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Comparative simulation study of electric motors for high performance of 3D printers

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ABSTRACT

3D printing is a process in which material is joined layer by layer under computer control to make a 3D object easy to get almost any shape. This technology finds applications in various fields and it is attracting considerable interest from industry and academia. There are many different brands and models of motors used in 3D printers, and they all vary in quality and effectiveness. In this article we present the principal of the 3D printer, types of motors used in 3D printer and mathematical modelling of this motors like brushless direct current (DC) motor, permanent magnet synchronous motor (PMSM), and stepper motor. The models of analytical equations describing the three systems of motors are evaluated and developed by Matlab/Simunlink. In this paper, we have conducted a comparison of the series of results from simulation between the performance of PMSM, brushless DC and stepper motor. Among several criteria, this simulation study allows to select the criterion of response time to reach the desired speed and the precision of the rotor position to choose the most performant motor for 3D printers.

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1. INTRODUCTION

3D printing is a manufacturing process that uses the information from a PC and constructs the pieces layer by layer. This technique has caught much attention of the engineering and sciences [1]. It is a suitable method to meet the increasing demand by manufacturing complex parts with good quality [2]. There are different types of 3D printing classes. However, fused deposition modeling (FDM) is the dominant process. Used technology because of its simplicity and the very low cost of its materials [3]. Most of 3D printers use an open-loop stepper motor [4]. There are several types of electric motors that can provide the same displacement function in the direction of the three axes. That’s why we want to compare the performance of three types of motors, that are permanent synchronous magnet motor (PMSM), direct current (DC) brushless motor and stepper motor, to improve the quality of 3D printers. However, in low-power applications such as 3D printers, electric induction motors (IMs) cannot be used due to their high weight-to-power ratio compared to the motors chosen for our study. Indeed, at equal power, the power density (kW/kg) of the induction machine is lower than that of the PMSM machine [5]. IMs are frequently not taken en consideration due to their limited power density and their lower efficiency [6]. Another disadvantage of IM is the losses in the rotor [5]. Indeed, the implementation of the induction motor in 3D printers is not adequate.

Most people are familiar with the various technologies related to these motors. PMSM have grown considerably in recent years [7]. These machines are perfectly designed for precise positioning, as they have feedback on the position, but they remain the most expensive solution [8]. The brushless DC (BLDC) machines are commonly used for high-speed applications [8], while stepper motors have the particularity that they can be moved at a desired interval and maintain this position [9]. Since they are an excellent motor for moving an object to a repetitive position, they are commonly used in the printers and robotics [10].

The operation of a PMSM is based on the attraction between the rotor and the stator. In the case of a PMSM, there is an attraction between the stator and the rotor. The main characteristic of the PMSM is the existence of a permanent magnet on the rotor, which makes the use of brushes unnecessary. The operation of the PMSM is based on the fixed magnetic field of the rotor and the rotating magnetic field of the stator [11]. Permanent magnets are employed as the rotor to generate a constant magnetic flux, to work and to be locked at the synchronous speed. In PMSMs, the torque ripple is due to the stator slot air gap and the non-sinusoidal flux density distribution around the air gap, which provides a variable magnetic reluctance function [12]. These kinds of motors are analogous to brushless DC motors.

The design of the BLDC motor is given into two parts: a) the stator and b) the rotor. This kind of motor is made with different concepts such as the inner rotor and the outer rotor [13]. The BLDC motor is a brushless DC motor, without the need for a brush and collector for commutation, which has three-phase windings and is powered by a trapezoidal current wave to generate precise and powerful torque. The BLDC motor is defined as an internal and external DC motor becauseits magnets is located in the rotor and its armature in the stator [14].

A stepper motor is an electrical motor that can be considered as an electric motor without a commutator. Its main characteristic is that its axis rotates in steps, which it moves by a defined number of degrees. In general, all motor windings are part of the stator, and the rotor is a permanent magnet. This characteristic also gives it a large variety of applications [15].

