Evaluation of the magnetization direction effects on ferrite PM brushless fractional machines

L.Ferraris, P. Ferraris, E.Pošković, A.Tenconi
Politecnico di Torino, Alessandria site, viale Michel 5, 15121 Alessandria (Italy)
luca.ferraris@polito.it

Abstract **– Permanent magnets are frequently adopted in small brushless machines for automotive applications. Normally anisotropic ferrites, but some research on bonded magnets is being carried on. Several types of magnetization can be proposed, involving different levels of complexity in the magnetization process. In the paper a comparison between parallel and radial magnetization is described, taking into account on one side the major complexity of the radial process and on the other the small power derating of the parallel.**

Index Terms **– Fractional PM machines, magnetization patterns, magnetization process, parallel and radial magnetization, performance**

I. Introduction

Among the applications of the automotive world where electric motors are required [1], [2], [3], the cooling systems with fans driven by small brushless motors are widely used.

Normally they are small machines with internal stator, dummy slots and outrunner rotor with Permanent Magnets; an example that has been considered for the present work is shown in Fig. 1 [4].

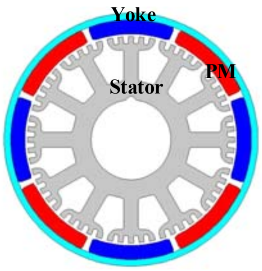

Fig. 1 – Brushless motor under exam

In the past activity a deep interest of the Authors has been addressed to new molding solutions for the realization of PM for such motor type [5]. A subject which constitutes object of technical debate concerns the type of the adopted magnetization methodology [6], [4], [7], [8]; in this work a comparison about the motor performances related to the two main types of magnet magnetization will be carried out: parallel and radial [9], [10], [11], [12], [4].

The comparison is here performed under the point of view of the effect of the selected magnetization technique [6], [13], on the potential transformed electromechanical power and to related energetic aspects [14], [15]. The justification of the attention for the argument is related to the strong differences in the magnetization process between the two solutions, under both technical and economic point of view. That is especially important for the case of low cost and mass production motors [1], [16] as the one that is here considered.

If the parallel magnetization should allow satisfactory energetic performances, such solution has to be carefully considered, especially in the case of small fan drives. The original samples of motor obtained by the manufacturer provides anisotropic ferrite magnets with radial magnetization; for the present work also prototypes with parallel magnetization have been realized in our laboratories, for a better results reliability [5], [9].

II. Materials and Magnetization Processes

The motor considered the present activity is equipped with anisotropic ferrite magnets, whose magnetic data are reported; in the following Table I:

Type of magnet		Anisotropic ferrite
Remanence	B_r [T]	0.420
Coercivity	H_c [kA/m]	-260
Intrinsic Coercivity	H_{cj} [kA/m]	-272
Max energy product	$(BH)_m$ [kJ/m^3]	36.70
Temperature coefficient up to 100 °C	dB_r/dT [%/°C]	-0,20
	dH_{cj}/dT [%/°C]	+0,32

Table I - Magnetic characteristic of the anisotropic ferrite

The aim of the present activity involves the evaluation of the magnetization direction impact on the machine performance [17], [18]. The magnetizations here considered are the parallel and the radial one [9], which present different levels of complexity and required devices.

Parallel magnetization is easy to be obtained inside the magnetizer coil directly in air, without the need of any particular adaptation; on the other hand radial magnetization requires the adoption of a dedicated magnetic circuit (Fig. 2) realized by the authors in their electromechanical laboratory with a high permeability material (Fig. 3) [9].

To get equal results in terms of final magnetization, the discharge level of the magnetizer if working in air or with the magnetic circuit is different.

