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Full Length Research Paper

Retrofitting industrial in electrical motor type: A matter of energy efficiency and reduction of maintenance

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This report aims to identify, in terms of economic and technical aspects, an electric motor whose characteristics meet a proposed replacement of a direct current (DC) motor in an aluminum extrusion plant, whose preventive maintenance has in the last years, the problem of technical and operational orders. Data relating to the preventive maintenance of motors in operation were used to estimate the performance of an induction motor in combination with an inverter for speed and torque control. The advantages were determined, and the investment costs can be reduced by maintenance. It was observed that the market offers an innovative solution by the use of a permanent magnet synchronous motor (PMSM), which is a brushless, alternating current (AC) motor, with reduced dimensions, and offers the same power as a three-phase induction motor (TPIM). Joule losses in the rotor are negligible because the rotor is fit internally with rare-earth-doped neodymium-iron-boron permanent magnets, which also minimizes motor temperature, thereby increasing its useful life. Estimates determined that the gains derived from preventive maintenance would be even greater than those expected for the induction motor. Simulations conducted in MATLAB showed that, in terms of energy efficiency, the PMSM is presently the most appropriate replacement for the DC motor.

Key words: Brushless, permanent magnets, preventive maintenance, retrofitting, electric motor.

INTRODUCTION

The large increase observed recently in the consumption of aluminum is an indication of its importance in modern industry. It is the most important non-ferrous metal, and is among the most highly consumed annually.

While the general economy grows worldwide at an average rate of 4.5% per year, aluminum consumption worldwide increases at an average annual rate of 6.3%, according to the Department of Industry, Base Area Input, Basic National Bank Development, Economic and Social (Bndes, 2011).

Given this scenario, aluminum extrusion companies should seek to improve their methods and processes to meet this rising demand. Improvement requires companies to minimize losses by reducing equipment downtime owing to machine failure, and in particular, downtime for preventive maintenance, which in the case of direct current (DC) motors is expensive and requires prolonged machine downtime. Furthermore, to increase

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Figure 1. Cutaway description of a DC motor (INO, 2010).

their productive capacity, aluminum companies must modernize their equipment, seek technological upgrades of their facilities, increase energy efficiency, improve reliability, and reduce electricity and preventive maintenance costs. The development of power electronics and microelectronics using microprocessors and microcontrollers has contributed to the application of alternating current (AC) motors, which allow the implementation of complex functions with a shorter and shorter response time. A good example of such an application is a permanent magnet synchronous motor (PMSM), which achieves torque performance and speed commensurate with those of a DC motor. The new efficiency standards impose high values for efficiency and power factor even for low power electric drives (Florin et al., 2014).

Taking the aforementioned points into account, this paper presents an investigation about of technical and economic feasibility and the general approach of a proposed retrofit by replacing DC motors used in the aluminum extrusion industry with PMSMs. The question to be addressed by this study is whether a PMSM can offer the same speed performance and torque as those of a DC motor, while reducing machine downtime and enhancing overall efficiency. Economic stresses and competitive markets have resulted in many industries turning towards maximizing cost-savings and developing more efficient operations. In terms of operating machines, the objectives have been to reduce maintenance costs, increase useful life of equipment and prevent catastrophic failures (Mahajan et al., 2013).

This paper examine the motors used in the aluminum extrusion industry to power equipment known as a “puller,” which is an auxiliary piece of equipment that grabs and pulls the profile material from the initial extrusion, directing and accompanying it during the process. Use of this equipment avoids the complications associated with table profile cooling, as well as providing better quality and greater agility to the profile extrusion process. The proposed retrofit process seeks, reduce maintenance costs, and increase system reliability. What happens a lot is also performing a modification to raise the level of performance and quality of the machine (Azevedo, 2007).

Maintaining the operational condition of industrial equipment, preventing industrial risks and ensuring the safety of persons and assets are just some of the principal challenges for production firms. Maintenance has been recognized as a fundamental function in the company and is transferred from the cost center to the profit center, which has led to massive development of maintenance support systems (Morello et al., 2014).

TECHNICAL DESCRIPTION

Historically, DC motors have been used to control machines for which speed and torque control are necessary. The ease of control allows for the precise adjustment of speed and torque throughout the operating range; however, the operation entails the use of many moving parts such as switches, brushes, and brush holders and the need for forced ventilation. High maintenance costs and limited applications in hazardous areas are the main limitations associated with DC motors. Figure 1 shows a DC motor cutaway highlighting the moving parts, brushes, brush holders, commutator, tachogenerator, and armature winding.

The disadvantages of the DC motor and the evolution of power electronics have led the three-phase induction motor (TPIM) be the most common engine used in drives with speed control, and it is a more attractive option because of its lower maintenance costs (Grandinetti, 2013). Figure 2 presents a cutaway description of the

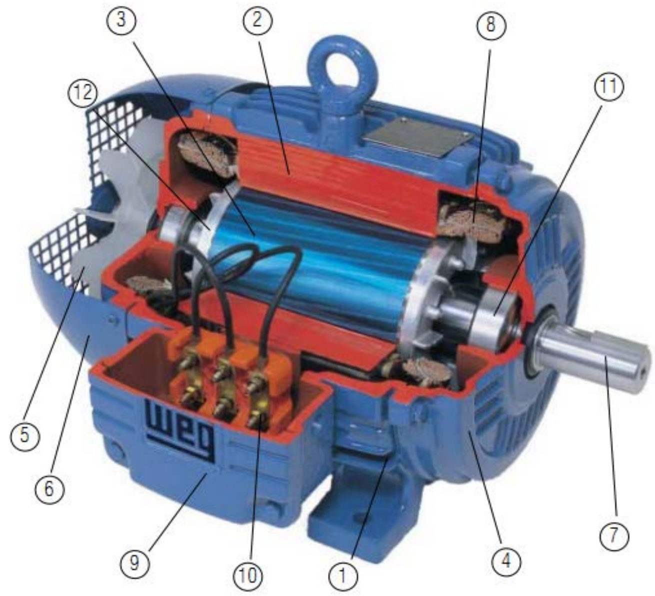

Figure 2. Cutaway description of the TPIM consisting of the following components: stator frame (1), laminated core (2), laminated magnetic core (3), end shields (4), fan (5), fan cover (6), rotor shaft (7), three-phase winding (8), connection box (9), terminals (10), bearings (11), short-circuit rings (12) (WEG, 2009).

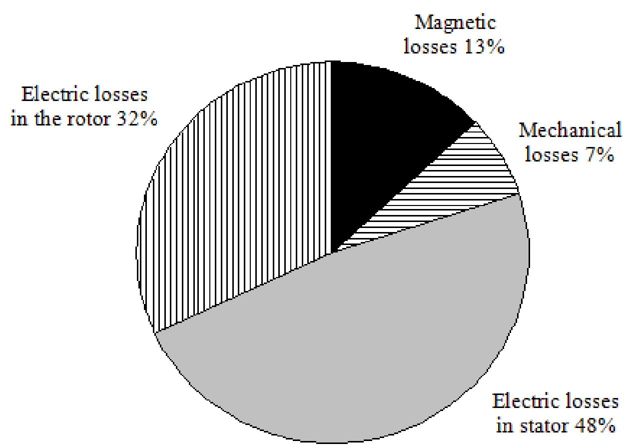

Figure 3. Losses in the TPIM (WEG, 2012).

TPIM consisting of the following described components and their functions. Stator: frame (1) is the supporting structure composed of a sturdy construction of cast iron, steel, or aluminum having high corrosion resistance and fins for heat dissipation; laminated core (2) silicon steel plates are heat treated to minimize eddy current losses; three-phase winding (8) consists of three sets of coils, one for each phase, forming a three-phase system. Rotor: shaft (7) transmits mechanical power; laminated magnetic core (3) plates have the same characteristics of the stator-laminated core plates.

Bars and rings: short-circuit rings (12) are single-piece injected aluminum. Other components of the TPIM are end shields (4), fan (5), fan cover, (6), connection box (9), terminals (10), and bearings (11) (WEG, 2009).

For applications involving fixed speeds, this type of motor is one of the best options. However, for applications in which it is necessary to control the speed and torque, this engine has some disadvantages, which translate into electrical losses such as, for example, the Joule effect on the rotor, which makes speed control difficult at slow speeds due to the increased operation temperature. Figure 3 depicts the losses of the TPIM.

