ANALELE UNIVERSITĂŢII
"EFTIMIE MURGU" REŞIŢA
ANUL XII, NR. 1, 2005, ISSN 1453-7394

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Comparative Analysis of Some Brushless Motors Based on Catalogue Data

Brushless motors (polyphased AC induction, synchronous and brushless DC motors) have no alternatives in modern electric drives. They possess highly efficient and very wide range of speeds. The objective of this paper is to represent some relation between the basic parameters and magnitudes of electrical machines. This allows to be made a comparative analysis and a choice of motor concerning each particular case based not only on catalogue data or price for sale.

1. Introduction

Electronically controlled brushless electric machines are unrivalled in modern electric drives, due to their high reliability, excellent operating, energy and regulating characteristics. Thanks to these properties they have almost entirely replaced collector DC motors in recent years. The wide application of these motors necessitates the conduction of a well-grounded analysis on the choice of the motor type for the variety of applications, depending on cost, dimensions and weight, inverter circuit and other specific requirements. The present paper aims to propose an approach to systemizing and summarizing of catalogue and other types of data about the three types of brushless motors, with view to allowing a well-grounded choice of one of them for a specific application. Over the last five years the improvement in electronically-controlled brushless electrical machines (ECBEM) has been going on in two directions: improvement of control circuits based on MOSFET and IGBT transistors and using DSP technologies, as well as improvement of rotor designs, the materials for permanent magnets and the optimal design as a whole.

2. Analysis

In addition to induction motors (IM) and permanent magnet brushless motors (PMBM), another type of brushless motors are equally suitable for high-frequency drives of low or medium power and are considered to be sufficiently competitive to them [1]. These are brushless motors without permanent rotor magnets – the rotor is composed of separate electric grade sheets. These motors are referred to as brushless reluctance motors (BRM) with variable magnetic resistance of the rotor. There are two basic reasons why these are studied in greater detail with view to their wider application. The first one is the low cost of the materials required for a unit of power and the low production costs. The second reason is the high efficiency ($\eta \geq 0.85$ in case of optimal design), high torque and relatively quiet operation. Each motor has its specific dimension-weight indicators, which are an indirect criterion for its optimal design (input of state-of the-art structural materials, choice of a structure consistent with the specific application, etc.).

The dimension-weight indicators, commonly used as a criterion for comparison of different motors, may include: relative mass (the motor mass for a unit of useful power), relative mass of the active materials input (electric steel, wiring, permanent magnets), torque for a unit of motor weight, power for a unit of weight, cost of the active materials input for a unit of torque or a unit of power, etc. There are specific cases when the motor to be chosen has to fit a strictly defined space (specific autonomous installations, manual electrical instruments and other processing equipment, medical equipment, etc.). It is advisable to make a preliminary comparative analysis of different dimension-weight indicators of the motors preferred for the purpose. As an object of exploitation they must have high reliability, high energy indicators, comparatively low cost and at the same time be compact. Such an approach can be seen in [1], the catalogue data being the output for each motor. It is completely applicable and convenient for comparison of these commonly used brushless motors – induction motors, permanent magnet brushless DC motors and brushless reluctance motors.On the basis of the catalogue data (power, rotation frequency, torque developed, weight and overall dimensions) provided by manufacturers of such motors [3, 4, 5], and using certain analytical dependences from electric motor design [2], it becomes possible to determine some important dimension-weight indicators. The data, summarized and processed, are presented in Tables 1, 2, 3, 4, 5 and 6, and the three types of motors discussed are shown in Fig. 1.The stators of the motors compared are produced from NEMA 184T steel, used by West European manufacturers. The motors are selected with identical overall dimensions, the same type of cooling, the same active lengths of stator packs and identical external diameters of the latter.For the identical output dimensions of the three motors mentioned above, some conclusions can be drawn. The induction motor has 3.7 kW output power, the permanent magnet brushless motor – 10.5 kW, and the brushless reluctance motor – 6.6 kW, i.e. in case of equal overall dimensions the permanent magnet brushless motor produces 2.84 times as much power, and the brushless reluctance motor – 1.78 times as much power, as that produced by the induction motor. The induction motor has the largest volume of the rotor and stator altogether – $1{,}427.10^{-3}m^3$, it develops the smallest torque and the least power per kilogram weight of the active materials – 0,85 Nm/kg and 0,159 kW/kg (Table 3). In this respect it is inferior to permanent magnet brushless motors – 2.7 times as much developed torque and 2.68 times as much output power per unit weight of the active materials and almost the same total weight and smaller volume (Table 5). The induction motor has greater relative volume of electric steel, longer butt joints of the stator winding and short-circuited rotor winding. This results in greater losses in steel and electric losses in the windings, respectively. Therefore the induction motor has a smaller efficiency.

