Direct-on-line-start permanent-magnet-assisted synchronous reluctance motors with ferrite magnets for driving constant loads

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ABSTRACT

For driving constant loads in industry, the use of direct-on-line-start permanent-magnet-assisted synchronous reluctance motors with ferrite magnets (DOL-Start-PMa-SynRM) is proposed. The bibliographic search demonstrated that this new motor has greater efficiency than one similar induction motor (IM). It was evidenced that the main element that is required for direct starting is to insert a squirrel cage into the rotor of a PMa-SynRM, which does not produce negative operational effects in a steady state. An economic evaluation was carried out in a sugar mill company, applying the differential net present value (NPV) method, and a sensitivity analysis, considering the four factors that present the most variation. It was demonstrated, by means of a Pareto diagram standardized for the NPV that the most significant factors are fuel factor, lifespan and the multiplication of both. With response surfaces that are obtained with a multilevel factorial experiment, it was determined that, by varying the factors in the ranges considered, the NPV always remains positive and higher than 2200 USD. This is mainly due to the notable difference between the efficiency of the DOL-Start-PMa-SynRM and that of the IM. Consequently, is proved that an investment in the DOL-Start-PMa-SynRM may be feasible.

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1. INTRODUCTION

Among the total energy demand in the industries, motors consume nearly 70%. Due to the great energy consumption that electric motors have in the industry, not only in conditions of adequate parameters of energy quality, but also in the case where there are quality problems, every day there is more concern to increase the efficiency of motors [1-4]. At present, great attention is being given to the development of synchronous motors without windings in the rotor, replacing the induction motors (IM). The improvement in efficiency is achieved, mainly, because there are no windings in the rotor, therefore the losses in it are almost eliminated, saving approximately 20-35% of the total losses in the IM.

Up to now, synchronous permanent magnet motor (PM-SynM), synchronous reluctance motor (SynRM) and synchronous reluctance motors assisted by permanent magnet (PMa-SynRM) (this last one with different types of magnets) have being developed [5-7]. None of these motors has starting torque and its use is appropriate to drive centrifugal pumps and fans that work at variable speed to control flow and for which variable frequency drives (VFD) are used. The VFD also allow starting these machines [8].

In the case of constant loads, with the aim of not using VFD or soft starts that are expensive equipments, variants such as the direct start to the line with a synchronous reluctance motor (DOL SynRM) [6], or with direct start to the line using a modified PM-assisted reluctance synchronous motor (DOL Start PMa-SynRM) [9-10], are possible solutions. This paper presents, firstly, a summary of the constructive and operational characteristics of a PMa-SynRM, with different types of PM; and afterwards, those characteristics of the DOL Start PMa-SynRM. The advantages and disadvantages of each motor are analyzed and compared among them, and with an IM. Through a case study in a sugar mill company, the economic advantages of using a DOL Start PMa-SynRM instead of an IM were demonstrated.

2. RESEARCH METHOD

2.1. Structure and principles of DOL Start PMa-SynRM

2.1.1. Permanent magnet-assisted synchronous reluctance motor

The DOL Start PMa-SynRM is conformed by a squirrel cage inserted into the rotor of a PMa-SynRM. The stator of the PMa-SynRM, is normally analogous to that of the IM, in order to save in the production process [11], however some variations can be found in order to improve some parameters, such as the case of the fractional-slot windings [12]. The rotor in these motors differ in the type of steel lamination as can be seen in Figure 1.

Figure 1. IM and PMa-SynRM with steel laminations placed [13], a) IM; b) PMa-SynRM

Figure 2 shows a lamination of two flux barriers per pole, for a four-pole motor, as well as the lamination and the general structure of a rotor with four barriers per pole, for the same number of poles. The bridge of electrical steel in the core of the rotor must be carefully designed, because it has impact in the magnetic rotor behavior and in the robustness of the rotor [14]. The reluctance moment occurs as the rotor d axis (less reluctance) is aligned with the axis of the rotating magnetic field of the stator and both rotate at synchronous speed.