In view of the background of the motors traditionally

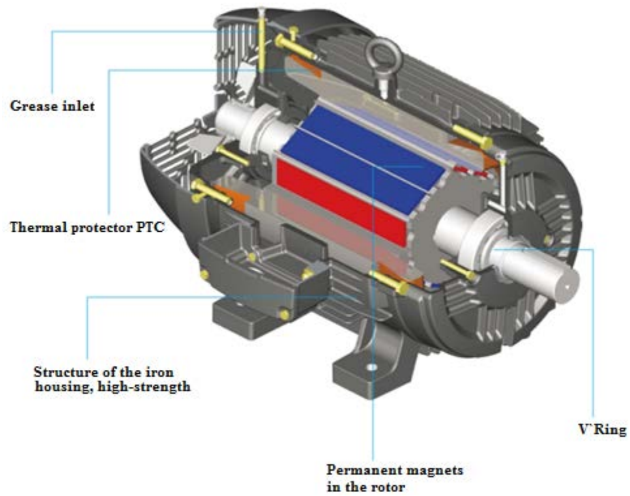

Figure 1. Cutaway of WEG's WMagnet with the following main components: grease inlet, thermal protector PTC, cast iron housing, permanent magnets, and V'ring (WEG, 2011a).

used in industry, this study sought other options highlighting the most advantageous use of motors with permanent rotor magnets.

THE PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM)

The PMSM is composed of a stator with three sets of coils arranged at 120°, and its rotor consists of permanent magnets. PMSMs are fed by an inverter voltage with frequency control. This allows for variable speed at constant torque, low vibration and noise, and high performance and reliability. These characteristics are fundamental for compressors, elevators, and conveyors. They are also attractive for applications in which there is limited space and a need to eliminate gearboxes, since it has reduced size and volume and can perform over a wide range of speeds. This motor suffers no Joule (RI^2) losses in the rotor, and therefore does not require ventilation, and heat dissipation is accomplished by natural convection. Its housing is necessarily shielded to protect the internal magnets against impurities (WEG, 2011b).

Figure 4 shows a cutaway description of the commercial motor manufactured by WEG, the WMagnet. The main components shown in the figure are as follows: grease inlet: device that allows for lubrication without stopping the engine, and in normal operation, the bearing lifetime is 100,000 h (SKF, 2007; SIEMENS, 2010); thermal protector PTC: responsible for feedback, the temperature of the stator winding to the control electronics; cast iron housing: supporting structure set with fins for heat dissipation; it is also composed of core silicon steel plates heat treated to minimize iron losses, three-phase winding has three equal sets of coils 120° out of phase, forming a three-phase system; permanent magnets are composed of neodymium-iron-boron internally installed in pairs on the rotor, which reduces power losses by the Joule effect, and thus ensures a lower motor temperature; the V'ring is responsible for sealing the internal parts of the engine to prevent the penetration of impurities into the motor and to mainly protect the magnet. Most permanent magnet materials lack ductility and are inherently brittle. Such materials should not be utilized as structural components in a circuit (MMPA, 2000).

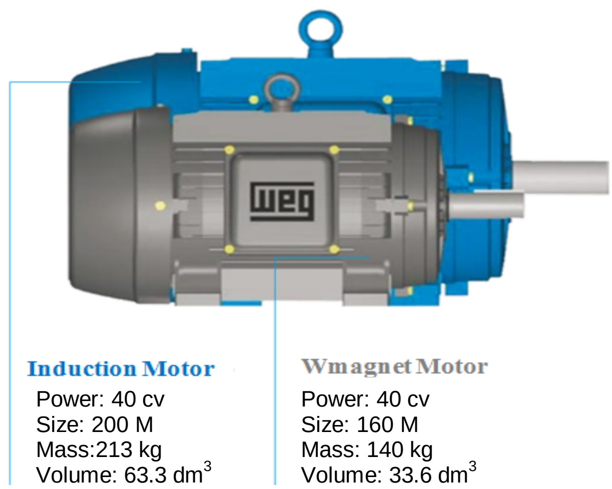

Figure 5. Comparison between TPIM and WEG's WMagnet PMSM (WEG, 2011a).

As a result, the volume and weight of WEG's WMagnet motor are lower than those of a TPIM of the same power, and the lifetime is significantly increased. Figure 5 shows a comparison between two motors of the same power,

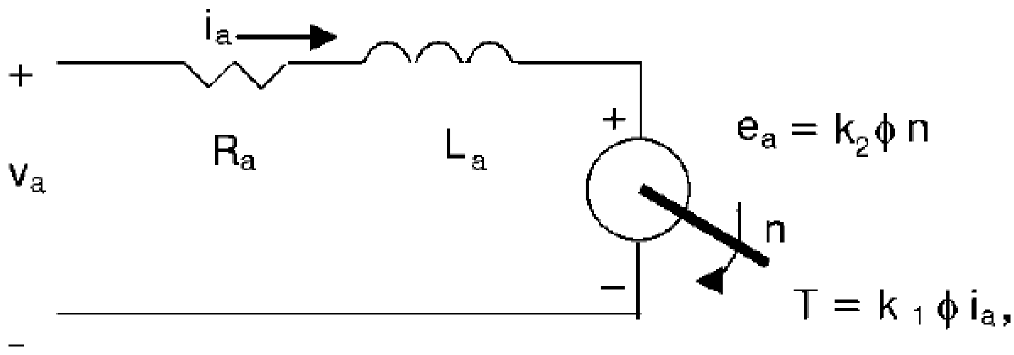

Figure 6. Equivalent circuit of the DC motor.

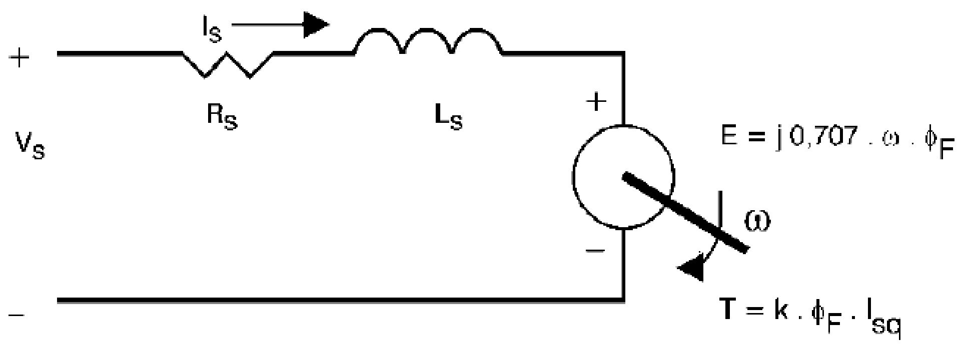

Figure 7. Equivalent circuit of a PMSM in stationary regime.

showing that the casing size, volume, and overall mass of WEG's are lower for WEG's WMagnet PMSM as compared with a typical TPIM.

ELECTRICAL CHARACTERISTICS

A comparison between Figures 6 and 7 show the similarity between electric synchronous of permanent magnet motors and DC motors. The PMSM however, present mechanical characteristics advantage over the DC motor, including: low maintenance (brushless), low inertia, feedback speed and greater relative power/volume, lower current and therefore temperature. Although the PMSM has similarity with DC motors, this has some complexity, including the condition of the field weakening as in DC and PMSM.

The torque of the DC machines is given by the relationship set forth in Figure 6 as

$$e_a = k_2 \phi n$$

$$T = k_1 \phi i_a,$$

Where T = torque; k_1 = a constant which depends on the characteristics construction of the machine; ϕ = magnetic flux; i_a = armature current.

Keeping ϕ constant, the torque can be directly modified by the current,

Where: V_a = armature voltage; R_a = armature resistance; L_a = inductance of armor;

And the back EMF is given by e_a,

Where: n = is the speed on the machine shaft; k_2 = constant dependent on the characteristics construction of the machine.

The decrease in the magnetic flux ϕ, maintaining the conditions of rated voltage and current, allows engine operating at higher rate than the rated speed, but with reduced torque. This can be concluded from observation of equations of electrical torque and EMF, with a reduction for ϕ to e_a and i_a constants. This mode operation is known as "weakening field "or as a region of" power available constant "(e_a and i_a= constant).

Synchronous motors with rare earth permanent magnets have higher power density than comparable DC motors because the limiting effects of the mechanical commutator are absent; the power density exceeds also that of induction motors because there are no losses by torque producing rotor currents that need to be removed by cooling (Leonhard, 2001).