Permanent magnet brushless motors and brushless reluctance motors have shorter butt joints and their rotor design includes a permanent magnet and a corresponding rotor pack composed of electric steel, i.e. there is no rotor winding, consequently, there are no losses in it. The brushless reluctance motor has 2.03 times as much torque developed and 2.02 times as much output power for 31.08% smaller volume and 11.61% lower weight than the induction motor (Tables 3, 4, 5). The analysis of the data in the Tables shows undoubtedly the advantages of the permanent magnet brushless motor and the brushless reluctance motor.The latter has very good energy indicators, an efficiency of 92% and the lowest cost of the input materials, therefore it is the cheapest. The permanent magnet brushless motor has excellent energy and electromagnetic parameters, the highest efficiency – 94 %, it is the most compact one, but is 8.17 times as expensive as the brushless reluctance motor and 6.5 times as expensive as the induction motor.Nevertheless, it is the specific requirements for each application that are decisive in making the final choice.Recently the tendency has been for the optimal design of these three types of commonly used motors to be oriented towards their mass minimization in case of optimal electromagnetic loads, input of new materials, improvement of their structures, as well as their control circuits.The undoubted advantage of permanent magnet brushless motors is mainly due to the use of high-energy rare magnets (NdFeB,Sm-Co). This allows a conceptual change in the device – a decrease in the motor overall dimensions, an increase in the power per unit of volume of the active parts, a considerable improvement of the machine efficiency and utilization factor. With induction motors and brushless reluctance motors the magnetic flux of the machine is produced by the current in the stator winding, while in the case of permanent magnet brushless motors the magnetic flux is produced by the permanent magnets in the rotor, which decreases the current of the inverter transistorized switches, i.e. the cost and the overall dimensions are reduced.

Table 1.

Motor type	Stator		Rotor		
	External D, $10^{-3}\,m$	Internal D $10^{-3}\,m$	External D, $10^{-3}\,m$	Air gap $10^{-3}\,m$	Air gap area , m^2
IM	193.67	113.36	112.6	0.38	0.045
PMBM	193.67	96.06	95.3	0.38	0.038
BRM	193.67	108.76	108	0.38	0.043

Table 2.

Rotor	Electric steel		Magnets		Aluminium		Total	
	Volume $10^{-3}\,m^3$	Weight kg	Volume $10^{-3}\,m^3$	Weight kg	Volume $10^{-3}\,m^3$	Weight kg	Volume $10^{-3}\,m^3$	Weight kg
IM	0.918	7.28	-	-	0.508	1.27	1.427	8.55
PMBM	0.738	5.9	0.118	1	-	-	0.902	6.9
BRM	0.81	6.71	-	-	-	-	0.116	6.71

Table 3.

Stator	Electric steel		Copper wire		Total		Rotor and stator	
	Volume $10^{-3}\,m^3$	Weight kg	Volume $10^{-3}\,m^3$	Weight kg	Volume $10^{-3}\,m^3$	Weight kg	Volume $10^{-3}\,m^3$	Weight kg
IM	0.951	7.71	771	6.99	4.33	14.7	5.756	23.25
PMBM	1.509	12.25	607	5.44	3.62	17.7	4.526	24.6
BRM	1.082	9.07	541	4.76	2.8	13.83	3.967	20.55

Table 4.

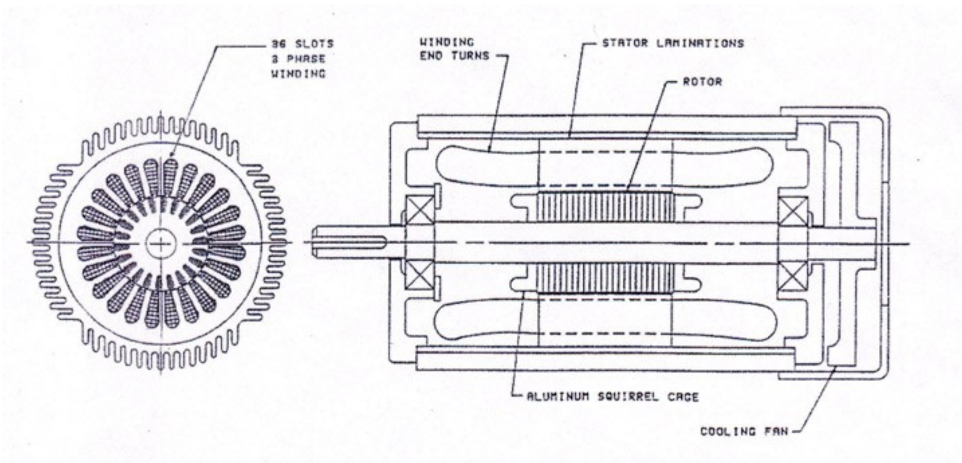
Motor type	Continuous torque, Nm $\left(n = 1800\,\min^{-1}\right)$	Continuous power, *kW*	Efficiency, %	Current density, A/mm^2
IM	19.78	3.7	90 (catalogue data)	7.8
PMBM	56.5	10.5	94 (measured)	7.65
BRM	35.6	6.6	92 (measured)	7.7