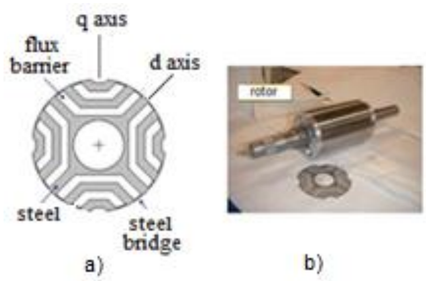

Figure 2. Rotor laminations of 4-pole motors [14],
a) Lamination of two barriers; b) Rotor with four barriers lamination

The developed torque, which is a reluctance torque, is given by (1):

$$M = \frac{3}{2}\frac{p}{2}\left\{\left(L_d - L_q\right)I_{ds}I_{qs}\right\}\ (\text{Nm}) \quad (1)$$

Where: p is the number of pole pairs; L_d and L_q are the inductances on the d and q axis, respectively in (H); and I_{ds} and I_{qs} are the currents on the d and q axis, respectively in (A).

2.1.2. Effect of permanent magnets in the PMa-SynRM

In order to improve the operational characteristics in terms of torque, power factor, efficiency and other parameters, an adequate amount of PM is added in the flow barriers of the rotor core. The magnets can be based on ferrite, or in rare earth: NdFeB (neodymium alloy, iron and boron), SmCo (samarium and cobalt), etc. Ferrite types offer less improvement in torque density and power factor, and have a higher risk of demagnetization, due to their low coercivity force (residual flux density less than 0.5 T), than those based on rare earths. Rare earths have residual flux densities of up to about 1.3 T and produce higher torque densities and power factor. However, its cost per kg increases significantly, by around 25 times in relation to ferrite types [11, 15].

The quantity, dimensions and placement of the PM, vary according to the geometry of the rotor, the operational characteristics desired and the cost of manufacture (which is one of the most important design restrictions) [16]. In Figure 3 a), a lamination, which exemplifies the placement of the ferrites and the position of the d and q axes, is shown [17]. In Figure 3 b) a rotor with the magnets placed can be observed [14].

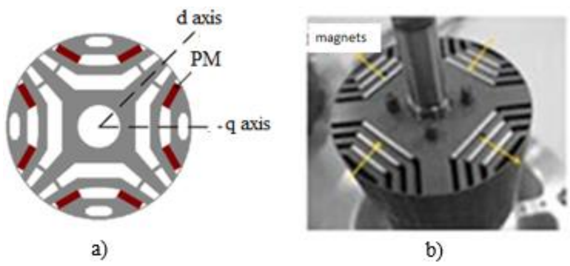

Figure 3. Positioning of the PM; a) Lamination showing a placement of the PM [14], b) Example of a rotor with PM placed [14]

The torque produced by the PM is determined from (1), adding the term λPMIds, according to (2):

$$M = \frac{3}{2}\frac{p}{2}\left\{\left(L_d - L_q\right)I_{ds}I_{qs} + \lambda_{PM}I_{ds}\right\} \text{ (Nm)} \quad (2)$$

Where: λ_{PM} is the flux concatenations caused by the PM (Wb-turn). Figure 4 shows the phasor diagram, where the emf created by the PM is given by (3).

$$E_{PM} = p\omega_S\lambda_{PM} \text{ (V)} \quad (3)$$

Where: ω_s is the synchronous speed of the rotating magnetic field of the stator (rad/s).

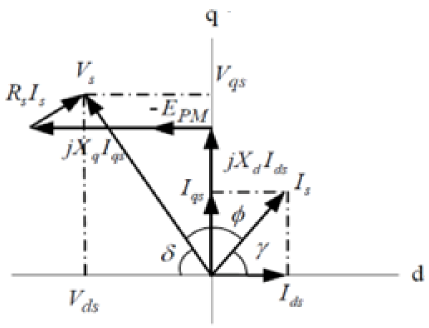

Figure 4. Phasor diagram of a PMa-SynRM [18]

When E_{PM} is present, depending on its value, Vs will move towards the first quadrant and, consequently, cosΦ will vary. For example, if E_{PM} increases (in the positive sense), Φ decreases and cosΦ increases. The torque density can be improved by approximately 45% using ferrite and by 100% using rare earth magnets [19].