The currents i_d and i_q of the stator current in synchronously rotating reference frame are analogous to the field current I_s and to the armature current I_a of the

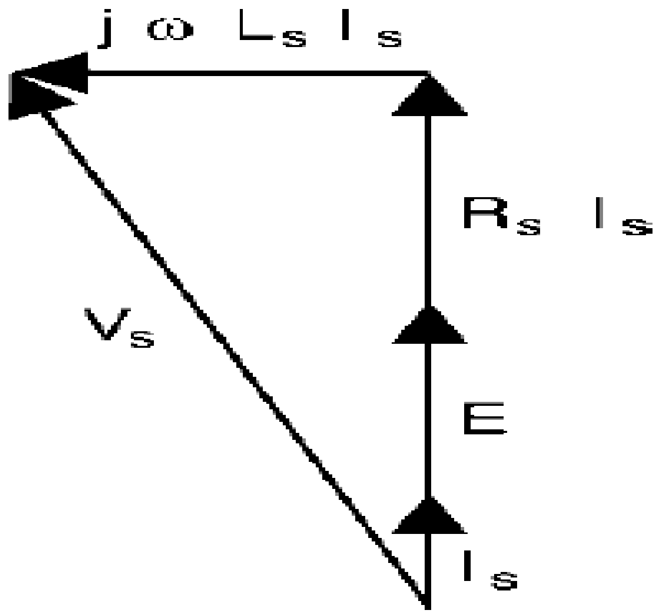

Figure 8. Phasor diagram on the condition of maximum torque.

DC machine (Sahoo and Ramulu, 2013).

The torque of the PMSM is presented in Figure 7 as:

$E = j\,0{,}707 \,.\, \omega \,.\, \phi_F$

$T = k \,.\, \phi_F \,.\, I_{sq}$

Where T = electrical torque; k = a constant which depends on the characteristics construction;
ϕ = magnetic flux; I_{sq} = is a current flows in fictitious coil positioned towards the rotor and in the orthogonal direction to the rotor. "s" refers to the stator and "q" quadrature axis.

It can be shown that the equivalent circuit of this motor, the steady-state condition is presented as follows:

Where V_s = phasor voltage terminal; I_s = phasor of the armature current, Is = Isd Isq + j; R_s = stator resistance; L_s = stator inductance; ω = angular frequency of the supply.

One of the difficulties is that the PMSM do not admits naturally the weakening condition field as occurs with a synchronous machine rotor winding machine or with a current continuous excitation Independent or even with one induction motor. The corresponding vector diagram is shown in Figure 8.

The field weakening correspond to a ϕF decrease, which cannot be directly performed, because the field given by a magnet permanent. This hypothetical decrease would result a loss torque, but starting from, allow an increase in rotational speed, for amplitude of V_s constant, as can be concluded from Equations 1 and 2.

$$T = k \,.\, \phi_F \,.\, i_{sq} \tag{1}$$

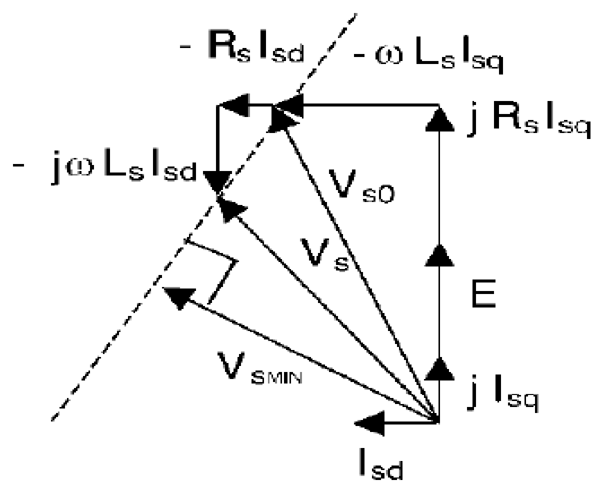

Figure 9. Phasor diagram in the presence of a negative component of I_{sd}.

$$E = j\,0{,}707 \,.\, \omega \,.\, \phi_F \tag{2}$$

The feature field weakening may be desirable in some applications where a rotation is necessary greater than the nominal torque request with reduced.

A similar effect to the field weakening PMSM, however, is obtained by imposing a negative component I_{sd}. The new diagram phasor corresponding to this situation is shown in Figure 9.

From the phasor diagram, we can see that this negative component of the current in the direction of the axis direct allows a decrease in the value of V_s. The place geometric end of the phasor is indicated V_s the dotted

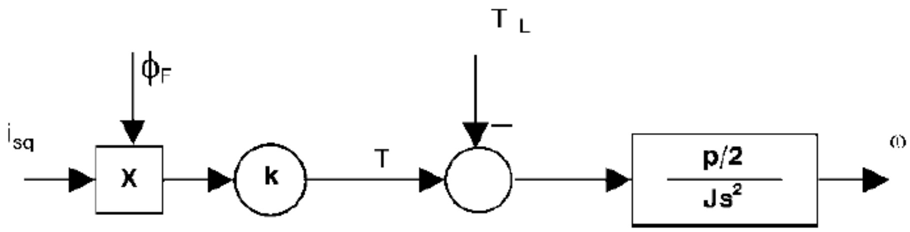

Figure 10. Block diagram of a permanent magnet synchronous motor.

Table 1. Information of the DC Motor and tachogenerator subject to retrofitting.

Information of the motor		**Information of the Tachogenerator**	
Model	MGL112M	Model	2R 60
Manufacturer	CEAR	Manufacturer	DEBU
Power	18,4 kW	Serial Number	6002068
U armature	400 V	Min. Tension	0.06 V
U field	220 V	n. Máx.	10000 min^{-1}
I armature	52 A	I. Máx.	0.25A
I field	2.3 A	IP	55
n nominal	2555 rpm	Direction	Reversible
M. de Inertia J	0.047 kgm^2	-	-
Reg. Service	S1	-	-
Torque	69 N.m	-	-

line in Figure 9. Minimum value occurs when V_s is perpendicular to this line. If | V_s | is kept constant, similar reasoning shows that a negative component I_{sd} leads to an increase of E and therefore the speed of rotation.

The torque given by Equation 1 is decreased because the presence of component I_{sd} implies a I_{sq} decrease in component so as to respect the maximum value of the total armature current | I_s |, given by:

$$|I_s| = \sqrt{I_{sd}^2 + I_{sq}^2} \quad (3)$$

This sequence, although not weak ϕF effectively corresponds to exactly one field weakening operation.

Anisotropic rotors is shown in Figure 4; the reactance of direct axis (ω, L_d) assumes higher values that the quadrature reactance (ω, L_q), like a machine with salient poles, allowing the field weakening with components I_{sd} minors.

The result of the low electrical modeling of PMSM is presented. The mechanical behavior of the motor is governed by Newton's equation:

$$T - T_L = J \,.\, (2/p) \,.\, (d^2\omega / dt^2) \quad (4)$$

Where TL = load torque; J = moment of inertia of the rotating parts; p = number of poles of the motor; ω = angular frequency of the power electric.

The equations worked in previous sections can be presented as a block diagram (Figure 10).

CHARACTERISTICS OF MAINTENANCE FOR MACHINE

Planned maintenance refers to periodic, often manufacturer specified, maintenance to check for signs of abnormalities. Condition Based Maintenance is typically performed when the need arises, when failure or a fault is imminent or when there is a noticeable decrease in performance (Mahajan, 2013). Nowadays, the global performance of the companies depends to a large extent on their performance in maintenance, but the increasing complexity and level of automation of the industrial equipment make it difficult for the users to operate, diagnose and maintain it efficiently. (Ruiz et al., 2014).

In search of a solution for the optimization of processes to meet the increasing market demand for aluminum, Exall Alumínio S.A., located in Pindamonhangaba - São Paulo - Brazil, decided to modernize their equipment, mainly because of high maintenance costs. Interventions to improve productivity and reliability of equipment are always needed, and it is a peaceful spot (Azevedo, 2007).

First, the puller had to be retrofit, which had been in continuous operation using a DC motor for over 15 years. Table 1 presents data from the motor nameplate and tachogenerator.

Table 2. Useful life of the lubricant for several bearings (WEG, 2012).