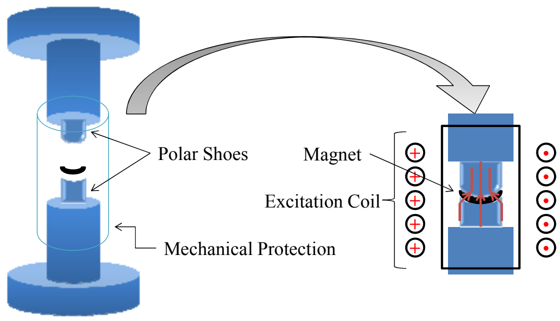

Fig. 2 – Adopted magnetic circuit for the radial magnetization

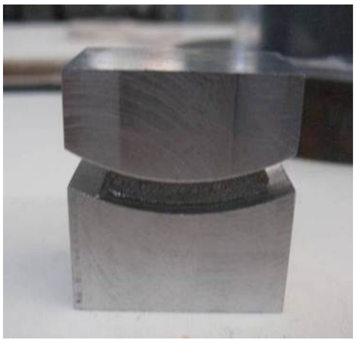

Fig. 3 – Polar shoes around the magnet

III. COMPARISON METHODOLOGY

The brushless motor object of the present analysis is belonging to the family the so called "trapezoidal" types [16], [19] and it is driven through a three phase transistor full bridge providing a basic six-step commutation (Fig. 4). The equivalent converter system is the one reported in Fig. 4: a PWM chopper stage providing the DC voltage regulation for the speed control and a six-step inverter realizing the motor phases commutation.

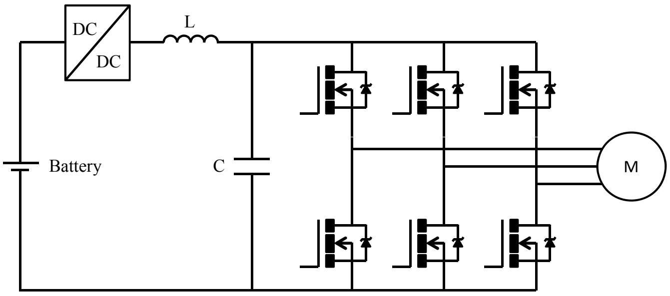

Fig. 4 – Ideal Drive structure

At a given speed, the situation is equivalent to consider the motor supplied by a DC bus having voltage value equal to the average value of the three e.m.f.. The PWM modulation will compensate the instantaneous, small difference between the rectified motor e.m.f. reflecting the motor voltage ripple and the constant DC supply voltage.

Such a DC voltage value may be utilized for a motor performance analysis: the analysis, concerning the handable electromechanical power of two motors providing different magnetization types, may be performed by comparing the average value of the mentioned obtainable rectified motor voltages V_{dc}.

The comparison between the obtained average voltages gives the possibility to deduce the comparison between the possible input electric power, which is given by the product of V_{dc} and the motor rated current which is not modified, being related to the windings characteristics. A higher average rectified voltage means a higher input electric motor power and viceversa. The knowledge of the different loss contributions makes possible to analyse also the effect on the usable power.

It has to be remembered that in the practical application the modulation system, with the six-steps commutation, also provides to the cancellation of the possible voltage ripple present in every conduction phase; for all this, a system of LC filters, interposed between drive and battery is normally adopted.

From what above reported, the comparison can be referred to constant voltage values, equal to the average value of the rectified voltage, V_{dc}.

The system "motor and drive" can be considered, for each speed and load, as a direct current load, with constant voltage and current.

At the aim of a basic comparison, as proposed in this work, it is enough to refer to the input power, obtainable as the product of the rectified ideal voltage induced in the motor phases and the rated current (on the dc side) specified by the manufacturer.

It must be underlined that the main goal of the work is the evaluation of the possible negative effects related to the adoption of an easier magnetization process (the parallel one); even a small allowable input power reduction, for those applications that don't require particular specifications typical of the automation systems, could be considered positive.

At the aim of comparing the useful power, the equivalent voltage drop due to the motor phase resistance must be taken into account; such voltage drop can be deduced from the manufacturer data, and it is equal to 0,42 V for the rated current I_r = 4,6 A; that brings to a rated joule losses value of 1,9 W.

In the real case of a power supply with constant voltage value (DC battery), for utilizing the eventual power advantages it should be necessary to provide a suitable modification of the motor windings.

On the basis of the above reported remarks we will proceed to evaluate the rectified e.m.f. value for motors presenting both parallel and radial magnetization, through finite element simulation [19], [9], [20], [21] and through bench measurements [5], [9], [22].

The first step is to take under consideration the use of ferrite magnets, as they are effectively adopted in the present production. The exam will be then extended to other types of magnets [23], [9] [24].

For each case some energetic considerations will be carried out [25], [26], [22].

IV. INVESTIGATION STEPS

The present analysis will be conducted with the following steps:

- determination of the simulated voltage waveforms at no load, in the case of motor adopting ferrites with radial and parallel magnetization; this will allow to evaluate possible differences of the voltage values due to the different kind of magnetization [27], and consequent different performances in terms of power;
- comparison of such voltages with those experimentally measured with the machine in rotation at no load.

As regards the power, for the case under exam, it is necessary to consider the DC voltage available before the structure of phases commutation; the no load voltage produced by the machine will be detected with a three phase rectifier bridge, simulating the phases commutation of the brushless six-steps drive.