Table 5.

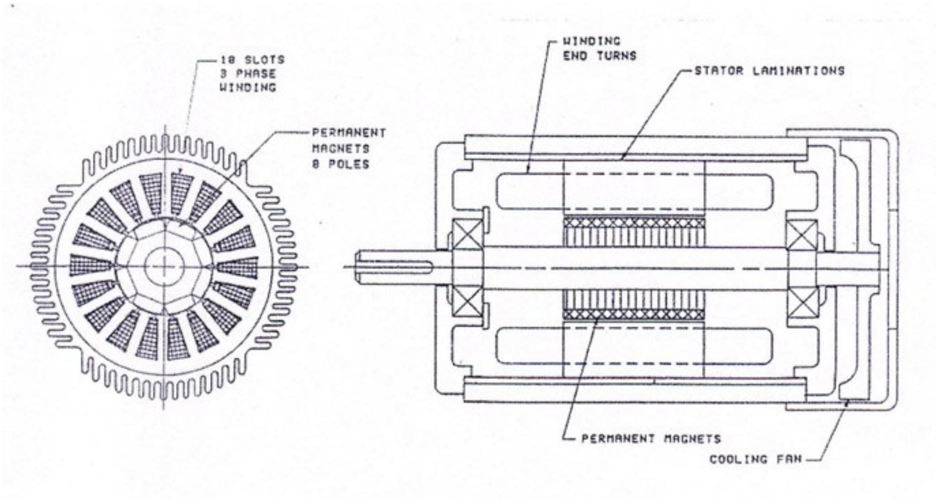
Motor type	Torque per unit of weight, Nm/kg			Power per unit of weight, kW/kg		
	Rotor	Stator	Total	Rotor	Stator	Total
IM	2.31	1.35	0.85	0.433	0.252	0.159
PMBM	8.19	3.19	2.3	1.52	0.593	0.427
BRM	5.3	2.57	1.73	0.984	0.477	0.321

Table 6.

Motor type	Torque per unit of weight, Nm/kg		Power per unit of weight, kW/kg	
	Electric steel	Wires	Electric steel	Wires
IM	1.32	2.39	0.247	0.448
PMBM	2.95	10.38	0.548	1.93
BRM	2.26	7.48	0.418	1.39



a)



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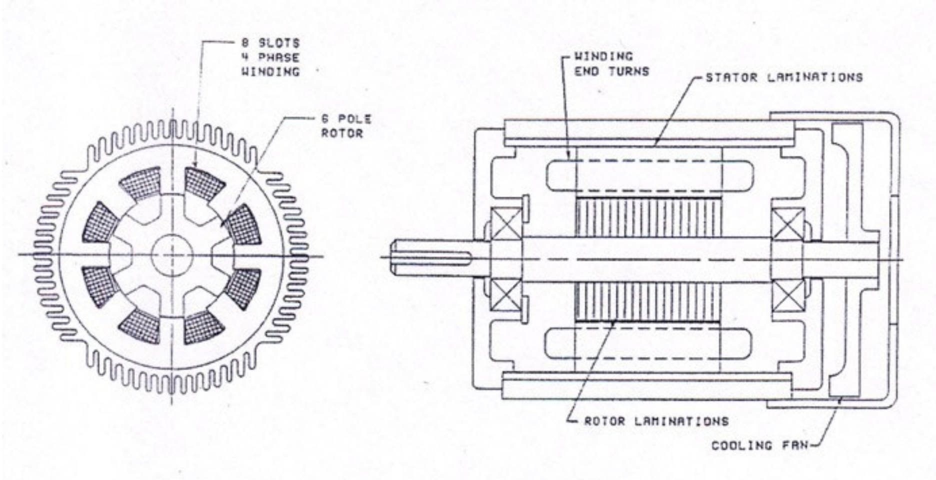

c)

Figure 1. General view of ECBEM – a) Induction motor; b) Brushless motor; c) Brushless reluctance motor.