Bearings of the frame 90 up to 132 - open machines						
Useful life of the lubrification grease in hours						
Bearing	Rotation (rpm)					
	1.000	1.200	1.500	1.800	2.400	3.000
Horizontal axis						
6205-2 RS	20.000	20.000	20.000	20.000	20.000	17.000
6305-2 RS	20.000	20.000	20.000	20.000	20.000	17.000
6306-2 RS	20.000	20.000	20.000	20.000	20.000	15.000
6307-2 RS	20.000	20.000	20.000	20.000	18.000	13.500
6308-2 RS	20.000	20.000	20.000	20.000	16.000	12.000

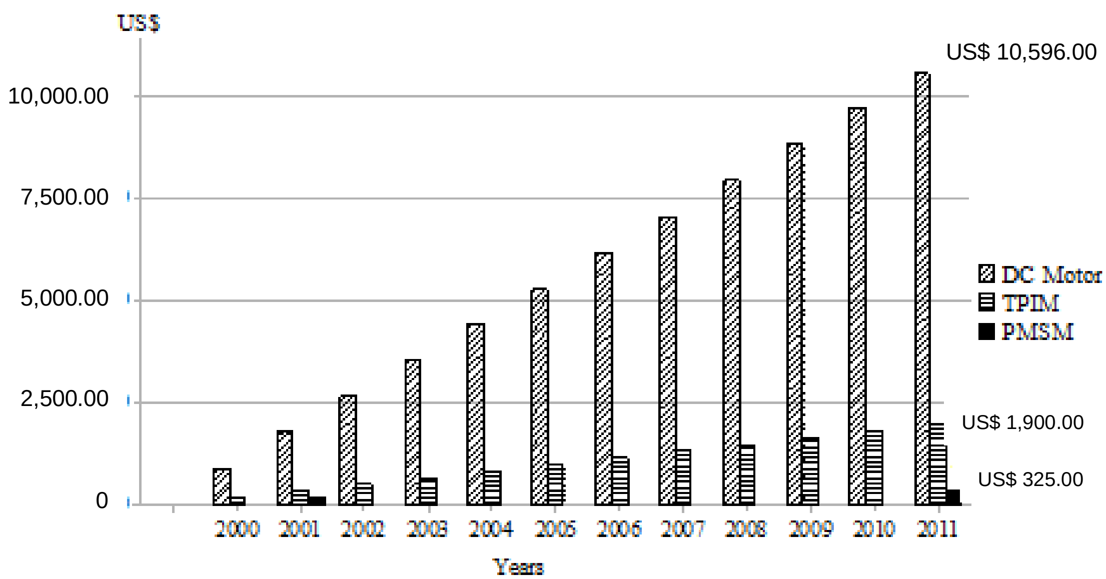

Figure 11. Accumulated costs of preventive maintenance for the DC motor, TPIM, and the PMSM (authors' design).

The manufacturer recommended replacing the bearings at the end of the useful life of the lubricant and setting the frequency of preventive maintenance to 12 months for an engine speed of 2555 rpm and bearings 6306 and 6308-ZZ-ZZ, as shown in Table 2. Since installation, the company always followed this schedule, and appropriate preventive maintenance was consistently performed on the DC motor. The cost of preventive maintenance for 2000 - 2011 is shown in Figure 6, with equivalent estimates for TPIM and PMSM.

The accumulated costs for the preventive maintenance of the DC motor during the period showed significant values. The maintenance of a TPIM is expected to be on the order of 18% of the amount spent on the preventive maintenance of the DC motor during the same period. On the other hand, the cost of maintenance of a PMSM is predicted to be on the order of 3% of the amount spent for the preventive maintenance of the DC motor during the same period measured. However, the PMSM also benefits from reduced heating, which increases the useful life of the lubricant, and permits the bearings to be replaced according to the manufacturer's recommendation of 95,000 h or 10 years of operation, the frequency range that defines preventive maintenance for PMSM. In addition, the grease nipple allows lubrication without stopping the motor, thus reducing downtime.

From the numbers presented in Figure 11, it appears that investing in new technology is an investment with a guaranteed return.

MEASUREMENTS AND SIMULATIONS

During analysis, it was found that the puller motor works in a low-speed high-torque region. Some measurements using an electrical equipment analyzer were subsequently conducted. The results generated the torque curve shown in Figure 12. It was observed that the critical point

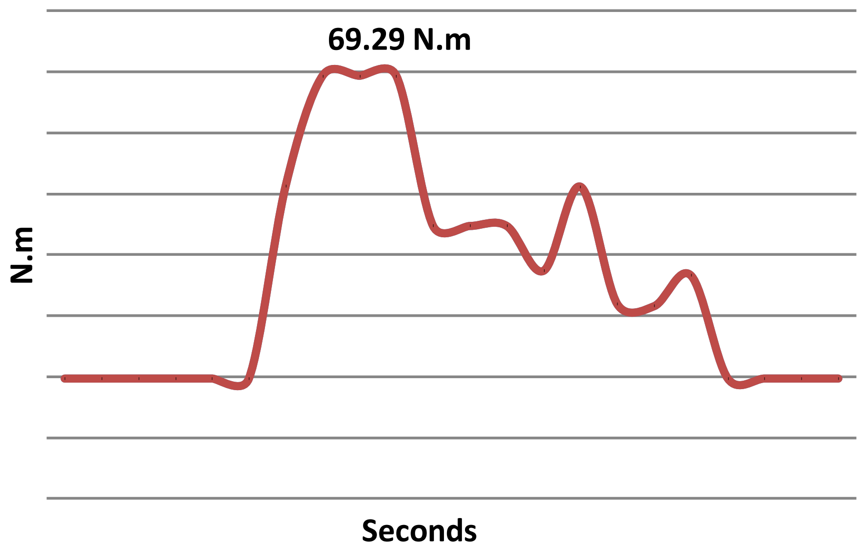

Figure 12. Torque of the DC motor over an operation cycle.

Table 3. Actual data collected.

T (N.m)	n (rpm)	t (s)
0	0	0
15	375	0.2
0	0	1
-15	-375	2
30	750	3
69	1725	4
0	0	5
-69	-1725	6
10	250	7
20	500	8

is the region of highest power and speed approaching the set point of the engine.

Before determining the best motor to replace the present DC motor, we decided to use the module and *Simulink* simulation software MATLAB (R2010a) to assistin the selection.

Simulations of the dc motor

The *Simulink* simulation environment was adjusted using the parameters collected in the field, actual data are machine cycle used in extrusion of aluminum profiles, as listed in Table 3, where *t* is the time in seconds, *T* is the torque in N·m, and *n* is the requested speed in rpm.

Figure 13 shows the circuit used for the simulation model of the DC motor. We attempted to fit simulations to the torque profiles collected in field trials and used some *Simulink* blocks for motor control aimed at determining and comparing the behavior of each of the motors tested.

For testing of the DC motor, we used a model of a three-phase, four-quadrant converter with torque proportional to speed, with closed-loop control for 25 Hp, independent power, armature voltage of 400 V, current armor of 52 A, rotation of 2555 rpm, field voltage of 220 V, and a field current of 2.3 A.

The converter is entirely built with standard *Simulink* blocks. Its output passes power control blocks before being applied to the DC motor block. The torque applied to the shaft of the machine is defined according to Table 3. As shown in Figure 14, simulation values of armature current, torque, and speed were calculated over 12 s. From the response of the DC motor, it is evident that efficient torque values are required by the system. One of the points of the simulation observed is the region where the torque is 20 N.m, where substantial torque is required at low speed, which, for the DC Motor, is not a problem because it has forced ventilation to ensure cooling. The values collected from DC motor simulations correspond well to the motor in actual operation.