For a proper comparison with the simulation results, the experimental voltages must also consider the voltage drops on the adopted diodes.

A. Flux and e.m.f. simulation

In the following the evaluation of the flux machines will be described for the case of ferrite magnets both for radial and parallel magnetization; on these basis, with the adoption of a derivative procedure the corresponding e.m.f. waveform and value has been deduced.

The theoretical value of the rectified e.m. forces seen through an ideal rectifying bridge is calculated; that is obtained through the evaluation of the average value of a single e.m.f. phase waveform during one of the six conduction intervals of 60 electrical degrees.

A.1 Ferrite magnets with parallel magnetization

The simulated flux density of the machine adopting ferrite magnets with parallel magnetization is reported in Fig. 5, while the stator pole flux over a complete electrical period is shown in Fig. 6.

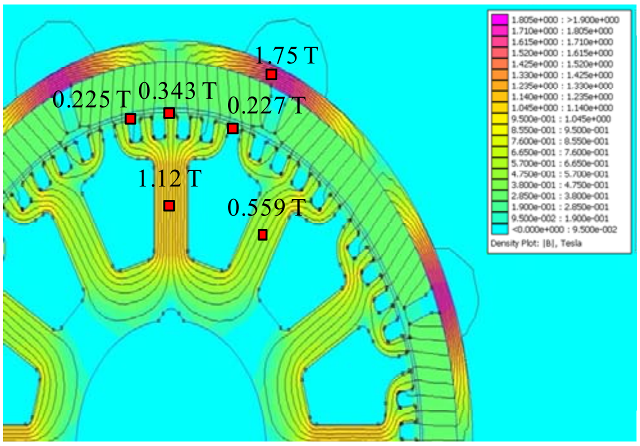

Fig. 5 – Simulated flux density for parallel ferrite motor

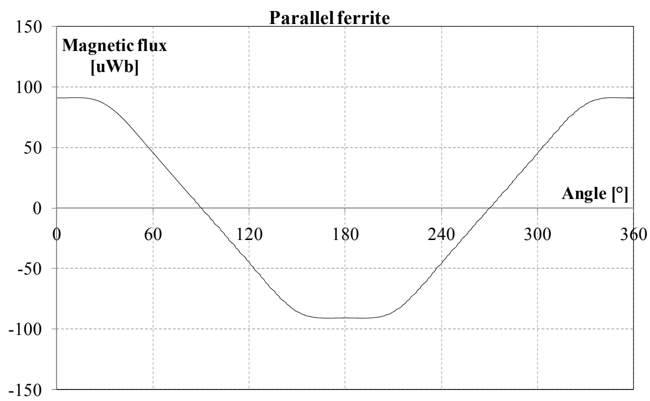

Fig. 6 – Simulated flux for parallel ferrite motor

In Fig. 7 the e.m.f. at the terminals of the machine obtained through the simulation process is reported:

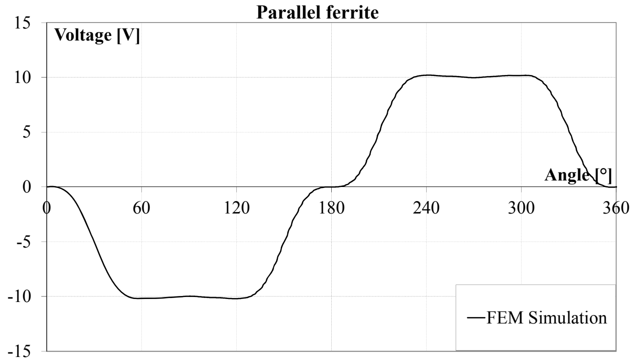

Fig. 7 – Simulated e.m.f. for parallel ferrite motor

In Fig. 8 the e.m.f. waveform during the conduction period and the related average value of the rectified ideal voltage are reported:

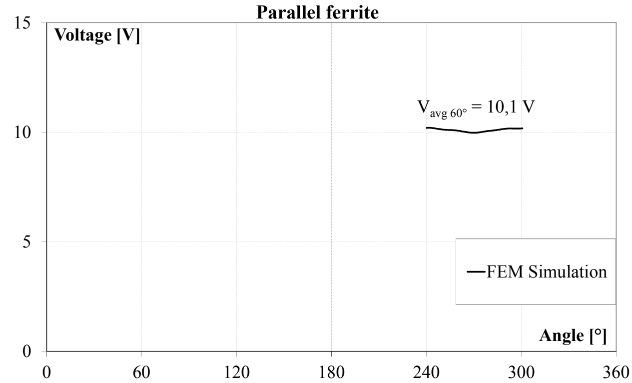

Fig. 8 – Simulated e.m.f. for **parallel ferrite motor**: waveform and average value V_{dc} during the conduction interval (rectified voltage value)

A.2 Ferrite magnets with radial magnetization

The simulated flux density of the machine adopting ferrite magnets with radial magnetization is reported in Fig. 9, while the stator pole flux over a complete electrical period is shown in Fig. 10.