For the sake of a more comprehensive analysis and to allow a better choice, a comparison should also be made of the control circuits of the three types of motors discussed. Fig. 2, 3 and 4 present the control circuits of the induction motor (Fig. 2), the permanent magnet brushless motor (Fig. 3) and the brushless reluctance motor (Fig.4), respectively. Given the same value of the unidirectional voltage U_d and the same power of the motors, the characteristics of each circuit can be compared and assessed. The efficiency η and the effective value of the inverter output current in case of rated load on the motors are determined from the motor data, knowing the value of the unidirectional voltage U_d and the motor rated power P_n. In addition, the value of the power factor cosφ must also be known for the induction motor.

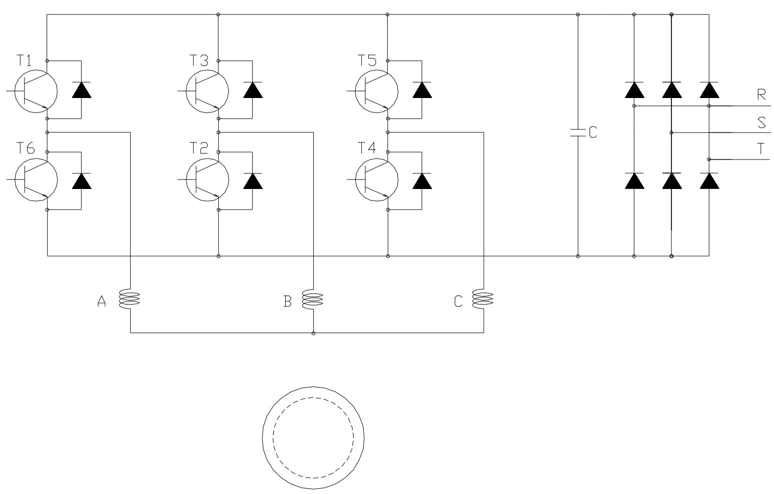

Figure 2. Control circuit of an induction motor.

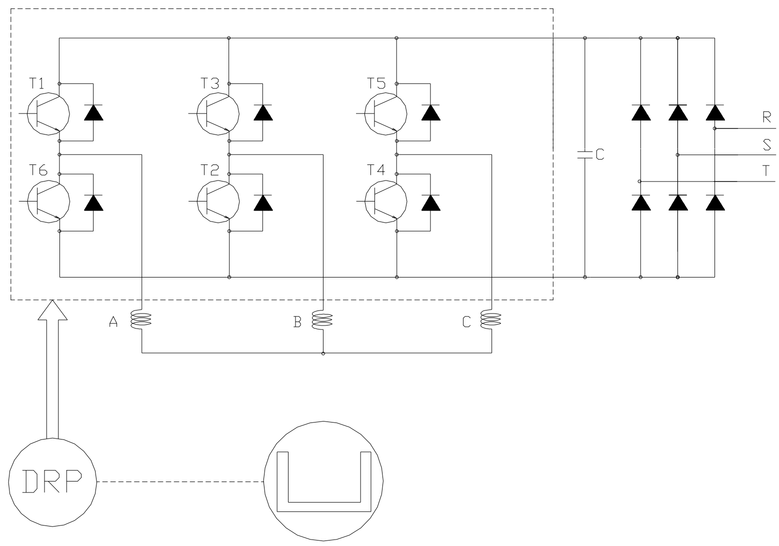

Figure 3. Control circuit of a permanent magnet brushless motor.