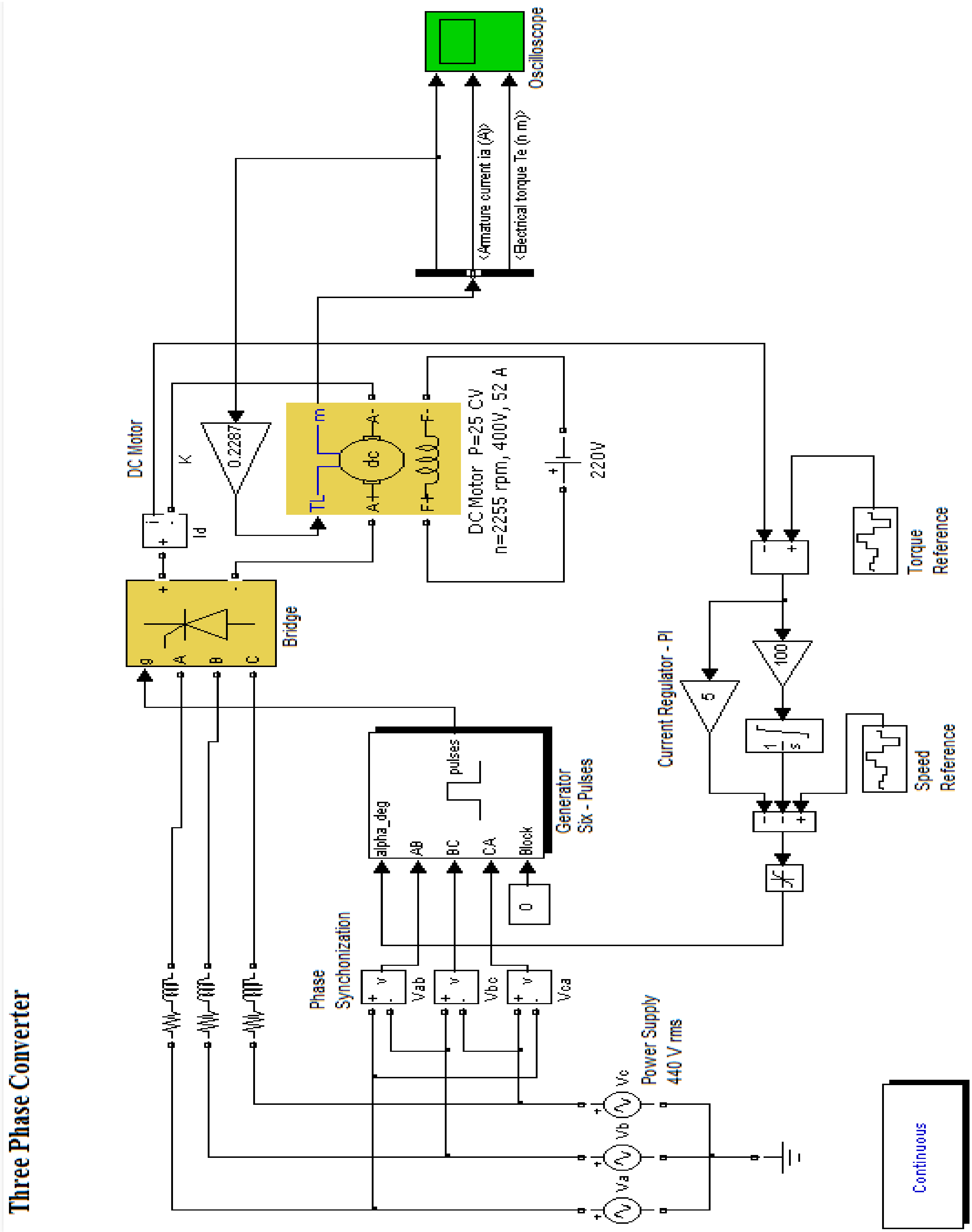

Figure 13. Three-phase four-quadrant converter model used in the simulations.

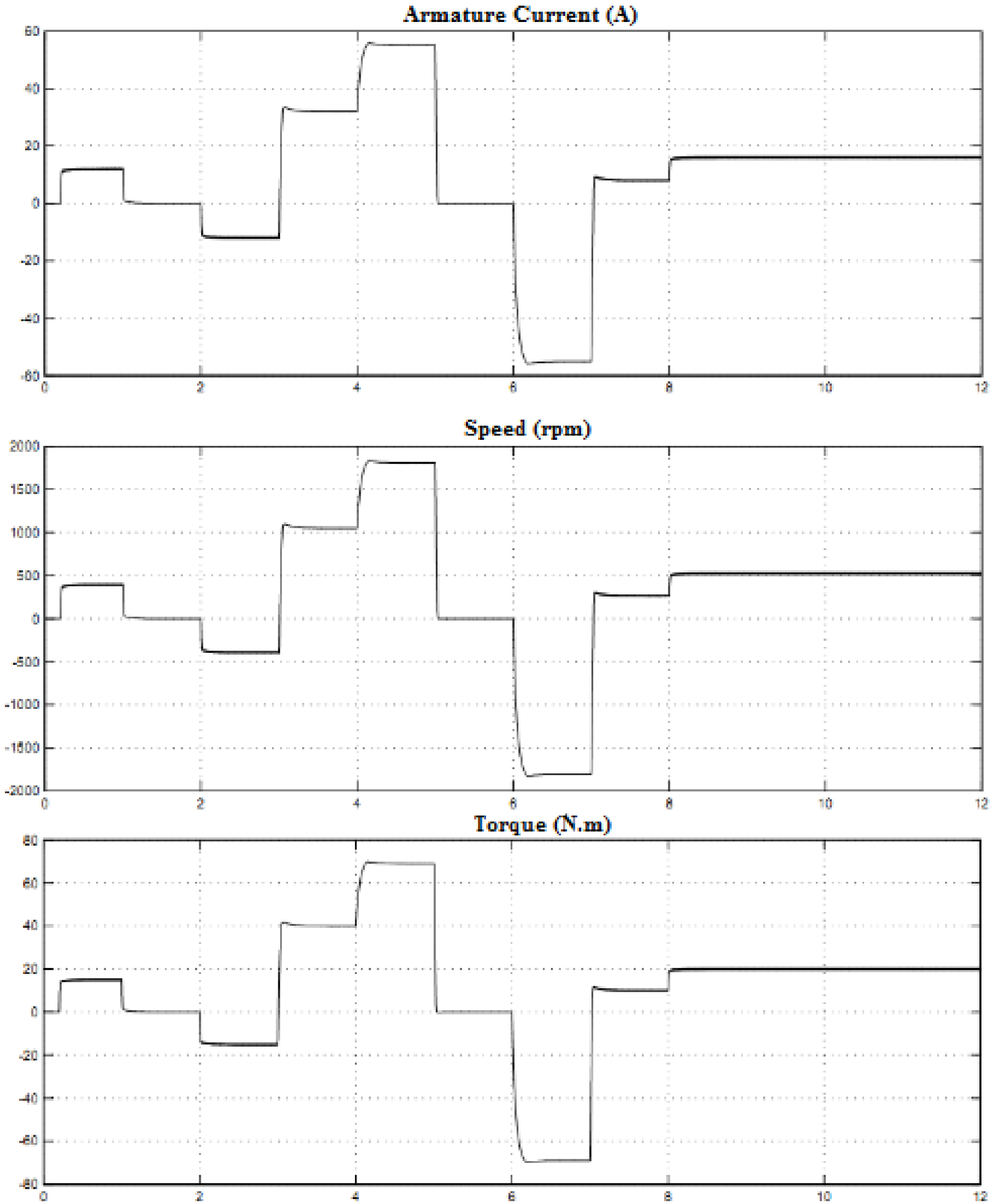

Figure 14. Values of armature current, speed, and torque collected from the simulations of the DC motor.