The stepper motor used in the 3D printer has a step loss problem. To solve this problem, the researchers replaced the stepper motor with a PMSM motor. The simulation performances of PMSM under closed-loop situation with stepper motor under both closed-loop and open-loop situation along are compared and analysed. Therefore, PMSM motor has the best performance for improving 3D printer [4].

This article discusses the differents type of motor such as the permanent magnet motor, BLDC and stepper motor to improve the characteristics of the 3D printer. The basic principles of the 3D printer and model of this machines will be presented as well as basic operation of each type of these machines and simulations result between the efficiency of PMSM, BLDC motor and stepper motor operate in 3D printing system. We will find that the PMSM have a great performance for improving 3D printer motor.

Performance of 3D printer can be expressed by 3 main criteria which do not have the same priority for everyone: a) the speed of printing, b) the aesthetic quality of the parts, and c) their dimensional quality. The purpose of this article is to test speed and acceleration. There are 4 main factors that are interesting for the choice of the electric motor: a) the parameters registered in the motor with the capacities of the printer, b) the mechanical limits, c) the power of the motors, and d) the available flow of the head for a given material. The accelerations of the motor, their speed, as well as the temperature of the nozzles are the important parameters for the high performance of the 3D printer.

2. 3D PRINTER

2.1. Construction of 3D printer

3D printing can easily manufacture complex geometry objects. Its flexibility is ensured by rapid design adjustments, which puts it in higher demand than subtractive manufacturing processes. Figure 1 presentes a typical design of FDM 3D printer. Principaly, this machine consists of a chassis that holds all the parts of the printer together and a build surface that moves along the linear X axis and on which the object is printed. The print head (extruder) extrudes the filament and by moving along the linear Z and Y-axes. The three motors allow the movement in the three directions X, Y, and Z. The role of motherboard is to control the motors according to the instructions sent by the computer and the signals from the sensors. Some time, a secure digital (SD) card, an universal serial bus (USB) port and/or an LCD user interface are present in the printer to allow input file of the part directly without using computer. The power supply unit is necessary to provide power for the operation of the 3D printer.

2.2. Principal of 3D printer

The main component of 3D printer is the extruder element. It is composed by a feeding mechanism (Figure 2) driven by electrical motor (Figure 3). The feeding system serves to supply plastic filament to the fusion chamber and to forced to pass through the extrusion orifice to guarantee the continuity of material flow at the end of extruder. The motor is assiciated with a gear mechanism to supply sufficient force to move the filament from the cold end to the hot end. The rotation of the motor is converted into linear movement of the filament with the help of a screw and nut mechanism. This mechanism is designed to be very precise, for this purpose, the choice of driving motor coupled to the driving-toothed wheel is essential.

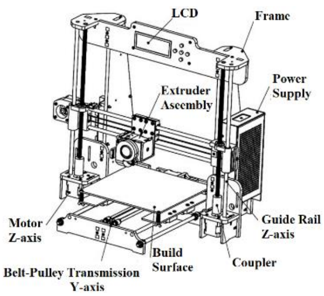

Figure 1. Construction of 3D printer [16]

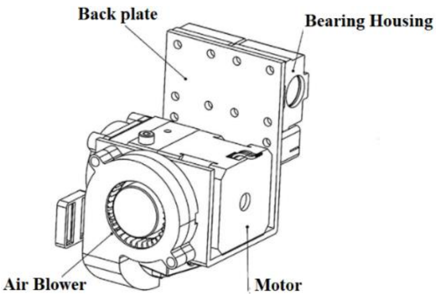

Figure 2. Extruder assembly of 3D printer [16]

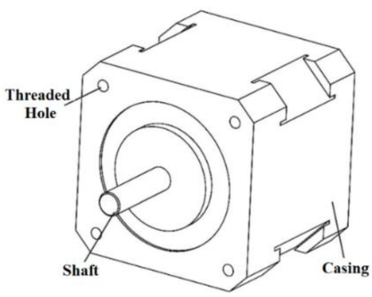

Figure 3. Motor of 3D printer [16]

3. PERMANENT MAGNET SYNCHRONOUS MOTOR

3.1. Principal of the PMSM

The permanent magnet synchronous motor is composed of a rotor and a stator. The rotor is usually located in the interior of the stator of the motor. Figure 4 shows an example of the PMSM motor construction [17]. The rotor is designed to create a number of magnetic poles equal or integral multiple of the number of stator poles. When the motor is energized, the rotor's magnetic field clings to the stator's magnetic field, and it turns at the same speed as the stator's field. The slip value of the synchronous motor is zero. The speed of the motor depends on the number of stator poles and the supply frequency.