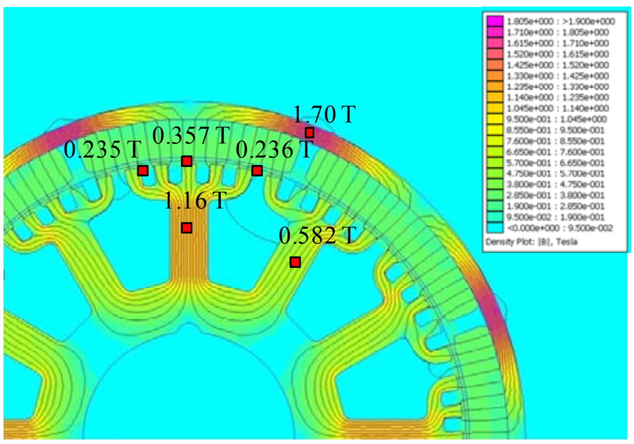

Fig. 9 – Simulated flux density for radial ferrite motor

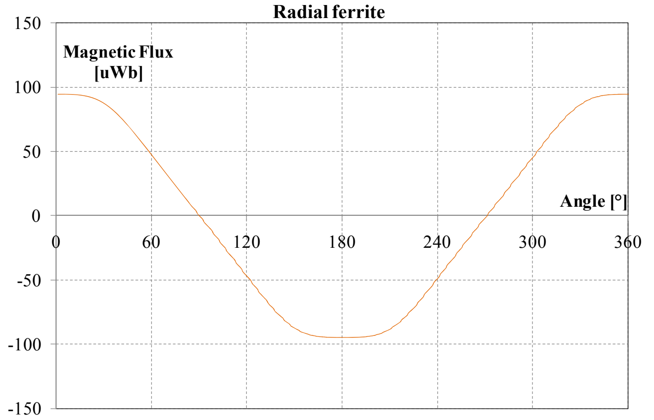

Fig. 10 – Simulated stator pole flux for radial ferrite motor

In Fig. 11 the e.m.f. at the terminals of the machine obtained from the simulation is reported:

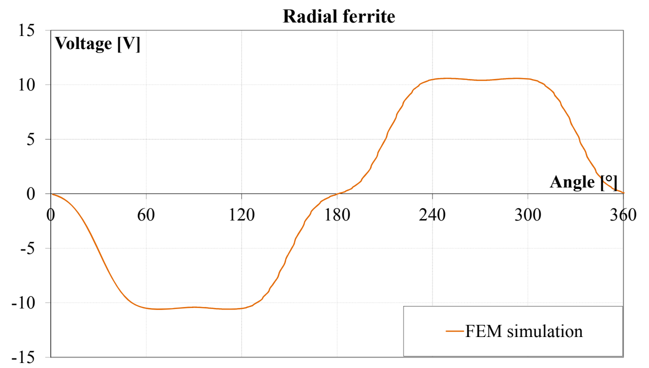

Fig. 11 – Simulated e.m.f. for radial ferrite motor

In Fig. 12 the waveform during the conduction period and the related average value of the rectified ideal voltage are reported:

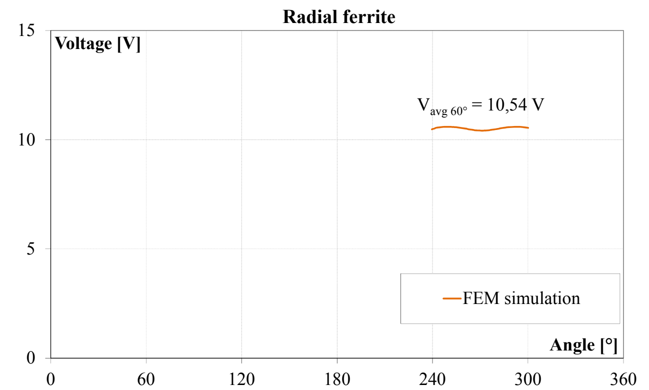

Fig. 12 – Simulated e.m.f. for **radial ferrite motor**: waveform and average value V_{dc} during the conduction interval (rectified voltage value)

B. *Experimental verification*

The simulation process has been followed and validated with an experimental activity conducted on a properly realized test bench (Fig. 13).