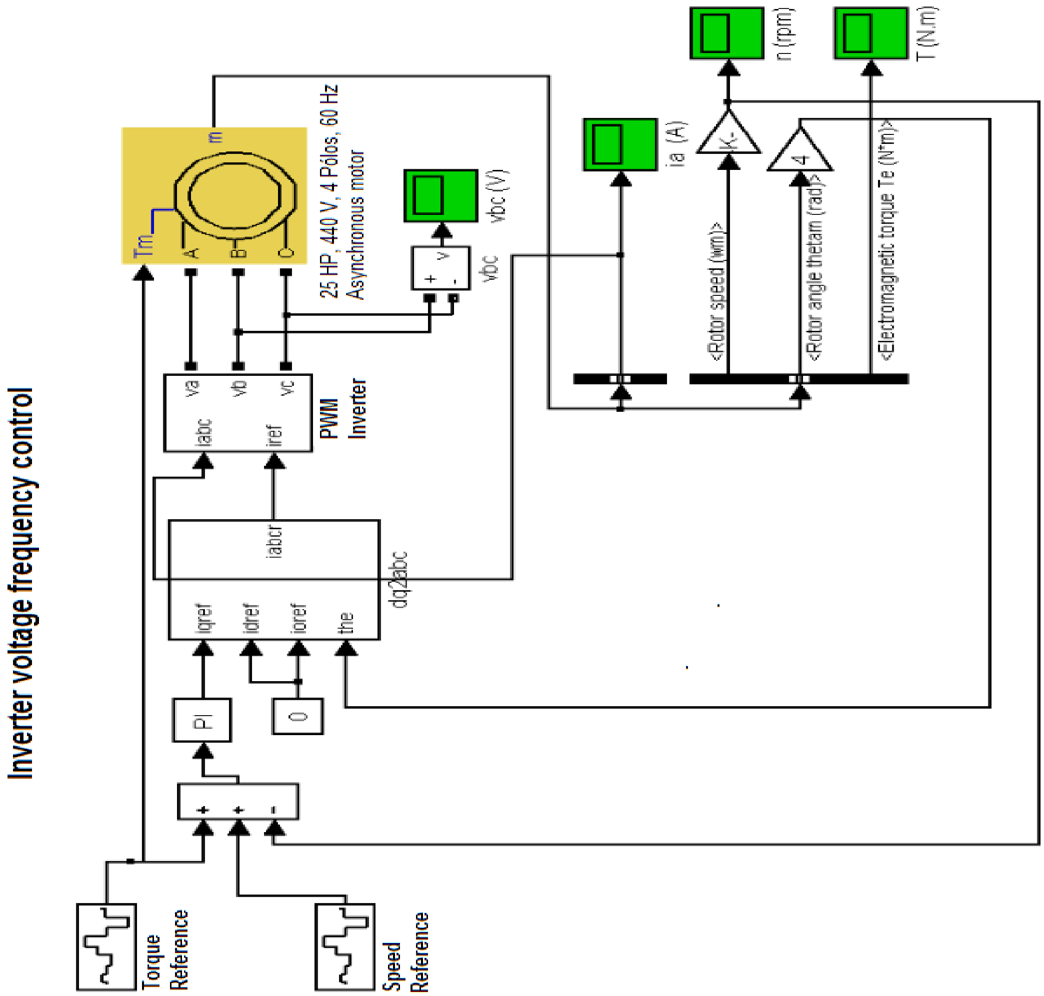

Figure 15. Inverter voltage with frequency control model used in the simulation of the TPIM.

Simulations of TPIM

Figure 15 shows the block diagram of the inverter model used in the simulation of the TPIM.

In order to ensure that the simulations were comparable, we used the same references and the same sampling period as shown in Table 3. The model of the inverter voltage with frequency control used in the simulation was built with standard *Simulink* blocks, whose motor parameters were as follows: power *25* CV, voltage 440 V, rated current of 32.3 A, and four poles. The model uses control feedback voltage and current, and torque is proportional to speed. As shown in Figure 16, the simulation values of stator current, torque, and speed were obtained over 12 s.

It can be observed that the TPIM response to speed values remained close to the values collected in the field. However, the rotor speed in the region of t > 9 s is low; the stator current reaches levels close to nominal values, and consequently causes a deficiency in ventilation, resulting in a temperature rise in the rotor and stator, which may even compromise motor insulation. A comparison of the characteristics of the DC motor with those of the TPIM indicates that the DC motor demonstrated faster response speed and torque. The speed of the TPIM was stable, but the torque was not reported with accuracy, suggesting that the rotor worked in a pulse. During the simulations sought to be the best parameter settings for TPIM who had the best representation of reality in the simulations.

Simulations of PMSM

Figure 17 illustrates the simulation model of the PMSM with closed loop control of voltage and current of a 25 HP motor for industrial applications, with a supply voltage of 380 V, rated current of 32.7 A, and a rotation of 1800 rpm. The PMSM inverter was entirely built with standard *Simulink* blocks, and the torque applied to the shaft of the

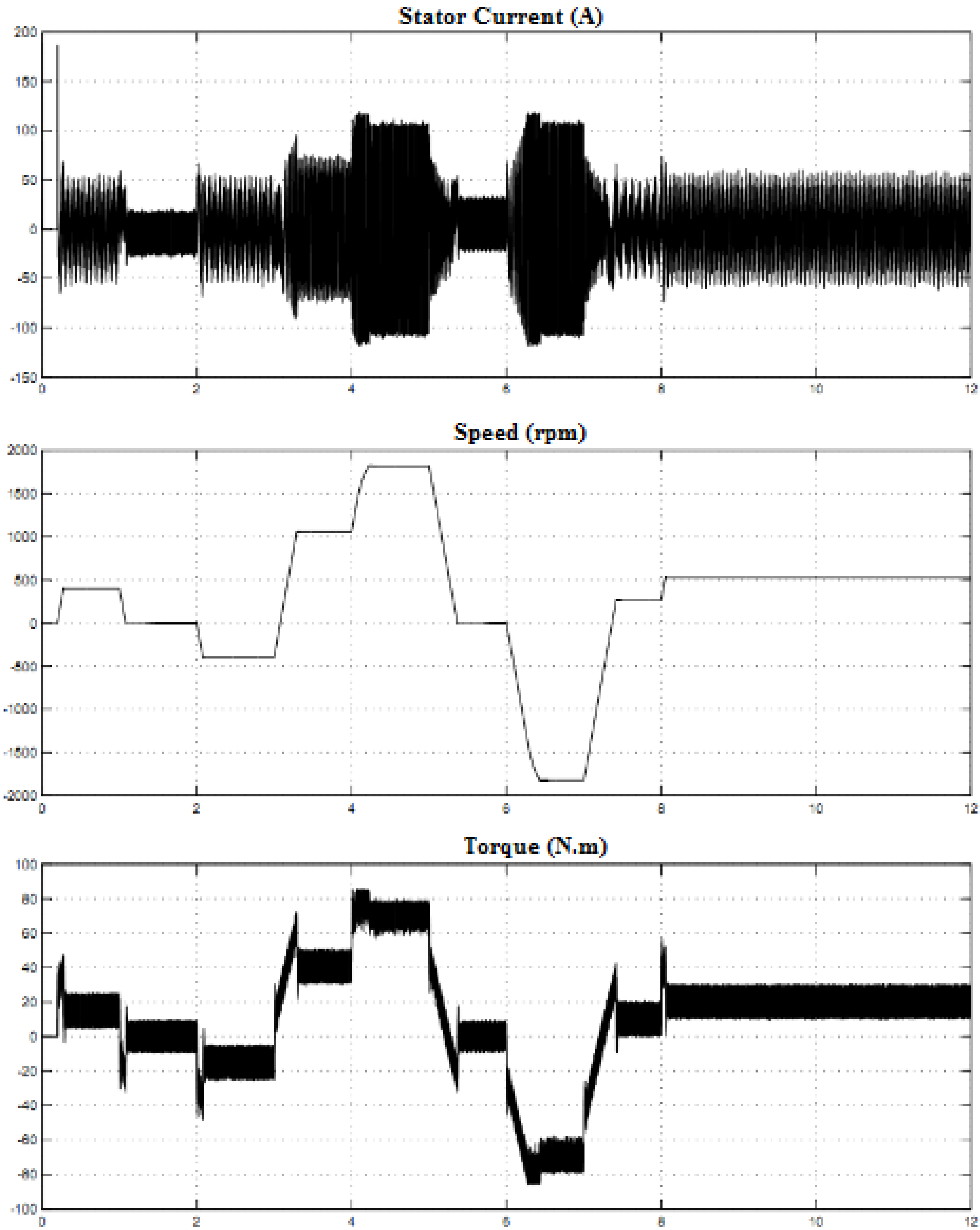

Figure 16. Values of stator current, speed, and torque collected from the simulations of the TPIM.