The PMSM is composed of a coiled stator and a permanent magnet rotor, as shown in Figure 5. The magnetic field created by the permanent magnets of the rotor is constant. The principal of the permanent magnet synchronous motor is characterized by the reaction between the constant magnetic field of the rotor and the rotating magnetic field of the stator [12]. The creation of the rotating magnetic field of the PMSM is based on the same principle as that of the induction motor. The torque is given by the interaction between the magnetic fields of the stator and the rotor. The torque becomes maximum when the stator magnetic vector is perpendicular to the rotor magnetic vector.

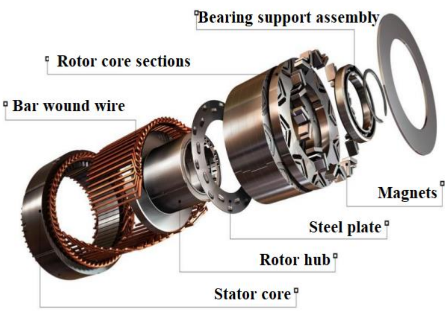

Figure 4. Construction of permanent magnet motor [17]

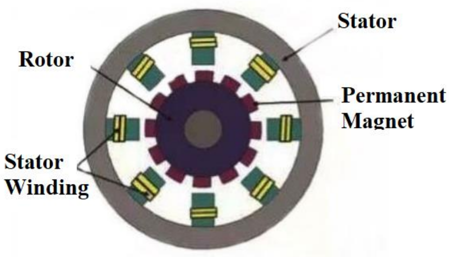

Figure 5. Permanent magnet synchronous motor structure [12]

3.2. Mathematical modelling of the PMSM

This section will present the most used model of a PMSM, it is beneficial to write the equations to be solved in another way [18]. Therefore, the two-axis mathematical representation is used. The stator supply voltage consists of two essential parts: a) the voltage drop across the stator winding resistance and b) the fem induced by the flux variation.

$$v_{sd} = R_s i_{sd} + \frac{d\emptyset_{sd}}{dt} - \omega\emptyset_{sq} \tag{1}$$

$$v_{sq} = R_s i_{sq} + \frac{d\emptyset_{sq}}{dt} + \omega\emptyset_{sd} \tag{2}$$

Where v_s represents stator voltage in dq-coordinates, $\Phi_s(d,q)$ represents stator flux linkage in dq-coordinates and R_s represents stator resistance. The resulting flux in the stator windings composed of two parts, the flux generated by the stator currents and the mutual flux created by the rotor field. So the total flux in the stator is expressed by (3), (4).

$$\emptyset_{sd} = L_d i_{sd} + \emptyset_f \quad (3)$$

$$\emptyset_{sq} = L_q i_{sq} \quad (4)$$

Where L_q and L_d are the stator inductance, Φ_f is the magnitude of the flux from the rotor magnets and $i_s(d,q)$ is the stator current in (d,q)-coordinates [19]. The flux vector of the rotor rotates with the electrical speed and is displaced with the electrical angle from the d-axis. Where Φ_f is the flux produced by permanent magnet. The mechanical modelling of PMSM motor (5), (6).

$$T_e = J\frac{d\Omega}{dt} + f\Omega + T_r \quad (5)$$

$$\omega = p\Omega \quad (6)$$

Where T_e is the electromagnetic torque, J is the motor inertia and Ω is the mechanical speed. The coefficient of friction is f and T_r is the resistant torque. ω is the electric rotation speed and p is number of pairs of poles.