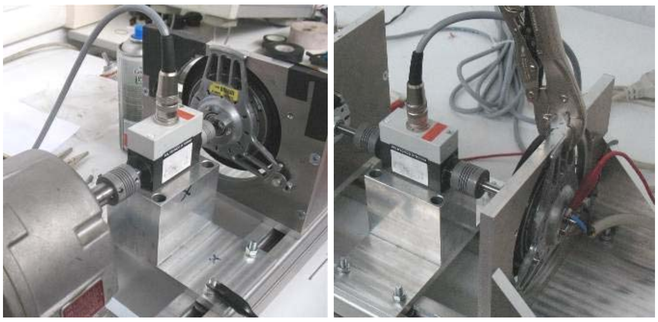

Fig. 13 – Experimental test bench

In Fig. 14 and Fig. 15 the comparison between the simulated and the experimentally measured values of the e.m.f. is proposed, with a good matching of the results.

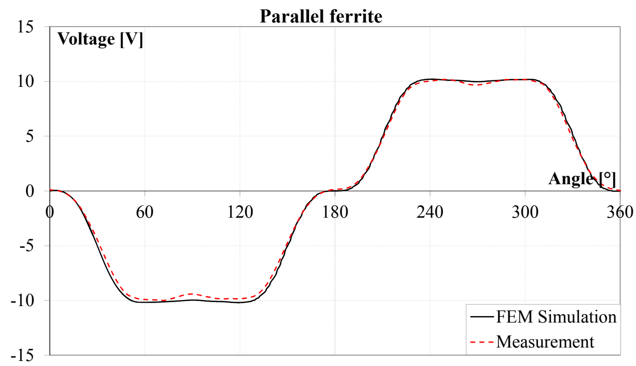

Fig. 14 – Experimental and simulated voltage for parallel ferrite motor

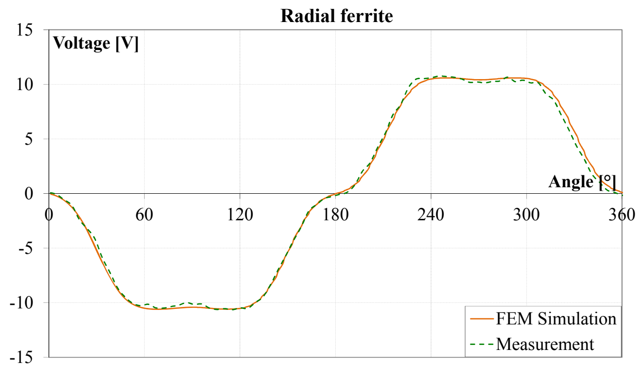

Fig. 15 – Experimental and simulated voltage for radial ferrite motor

It can be observed that a very small difference between the measurements and the simulations is present; the average values of the voltages ($V_{dc} = V_{avg\ 60°}$) evaluated in the conduction period of 60 electrical degrees is hereafter reported in Table II:

	Parallel	Radial	Δ parallel/ radial
FEM simulation	10,1 V	10,54	-4,35%
Experimental measurements	10 V	10,41	-3,9%
Δ simulation/experimental	1%	1,3%	

Table II - Simulated and the experimental average voltages V_{dc} for anisotropic ferrite magnets with parallel and radial magnetization

V. Results Analysis

The experimental activity conducted on the different machines that have been assembled to perform the comparison between the effects of the different kinds of magnetization allowed to verify the values of the rectified voltages.

It can also be observed from Fig. 14 and Fig. 15 that the simulation process considers a perfect magnetic symmetry of the flux density distribution in the machine; such a fact is not perfectly verified in the practical realization, mainly when a radial magnetization has to be obtained.

All that may also justify the major difference, even if very small, between the calculated and measured values reported in Table II concerning the radial case.

That imply also a non perfect symmetry in the voltage waveform, especially just for the radial magnetization motor, which is belonging to the normal production series.

To underline such phenomenon, in any case having side importance, in Fig. 16 and Fig. 17 the rectified voltage waveforms are reported for qualitative observations: the voltage drops concerning two diodes should have to be added to the measured average values.