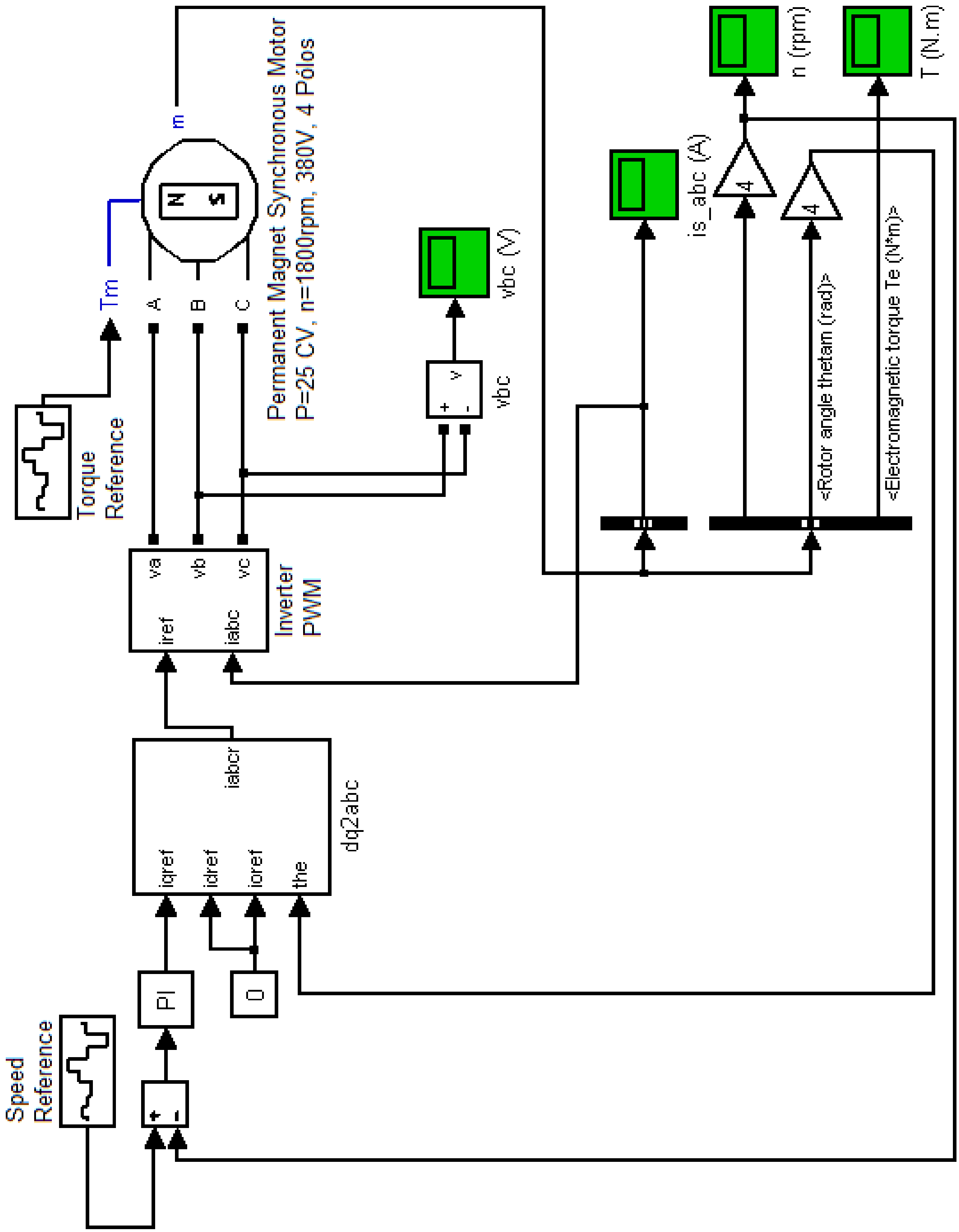

Figure 17. Inverter voltage frequency control model used in the simulation of the PMSM.

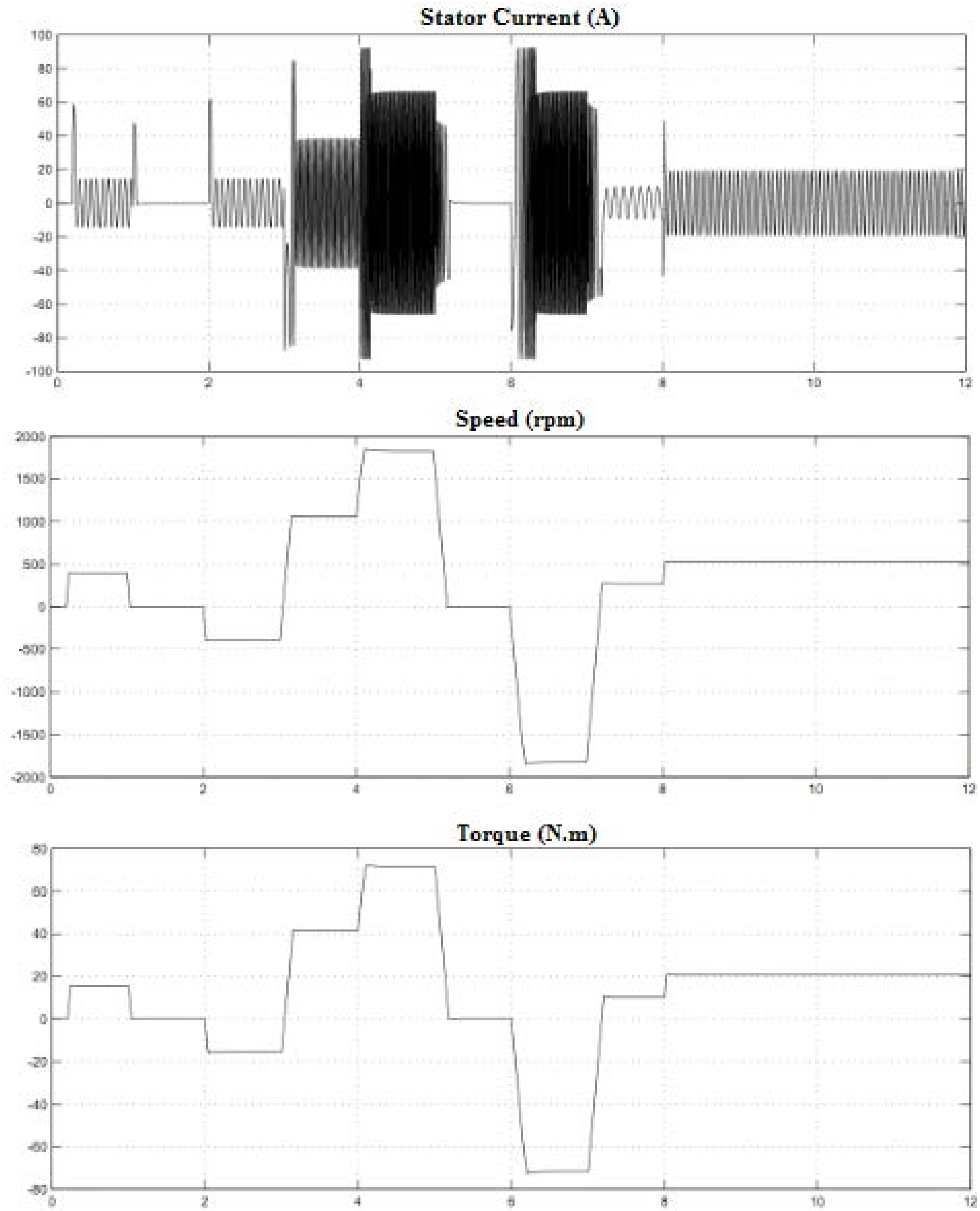

Figure 18. Values of stator current, speed, and torque collected from the simulations of the PMSM.

machine was set according to the values given in Table 3.

The results presented in Figure 18 demonstrate that the curves of speed and torque are maintained with a slight instability and were quickly corrected. The figure also indicates good stability and system response with