3.3. Implementation of the PMSM

In Matlab/Simulink environment, using the module library in SimPowerSystem, we build a simulation model based on PMSM motor, which is shown in Figure 6. The PMSM block designs a permanent magnet synchronous motor with a three-phase star-wound stator. The current and speed loops are equipped with a PI controller to reduce the static error. The PMSM system principally consists of: PMSM model, pulse width modulation (PWM) converter model, $dq2abc$ coordinate transformation model. We have chosen one of the most common type of electric motor used in 3D printer, with the following characteristics: V = 24 V, R = 0.34 Ω, L = 0.08 mH, J = 8 10^{-6} kgm^2, T = 0.18 Nm.

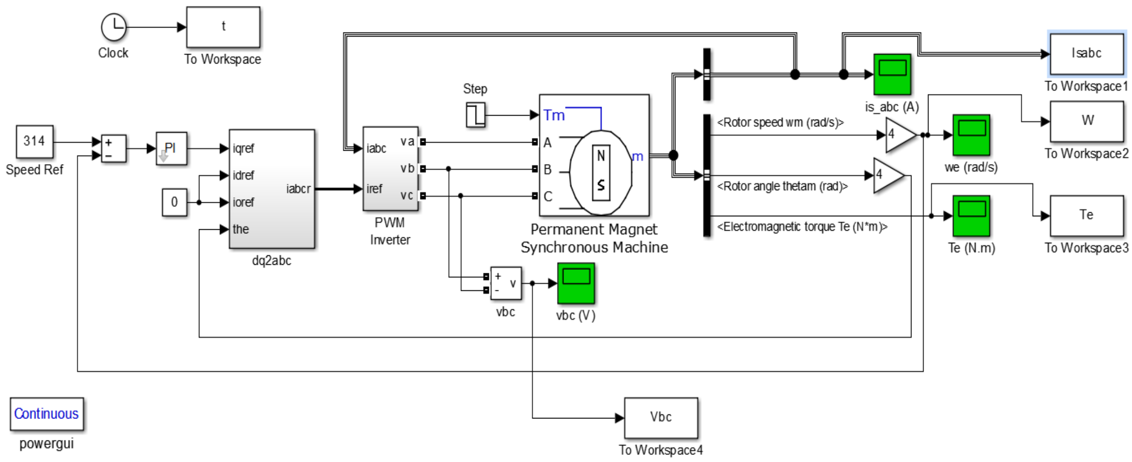

Figure 6. PMSM model

3.4. Simulations results

Figure 7 shows the shape of the three-phase current, when the motor is supplied with a constant torque. We adopted the transformation of park to simulate the current result, we have noticed that the current only becomes sinusoidal after a starting time. The torque generated by the motor is determined in Figure 8. At start-up the torque is too high, after which it becomes stable at a value of 0.2 Nm, which is adequate for moving the extruder and the build surface of 3D printer.

The speed of the PMSM motor is given by Figure 9. We notice that the speed increases linearly at 6000 rpm after 0.8 ms, which improves the speed of 3D printing. The PMSM simulation model shows that the produced rotor angle will be used to have a sinusoidal current waveform to reduce the torque ripple. Figure 10 presents the form of the phase currents, voltages and the estimated rotor position using a reference model. The rotor angle initially at 0 increases to 1.8° in 0.3 ms, which improve the accuracy of 3D printing.

