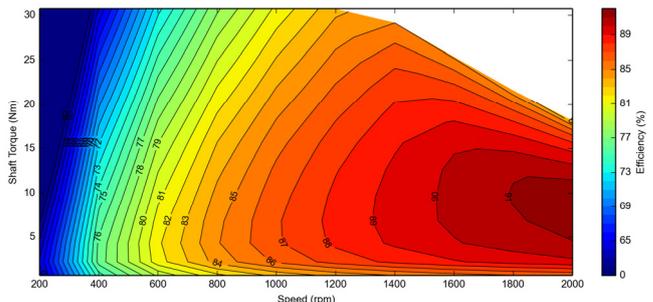


Fig. 7. SynRM FE Analysis: efficiency map (MTPA Control)

Analyzing the efficiency maps of the motors one can notice that the higher efficiency regions are located at high speed and at a torque levels about half the rated one. In both the proposed solutions, the efficiency drop quickly at low torque levels in particular for the SynRM. The efficiency at low torque can be enhanced moving from the MTPA control strategy to a MEPT control strategy, this topic will be addressed experimentally as discussed in the next sessions.





Fig. 10. Prototype of the die-cast Copper Rotor of the IM.



Fig. 11. Prototype of the Synchronous Reluctance Rotor



Fig. 12. Test bed adopted for experimental results: view of the instrumentation setup (Top) and motor on the test bench (bottom).

The data for each specific torque value has been collected at the relative thermal steady state of the motor, the temperature on the TEFC housing has been measured by an infrared fluke 62 thermometer on the top of the front end-shield.

The experimental results are reported in Tables III to VII, in details, Table III reports the Performance of the two motor solutions at rated power controlled with MTPA. Both the rotors achieve the rated torque at rated speed with less current with respect to the stator ratings (originally designed for an induction motor with aluminum rotor) (7.7Arms, Table I).

The SynRM confirms a better efficiency but it is affected by a lower power factor that can arise to oversizing of the power converter and additional losses on the converter side.

Table IV to Table VI report the comparison of the efficiency of the motors operated with MTPA or MEPT controls at different torque and speed values. The results are in good agreement with the efficiency maps reported in section III.

As expected, the efficiency of the SynRM is higher than the IM one all over the torque and speed range due to the absence of the cage losses. The MEPT control algorithm increases the efficiency of both the motors at low torque values and the effect is predominant at high speed where the core losses increase while the two control strategies give the same results at high torque values.

TABLE III  
EXPERIMENTAL PERFORMANCE AT RATED POWER, MTPA CONTROL.

		IM	SynRM
Speed	(rpm)	1500	1500
Torque	(Nm)	20.00	20.00
Output Power	(W)	3145	3145
Input Power	(W)	3715.4	3613.7
Phase Current	(Arms)	6.787	7.544
Phase voltage	(Vrms)	235.60	219.5
DC Bus Voltage	(V)	600	600
Frequency	(Hz)	51.46	50
Power Factor	(-)	0.775	0.728
Efficiency	(-)	0.844	0.870
Temperature	(°C)	47	45
Gross Motor Weight	(kg)	23.5	20.5

TABLE IV  
EFFICIENCY COMPARISON BETWEEN IM AND SYNRM  
BY USING MTPA OR MEPT CONTROL STRATEGIES: 1000RPM.

Speed: 1000rpm	IM		SynRM	
Torques [Nm]	MTPA	MEPT	MTPA	MEPT
2	0.846	0.852	0.881	0.888
4	0.849	0.850	0.876	0.878
6	0.851	0.852	0.877	0.879
8	0.846	0.846	0.873	0.874
10	0.843	0.843	0.870	0.870
15	0.821	0.821	0.841	0.841
20	0.813	0.813	0.843	0.843

TABLE V  
EFFICIENCY COMPARISON BETWEEN IM AND SYNRM  
BY USING MTPA OR MEPT CONTROL STRATEGIES: 1500RPM.

Speed: 1500rpm	IM		SynRM	
Torques [Nm]	MTPA	MEPT	MTPA	MEPT
2	0.870	0.878	0.891	0.904
4	0.870	0.875	0.894	0.901
6	0.875	0.877	0.898	0.901
8	0.872	0.873	0.899	0.900
10	0.865	0.866	0.895	0.896
15	0.852	0.852	0.881	0.881
20	0.847	0.847	0.870	0.870

TABLE VI  
EFFICIENCY COMPARISON BETWEEN IM AND SYNRM  
BY USING MTPA OR MEPT CONTROL STRATEGIES: 2000RPM.

Speed: 2000rpm	IM		SynRM	
Torques [Nm]	MTPA	MEPT	MTPA	MEPT
2	0.866	0.875	0.892	0.903
4	0.873	0.881	0.896	0.904
6	0.878	0.882	0.906	0.908
8	0.877	0.879	0.908	0.908
10	0.877	0.877	0.899	0.899
15	0.854	0.854	0.838	0.838

Table VII reports detailed measures of the meaningful working point of 2Nm@2000rpm where the adoption of the MEPT control strategy gives the main advantage in term of efficiency. One can notice how the MEPT control strategy also increases the power factor in both the motors.

TABLE VII  
DETAILED PERFORMANCE @ 2NM-2000 RPM:  
MTPA AND METP CONTROL STRATEGIES.