Table 1 shows the comparative results between a PMa-SynRM with a ferrite magnet and another of the same type, but with a rare earth magnet (NdFe35H) [18]. The comparison is made for a constant current of Is = 6 A for the two motors. The increase of the power factor, the efficiency, the output power and torque with the use of NdFe35H PM can be observed. However, PMa-SynRM with ferrite has some benefits in relation to IM such as good torque and power density per unit volume, increase in the power factor, better efficiency and low cost of ferrite [18]. The principal disadvantages of this PM type are the higher cost in relation to IM, risk of demagnetization of ferrite magnets and relatively high parasite torques (although this torques can be reduced with special designs) [20]. Table 2 shows the comparison of rated parameters of an IM and a ferrite magnet PMa-SynRM.

Table 1. Comparison between two equal PMa-SinRM motors but with different PM

Values	PMa-SinRM	PMa-SinRM
PM	Ferrite	NdFe35H
Salience*	2.13	2.5
γ (º)	38	34
λ_{PM} (Wb)	0.05	0.16
I_s (A)	6.0	6.0
V_s (V)	61.04	69.84
cosΦ	0.64	0.91
M (N-m)	3.2	5.6
n (rpm)	1800	1800
Pout (W)	603.19	1055.58
Pin (W)	704.79	1144.04
η	0.86	0.92

(*Salience is the ratio L_d/L_q)

Table 2. Comparison between an IM and a PMa-SynRM

Parameters	Induction motor rated values	PMa-SynRM rated values
Output Power	37 kW	37 kW
Input Power	39.79 kW	37.41 kW
Voltage	460 V	460 V
Frequency	60 Hz	60 Hz
Power factor	0.84	0.89
Efficiency	93.0%	98.9%
Line current	59.5 A	52.82 A
Speed	1775 rpm	1800 rpm

As can been observed in table for a same output power, the input power is lower, so the efficiency of the PMa-SynRM is 5.9 percentage points higher than the IM, which is remarkable. It is also shown that the power factor is substantially higher than in the IM [2]. The cage of PMa-SynRM has the same effect as in a squirrel cage induction motor at start-up. When the DOL Start PMa-SynRM is in synchronism, the cage only acts as a damper. In steady state operation, the slip is zero, and there are no losses in the cage. With the aim of achieving direct line starting and obtaining a high efficiency, superior to that of an IM, several variants of PM-assisted reluctance motor have been developed for direct line start [10, 21-23]. All the solutions are achieved by adding a squirrel cage to a PMa-SynRM design and adjusting certain parameters [24].

The design of the cage should be done to obtain, as much salience as possible, in order that the PM can be properly installed and for having a safer operation during the starting period. In addition, a lower salience value can be compensated to some extent with the action of the PM. Figure 5 shows a design example of a lamination of a DOL Start PMa-SynRM. Certain parameters can be adjusted when designing the electric steel ribs and flux barriers such as the number of barriers, its shape, its average thickness, the distance between the barriers, as well as, the number, thickness and position of the bridges that retain the rotor structure [10]. In Figure 6 a) and b) different geometrical methods are shown to reduce the risk of irreversible demagnetization of ferrite PM, which is a significant risk of using them [10]. In addition, the different inertia torques of the system can have an influence on the irreversible demagnetization during the starting period, which also has to be taken into account in the rotor design.

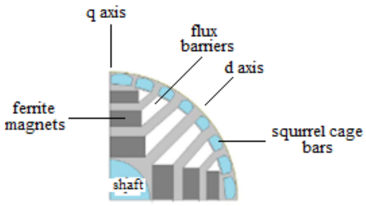

Figure 5. Lamination design of a DOL Start PMa-SynRM [10]

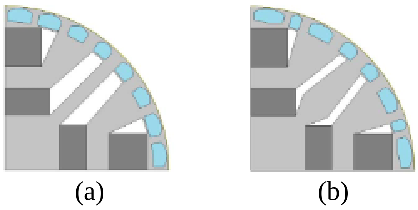

Figure 6. Different geometries of rotors to reduce the risk of demagnetization [10], a) Two-pole rotor with original barriers; b) Rotor with reduced flow barriers

3. RESULTS AND ANALYSIS

3.1. Operational characteristics of a DOL Start PMa-SynRM

Table 3 shows the rated values of a DOL Start PMa-SynRM and an IM, both of 37 kW, 4 poles, 60 Hz. The efficiency class of the two motors is IE 4 (Super Premium Efficiency). Both are total enclosed fan cooled (TEFC), Class F insulation and 1.15 service factor. The stator of the DOL Start PMa-SynRM is identical to that of the IM.