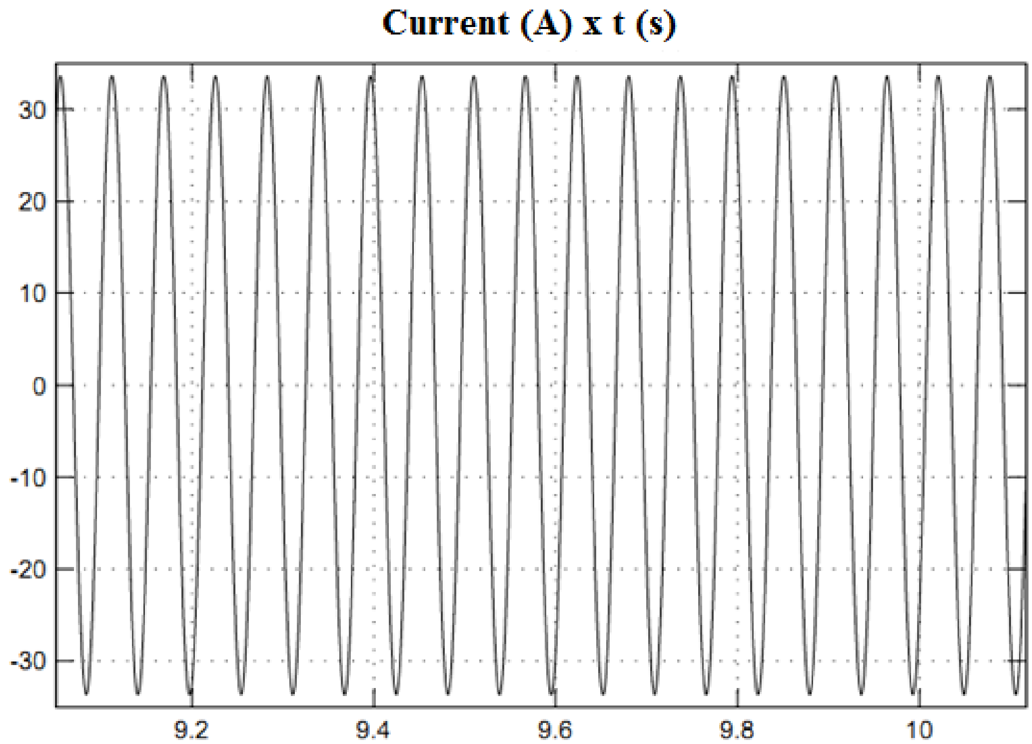

Figure 19. Stator current at a flux of 0.2 T and a torque of 20 N.m.

behavior similar to that of a DC motor. In the region of t >9 s, the torque is 20 N.m, the stator current remained close to 41% of the rated current, and the rotor speed is low, around 500 rpm, demonstrating that, for this type of motor, there is no problem associated with Joule losses in the rotor.

During the simulation, it was observed that by varying the flux linkage produced by the magnet rotor or replacing ferrite magnets with rare earth magnets, for example, caused the stator current to change dramatically. The Figure 19 shows a stator current of 35 A_p or 24.75 A_{rms} for a flux of 0.2 T and a torque of 20 N.m. With increased flux linkage to 0.9 T, maintaining a torque of 20 N.m requires, according to Figure 20, a current of 8.2 A_p or 5.8 A_{rms}.

The results summarized indicate that the application of the hybrid rotor resulted in an increase in the motor efficiency from 63% to 78% and an increase in the power factor from 0.68 to 0.97 (Slusarek et al., 2014).

From simulations, it was found that PMSM technology provides a higher gain compared to TPIM. Table 4 presents a comparison between a TPIM and a PMSM. It was found that, for the same power and torque, the PMSM has a reduced size. For example, for a power of 25 HP and a torque of 49.1 N.m, the volumes of the TPIM and Wmagnet PMSM housing are 160 M as housing 132 s, respectively. This smaller volume has become a significant benefit for the PMSM application.

Among other advantages of permanent magnets, there is an additional gain in yield of 92.8% for the TPIM and 94.6% for the PMSM for a power of 25 CV, as shown in Table 5. WEG's PMSM WMagnet was used for the retrofit objective of this study. According to the rotation and power data found in the catalog, as shown in Table 5, WEG's PMSM suitable for application to the puller is the model with the following specifications: 25 CV, 380 V, 4 pole, 132 M housing, torque 98.1 N.m, to yield 94.6%. For motor control, the manufacturer recommends using the CFW11 Inverter, which has a current rated at 38 A, an output voltage of 380 V, a 440 V supply, and inputs and control outputs compatible with existing control.

Conclusion

A study was conducted regarding the replacement of a DC motor with a PMSM for working under conditions of high torque at low speeds. It was found that, by eliminating Joule losses in the rotor, the PMSM operates at a low temperature, minimizes the fatigue of the moving parts, and increases the service life of bearings and lubricants. Another advantage is that PMSMs have lubrication points that allow the replacement of the lubricant without stopping the motor, thus increasing the period between preventive maintenance shutdowns. Owing to this combination, the preventive maintenance interval for PMSM is 95,000 h or 10 years, which is an

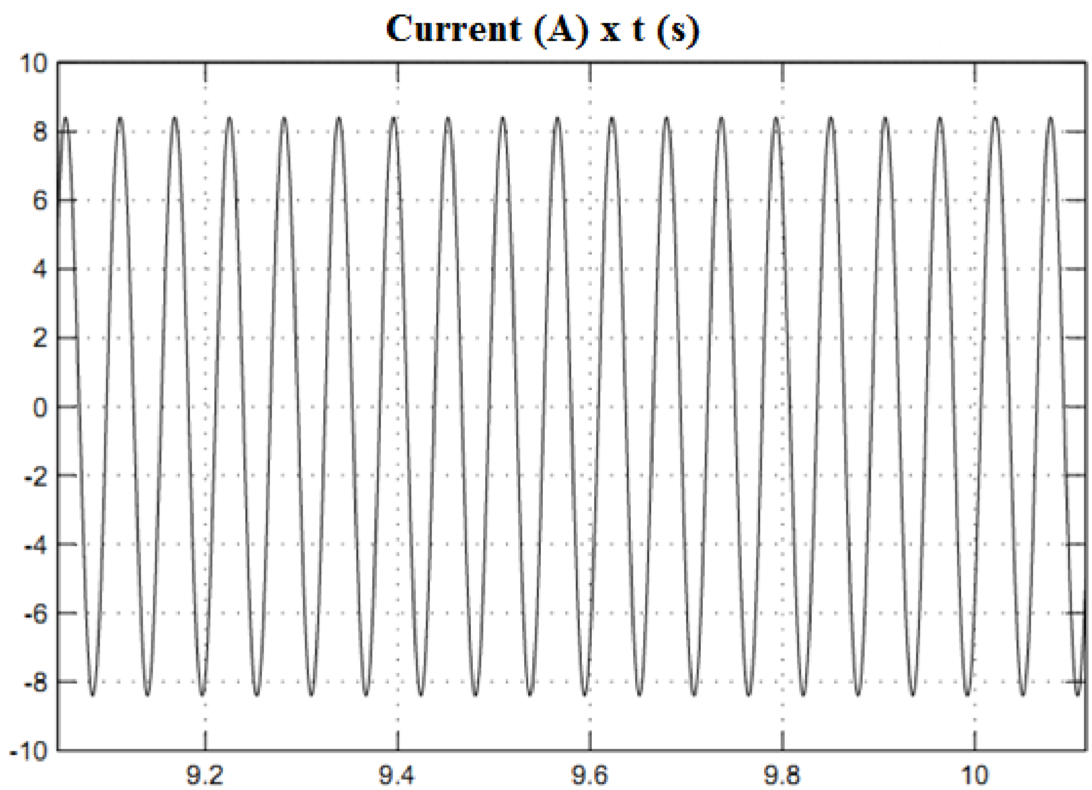

Figure 20. Stator current at a flux of 0.9 T and torque of 20 N.m.

Table 4. Comparisons between the TPIM and PMSM (WEG, 2011a).

Power (CV)	Torque (Nm)	Frame	
		Induction motor	Wmagnet motor
20	39.8	160 M	132 S
25	49.1	160 M	132 S
30	58.4	160 L	132 M
40	79.6	200 M	160 L
50	98.1	200 L	180 M
60	119.0	225 S/M	200 M
75	145.0	225 S/M	200 L
100	198.0	250 S/M	225 S/M

Table 5. Electrical characteristics of the 4-pole PMSM WMagnet (WEG, 2011a).

Motor							
Power		Frame	Torque (Nm)	Rated current in 380 V (A)	Efficiency (%)	Sound pressure level [dB(A)]	Weight of engine (kg)
CV	KW						
15	11	132 S	58.4	19.2	94.1	61	58
20	15	132 M	79.6	28.5	94.6	61	63
25	19	132 M	98.1	32.7	94.6	61	74
30	22	160 L	117.0	37.5	94.7	69	144
40	30	180 M	159.0	50.2	95.2	68	202
50	37	180 L	196.0	62.2	95.2	68	219

impressive number.

Associated with the motor, the sensorless vector inverter reduces mechanical connections of the angular position sensors, thereby minimizing mechanical failures, making the motor safe and reliable for applications where torque and variable speed are needed. It was found that the costs of preventive maintenance of PMSMs would be about 3% of DC motors, and about 18% of the TPIM.

The simulations indicate that the best engine for replacing the DC motor is the PMSM, which, in addition to meeting technical needs, preventive maintenance costs are minor and this guarantees a return on investment.

Conflict of interest

The authors are solely responsible for the material included in the article.

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