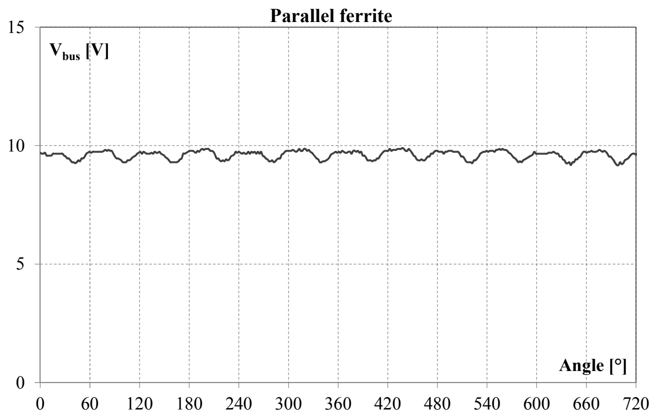

Fig. 16 – Experimental rectified voltage for parallel ferrite motor

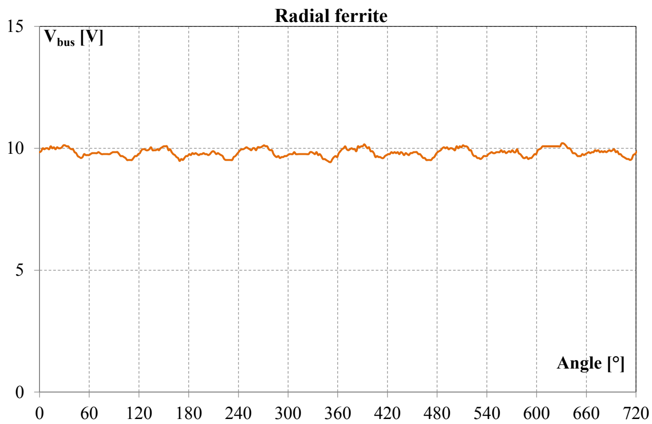

Fig. 17 – Experimental rectified voltage for radial ferrite motor

From all the above results it is possible to deduce:

- a major regularity in the time development for the motor providing parallel magnetization
- a confirmation of a limited major average voltage in the case of radial magnetization.

It must be again underlined the basic character of the research, that aims to consider the eventual tendency effect of the chosen magnetization methodology on the electromechanical transformation. Under this point of view it has been considered enough to perform the further evaluations on the basis of the results obtained through the simulation approach.

Power evaluation

As it is described in the Section II and taking into account the results of Table II, the following considerations can be obtained:

- input power P_{iR} allowable for the case of radial magnetization:
  $P_{iR} = V_{dc} \times I_r = 10{,}54 \times 4{,}6 = 48{,}48$ W

- input power P_{iP} allowable for the case of parallel magnetization:
  $P_{iP} = V_{dc} \times I_r = 10{,}1 \times 4{,}6 = 46{,}46$ W

For an evaluation of the allowable output power P_{oR} and P_{oP} the different loss contributions at the speed of 4000 rpm have to be considered.

The following values are valid for *both cases*:

Bearing losses	3,4	W
Fluidic friction losses	2,0	W
Joule losses	1,9	W
Total basic losses	7,3	W

As regards the iron losses, the Authors, in a parallel activity deduced the following data:

radial magnetization:

hysteresis losses	1,53	W
eddy current losses	4,39	W
Total Radial iron losses	5,92	W

parallel magnetization:

hysteresis losses	1,45	W
Eddy current losses	4,91	W
Total Parallel iron losses	6,36	W

From the above elements, the following results are obtained:

$$P_{oR} = P_{iR} - \Sigma\text{losses} = 48{,}48 - 7{,}3 - 5{,}92 = 35{,}26 \text{ W}$$

$$P_{oP} = P_{iP} - \Sigma\text{losses} = 46{,}46 - 7{,}3 - 6{,}36 = 32{,}80 \text{ W}$$

VI. Final considerations

Even if the present analysis has to be considered of a general information character, it provides some univocal results: the adoption of the parallel magnetization magnets brings to a derating of the obtainable output power from the same electromechanical structure with respect to the one adopting magnets providing a radial magnetization. The obtained derating value of a few percent has to be considered representative enough.

Apart from this, all the performed activity and the reported analysis allow to establish that the power reduction is limited to a percentage which may be often considered small enough to adopt the easier parallel magnetization process when the magnets are subjected to the magnetization action before the introduction in the motor, as it is verified in a large number of applications.

All that, of course, when other performances aspects don't make necessary other analysis typologies [28], [29], [30].

VII. Acknowledgment

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