Table 3. Rated values of an IM and a DOL Start PMa- SynRM of 37 kW, IE 4 TEFC

Parameters	Induction motor rated values	PMa-SynRM rated values
Output Power	37 kW	37 kW
Input Power	39.15 kW	37.6 kW
Voltage	460 V	460 V
Frequency	60 Hz	60 Hz
Power factor	0.86	0.885
Efficiency	94.5%	98.4%
Line current	57 A	53.33 A
Speed	1775 rpm	1800 rpm

3.2. Economic analysis: case study

To analyze the economic advantages and other aspects of the DOL Start PMa-SynRM, an economic analysis was carried out, using data from a residual pump in the residuals station of “Ciudad Caracas” Sugar Mill in Cienfuegos, Cuba. The analysis was carried out using the differential net present value (NPV) discount method. This variant of the NPV allows eliminating equal (or almost equal) costs, for instance, installation costs, maintenance costs, and the cost of the stator (which in this case will be the same), etc. The study was done considering that, the motor works under the following conditions:

- Average load factor: 0.85
- Annual operating hours: 8040

The M1D electricity tariff (medium voltage tariff for 34.5 kV services, next to 110 and 220 kV substations) is applied to the company object of study, according to Resolution 28-2011 of the Ministry of Finance and Prices of Cuba [25]. The rates according to this resolution include a so-called K factor (fuel factor), whose value reflects the proportion in which the weighted average of the prices of all fuels used in electricity generation varies, and which is applied to the cost of energy consumption. For this study, K (3.4), Cost of IM IE 4 TEFC (3685 USD), Cost of the DOL Start PMa-SynRM IE 4 TEFC (4904 USD), Cost difference (1219 USD), Interest rate (35%), Discount rate (15%) and Lifespan (10 years). Since it was necessary to evaluate the effect of the economic uncertainties, a multifactorial sensitivity analysis was done, as it is shown below. Under these conditions, the differential NPV is 3301.56 USD.

3.3. Sensitivity analysis

For determining the influence of the uncertainty of some economic factors in the investment feasibility, a sensitivity analysis was carried on. According to this, an experimental design was made, considering the values obtained from the discounted flow economic analysis. This allows the simultaneous assesment of the influence of several factors on the response (NPV). The four experimental factors used were:

- Cost of the investment
- K factor
- Interest rate
- Lifespan

The maximum and minimum values of the analyzed data range are shown in Table 4.

Table 4. Experimental factors maximum and minimum values

Experimental factor	Minimum	Maximum
Cost of the investment	4400 USD	5400 USD
K factor	3	6
Interest rate	8%	17%
Lifespan	6 years	10 years

A multilevel factorial design consisting of 81 single block runs with a completely random order was designed. In the standardized Pareto diagram of Figure 7, it can be seen, in descending order of importance, the effect of the factors. It can be noticed that the K factor, the lifespan and the product of both are significant. This corresponds to the fact that, in the case of the first, it directly affects the price of energy and, therefore, the income obtained by the savings achieved; and the second has a direct effect on depreciation and accumulated discounted cash flow. In both cases, an increase in these factors leads to an increase in the NPV. The statistical significance of the factors is proven in the analysis of variance shown in Table 5.