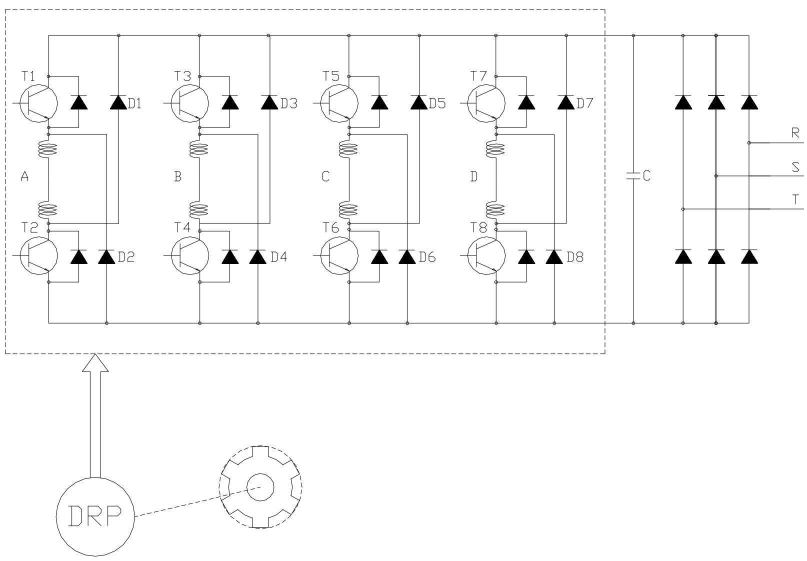

Figure 4. Control circuit of a brushless reluctance motor.

For the sake of the comparison, it can also be assumed that the inverters for the induction motor and for the permanent magnet brushless motor operate with $2\pi/3$ commutation, which guarantees fairly good indicators with a simple circuitry and at a lower price. The inverter of the brushless reluctance motor is non-reversible, the reactive energy of the disconnected phase being returned to the filter capacitor of the rectifier. Taking into consideration the fact that the power unit of the inverters is controlled by microprocessors of virtually identical features and cost, the value of the inverter is mainly determined by the power unit, comprising the power transistorized modules, the rectifier unit and the filter capacitor. The circuits in Fig. 2 and 3 are designed using a more or less identical number of elements and the same switching frequency $f_k = 120Hz$, but the circuit in Fig. 4 is more complex, with more elements and a greater switching frequency $f_k = 720$ *Hz*. Furthermore, the filter capacitor of the power unit must absorb the reactive energy stored in the disconnected phase, the frequency of the reactive current being 2880 Hz, and its maximal value being equal to the maximal value of the phase operating current. Taking into account the above features of the three types of motors and assuming that the inverters are compared for the same rated power of the motors $P_н = 3,7$ kW, the rated currents can be determined as follows:

- rated current of the induction motor (peak value) -
$I_n = 1,41P_n/(1,73.U_n.\eta.\cos\varphi) = 1,41.3700/(1,73.440.0,9.0,85) = 9$ A
- rated current of the permanent magnet brushless motor (peak value) -
$I_n = 1,41P_n/(1,73.U_n.\eta) = 1,41.3700/(1,73.440.0,94) = 7,2$ A
- rated current of the brushless reluctance motor (peak value) -
$I_n = P_n/(U_d.\eta.k_p) = 3700/(1,24.440.0,92.0,81) = 9,1$ A

where U_n is the effective value of the motor rated voltage, k_p is a coefficient indicating the reactive component of the current of the brushless reluctance motor. The inverter costs for the three types of motors in case of three-fold current overload in a dynamic mode, taking into consideration the number of electronic components of the inverter and the required properties of the filter capacitor, can be compared using Table 7.

Table 7.

Motor type	**Number of transistorized switches**	**Rated current of transistors** *A*	**Number of diodes of the additional bridge**	**Rated frequency of transistor commutation,** *Hz*	**Rated frequency of current through the filter capacitor,** *Hz*	**Amplitude of current through the filter capacitor** *A*
IM	6	27	-	120	240	27
PMBM	6	21.6	-	120	240	21.6
BRM	8	27.3	8	720	2880	±27.3

It can be seen from Table 7 that the inverters for permanent magnet brushless motors and induction motors are of almost equal value, the maximal current of power devices for induction motors being 25% greater due to the magnetizing current of induction motors, which also raises their price. The current of the transistorized switches in brushless reluctance motors is virtually the same as for induction motors, but the number of transistorized switches is 8, i.e. they are 33% more and eight quick-operating diodes are required for returning the reactive energy to the filter capacitor, which must be far superior – for current twice as great in amplitude in case of frequency 12 times as high. The features discussed make the inverter for brushless reluctance motors much more expensive than the one intended for permanent magnet brushless motors and induction motors (twice and more as expensive). The higher costs reduce the advantages of the motor in terms of price and necessitate a precise cost-benefit analysis to be made for each specific case.

3. Conclusion

All motors presented here exhibit good performance and therefore, high efficiency, they are reliable and have high energy characteristics.In conclusion, there are two different ways for a relatively quick assessment of the properties of a certain motor – continuous torque developed, in relation to the cost of magnetic materials, and the cost of active materials input in the motor per unit of output power developed. These two approaches can also be used for assessing inverters.

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