	IM		SynRM	
	MTPA	MEPT	MTPA	MEPT
Output Power (W)	418	418	418	418
Input Power (W)	482.55	477.7	468.55	462.8
Phase Current (Arms)	1.782	1.855	1.903	1.999
Phase voltage (Vrms)	130.17	108.82	142.11	123.51
DC Bus Voltage (V)	600	600	600	600
Frequency (Hz)	67.31	67.63	66.66	66.66
Power Factor (-)	0.693	0.789	0.577	0.625
Efficiency (-)	0.866	0.875	0.892	0.903

## VI. CONCLUSIONS

Two prototype of SynchRel Motor and induction motor have been designed starting from the same stator of the motor. The aim of the study is to compare the machines at the same machine volume with focus on the rotor side.

The motors have been tested with a proper Variable Speed Drive equipped with two different control strategies: Maximum Torque Per Ampere and Maximum Efficiency Per Torque. Rated performance and efficiency at different speed and torque have been reported.

Globally, SynRM is able to provide the same output performance of the IM but at higher efficient over the whole speed range. Nevertheless it is affected by a lower power factor that can arise to oversizing of the power converter and additional losses on the converter side.

The adoption of control strategies designed to optimize the Maximum Efficiency with respect to the output Torque gives advantages in enhancing the efficiency of the motors at low load in the whole speed range, and in particular at high speed.

The Maximum Efficiency Per Torque control algorithm seems to be promising to significantly enhance efficiency in motors with a wide constant power region in particular in those application where high efficiency is required even at low load such as automotive applications.

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## VIII. BIOGRAPHIES

**Marco Villani** received the M.S. degree in electrical engineering from the University of L'Aquila, L'Aquila, Italy, in 1985.

He became an Assistant Professor of power converters, electrical machines, and drives in 1993. In 1990, he was Research Fellow at the University of Dresden, German, and in 1995 at the Nagasaki University, Nagasaki, Japan. In 1998 he cooperated in two EU-SAVE projects concerning the Energy efficiency improvements in three-phase induction motors. He is currently Associate Professor of Electrical Machines Design for the degree of Engineering at the University of L'Aquila.

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**Marco Tursini** (M'99) received the M.S. degree in electrical engineering from the University of L'Aquila, in 1987.

In the same year he joined the Department of Electrical Engineering, University of L'Aquila, as an Associate Researcher, and he became an Assistant Professor of power converters, electrical machines, and drives in 1991. Since 2002 he is Associate Professor at the Department of Industrial and Information Engineering and Economics.

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His research interests are focused on advanced control of ac drives, including vector, sensorless, and fuzzy logic control, digital motion control, DSP-based systems for real-time implementation, and modeling and simulation of electrical drives. He has authored more than 120 technical papers on these subjects.

**Mircea Popescu** (M'98 –SM'04 – F'15) is the Head of Engineering at Motor Design, Ltd., a software and consultancy company headquartered in the UK. He has more than thirty years of engineering experience. Earlier in his career, he was with Helsinki University of Technology (now Aalto University) in Finland and with the SPEED Lab at University of Glasgow, UK. Dr. Popescu published more than one hundred papers and his publications have received three IEEE best paper awards. His consultancy contributions for industry are incorporated in many state-of-the-art products. Current major projects include electrical machines and drives for hybrid/electrical vehicles, and formula-e racing cars. An IEEE Fellow, Dr.

Popescu was 2014-2015 Chair of the IEEE Industry Application Society (IAS) Electrical Machines Committee and 2014-2016 IAS Prominent Lecturer.

**Giuseppe Fabri** received the M.S. degree in electronic engineering and the Ph.D. degree in Electrical and Information Engineering from the University of L'Aquila, Italy, in 2009 and 2013, respectively. He is currently researcher at the Department of Industrial and Information Engineering and Economics, University of L'Aquila.

In 2013 he was Research Fellow at the Swiss Federal Institute of Technology, Lausanne, Switzerland. The main research activities concern development, control and test of electrical motor and drives mainly related to fault-tolerant systems for aircraft and automotive applications. In details, he has experience in design of power electronics, DSP-based control platforms and implementation of motion control algorithms for AC drives. He designed and tested different development tools, test-benches and demonstrators as aid to the design and validation process of innovative electric drives.

**Andrea Credo** was born in L'Aquila, Italy, in Novembre 1993. He is an Electrical Engineer graduated with honour at the University of L'Aquila on July 2017. His M.S. thesis concerned the design of Permanent Magnet assisted Synchronous Reluctance Motor and modelling with Finite Elements

Analysis and control of Synchronous Reluctance machine. He is going to start his Ph.D. studies in University of L'Aquila. His main interests are focused on design, modelling and control of electrical rotating machines, with particular emphasis of automotive applications.

#### **Lino Di Leonardo**

Lino Di Leonardo was born in Pescara, Italy, on October 28, 1986. In 2012 he was visiting Ph.D student at the École Supérieure d'Ingénieurs en Électrotechnique et Électronique d'Amiens (ESIEE-Amiens).

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Currently, he works as Assistant Researcher in the Department of Industrial and Information Engineering and Economics, University of L'Aquila. In particular his Ph.D. thesis concerns dynamic co-simulation analysis of motor drives. His research activities involve design, modelling and simulation of electrical machines with focus on permanent-magnet synchronous motors, Dual-Rotor Permanent Magnet Induction Machine and reluctance motors. He has experience with finite-element and multi-physics integrated simulation tools along with DSP-based real-time simulation platforms.