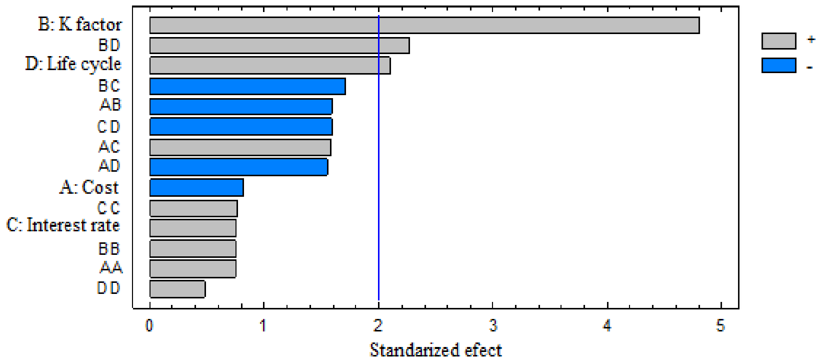

Figure 7. Standardized Pareto diagram for NPV showing the significance of the effects

Table 5. Analysis of variance for NPV

Source	Sum of squares	Gl	Medium Square	Ratio-F	Value-P
A: Cost	1.42101E6	1	1.42101E6	0.66	0.4189
B: K factor	4.9516E7	1	4.9516E7	23.05	0.0000
C: Interest rate	1.22124E6	1	1.22124E6	0.57	0.4535
D: Lifespan	9.49247E6	1	9.49247E6	4.42	0.0393
AA	1.20987E6	1	1.20987E6	0.56	0.4556
AB	5.44445E6	1	5.44445E6	2.53	0.1161
AC	5.39604E6	1	5.39604E6	2.51	0.1177
AD	5.14624E6	1	5.14624E6	2.40	0.1264
BB	1.20988E6	1	1.20988E6	0.56	0.4556
BC	6.22235E6	1	6.22235E6	2.90	0.0934
BD	1.11391E7	1	1.11391E7	5.19	0.0260
CC	1.26411E6	1	1.26411E6	0.59	0.4457
CD	5.44444E6	1	5.44444E6	2.53	0.1161
DD	490284.	1	490284.	0.23	0.6344
Total error	1.41753E8	66	2.14777E6		
Total (corr.)	2.4637E8	80			

R-square = 42.4635 percent.
R-squared (adjusted by Gl) = 30.2588 percent.
Standard error of est. = 1465.53.
Average absolute error = 602.96.
Statistical Durbin-Watson = 2.04388 (P = 0.5886).
Residual autocorrelation of Lag 1 = -0.0219967

As shown in table, the K factor, the lifespan and the product of both have a P-value less than 0.05, indicating with a confidence level of 95.0%, that there is a significant correlation between the variables. The response surfaces obtained by varying the different factors are shown in Figures 8-13. In Figures 8-13 can be observed that by varying the factors in the considered intervals, the NPV always remains positive and higher than 2200 USD. This is mainly due to the significant difference in efficiency between the DOL Start PMa-Syn RM and the IM, in any case. For an initial maximum differential cost of 1715 USD, which occurs when the initial cost of the DOL Start PMa-Syn RM is 5400 a shown in Table 4, with a differential NPV of no less than 2200 USD, it is evident that with whatever may be the values (within the indicated intervals) of the 4 factors considered, the investment is feasible.

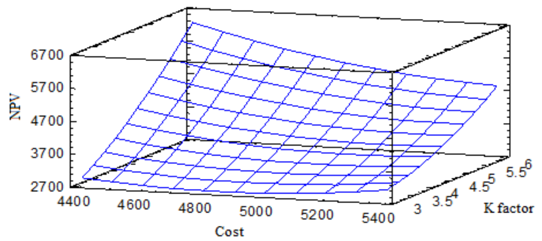

Figure 8. Estimated response surface for an interest rate of 15% and a lifespan of 10 years

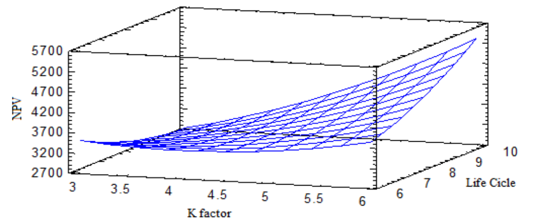

Figure 9. Estimated response surface for an interest rate of 15% and an initial cost of the proposed motor of 4904 USD

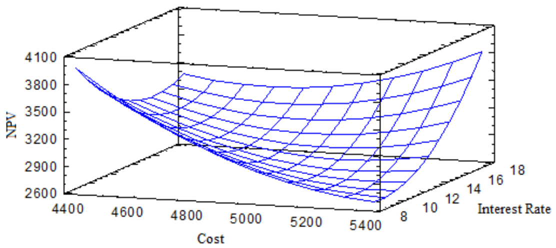

Figure 10. Estimated response surface for a K factor of 3.4 and a lifespan of 10 years

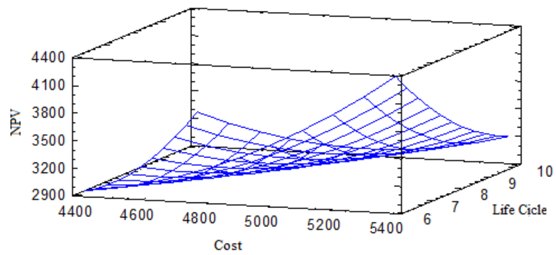

Figure 11. Estimated response surface for a K factor of 3.4 and an interest rate of 15%

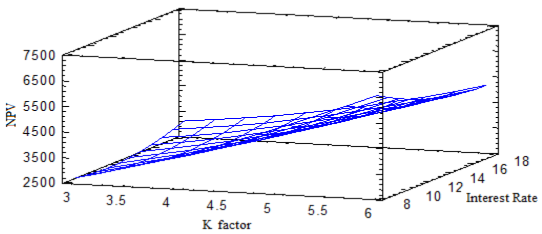

Figure 12. Estimated response surface for a proposed initial motor cost of 4904 USD and a live cycle of 10 years

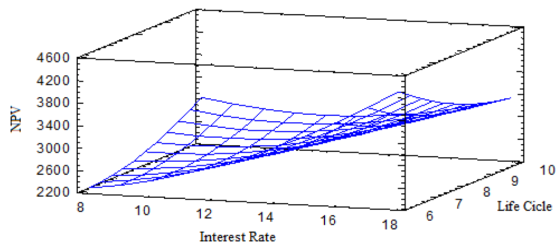

Figure 13. Estimated response surface for an initial motor cost of 4904 USD and a K factor of 3.4

4. CONCLUSIONS

A bibliographic search was carried out on constructive, operational and economic characteristics of direct-on-line-start permanent-magnet-assisted synchronous reluctance motors (DOL Start PMa-SynRM), with the purpose of studying the advantages and disadvantages of its use to drive constant loads, instead of the induction motor (IM). It was shown that with certain necessary constructive modifications with respect to the PMa-SynRM with ferrite, magnets (used with variable frequency drives to start and operate with variable speed loads), the DOL Start PMa-SynRM is considerably more efficient than the IM and does not present disadvantages of operational or economic importance. It was evidenced that the main modification, which is the insertion in the rotor of a squirrel cage for the start, does not produce a reduction in the efficiency and in other operational values of importance, since the cage does not act in a steady state (s = 0). Other modifications, such as the structure of the rotor (salience, flow barriers, shape and placement of magnets, etc.) do not introduce negative operational effects that could be significant.

An evaluation was performed with the use of a discount method: the differential NPV; and a sensitivity analysis using a multilevel factorial experiment design. The study was applied to a residual pump in the residuals station of a sugar mill, in which the comparative study was conducted. Four experimental economic factors which present the fundamental variation: initial cost of investment, fuel factor K (which influences the cost of energy), interest rate and lifespan, were considered. For each of them, a maximum and a minimum value were established and the mathematical relationship between the NPV and the four influencing factors was found. It was demonstrated, using a standardized Pareto diagram for the NPV, that the most significant factors are the K factor (in the very first place), the lifespan and the product of both. In the case of the first, it directly affects the price of energy and, therefore, the income obtained by the savings achieved. An increase of these factors increases the NPV. With response surfaces that are obtained with the multilevel factorial experiment by varying the factors in the ranges considered, the NPV always remains positive and higher than 2200 USD. This is mainly due to the notable difference between the efficiency of the DOL Start PMa-SynRM and the efficiency of the IM. Consequently, the investment is feasible.

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