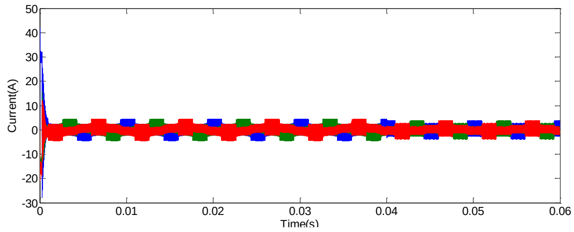

Figure 7. Currents of the PMSM

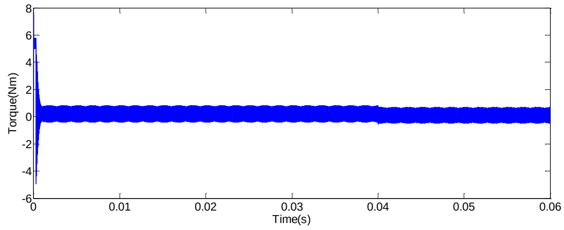

Figure 8. Electromagnetic torque of the PMSM

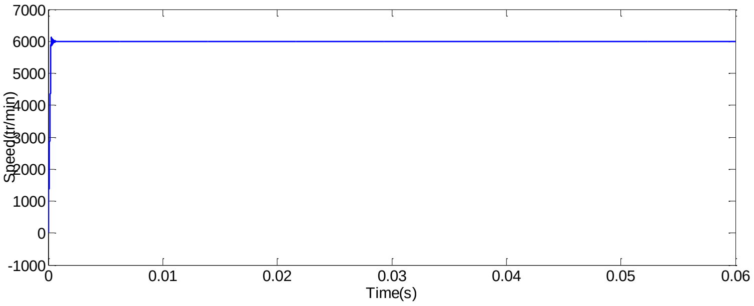

Figure 9. Speed of the PMSM

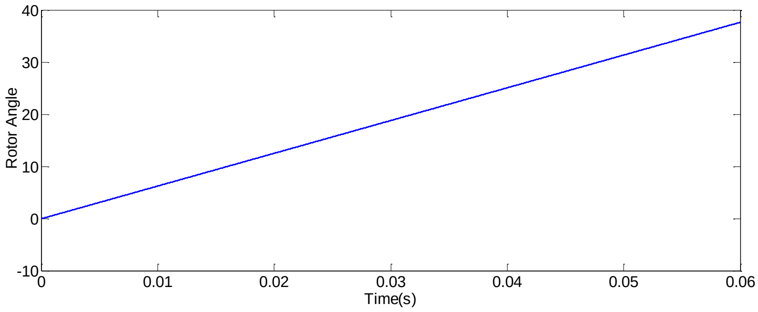

Figure 10. Rotor position of PMSM motor

4. BRUSHLESS DC MOTOR

4.1. Construction of BLDC motor

BLDC motors are built in different configurations. They can be single phase, two phase or three phase depending on the number and configuration of stator windings [20], [21]. This motor has a lot of similarity with the induction motor as well as with the classical DC motor. This motor consists of a stator and a rotor, as shown in Figure 11.

The stator of a BLDC motor resembles that of an asynchronous machine apart from the windings being distributed differently. It consists of three star-connected stator windings. The rotor consists of a permanent magnet.

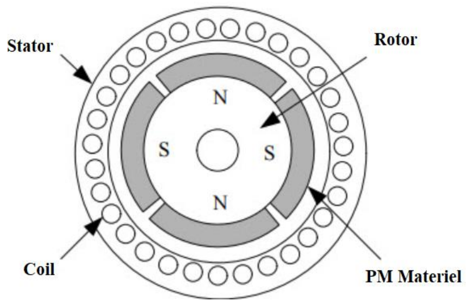

Figure 11. Construction of brushless DC motor [22]

4.2. Operating principl of a BLDC motor

BLDC motor is a brushless DC motor, it has the same elements as DC motor but the location of coils and permanet magnets are reversed. The stator structure of a BLDC motor is the same as that of a PMSM. It is composed of stacked steel sheets with slots cut axially for the winding; the rotor is made up of permanent magnets. BLDC motors are provided in three types of designs: a) single-phase, b) two-phase, and c) three-phase. The three-phase BLDC is the most common of these, with the coils being powered sequentially, and this mode of operation creates a rotating magnetic field at the same frequency as the supply voltages. Thus, the permanent magnet of the rotor seeks to orient itself in the direction of the rotating field.

BLDC motors do not experience "slip", they are like a synchronous motor. It works as: the two magnetic fields produced by the stator and the rotor at the identical frequency. We can find BLDC motors in single-phase, biphase and 3-phase [8].

There are different types of back electromotive force (EMF) depending on the type of stator windings which are trapezoidal and sinusoidal. The Figure 12 and Figure 13 show the type of the sinusoidal motor which gives a back EMF sinusoidal and the trapezoidal back EMF of the motor is trapezoidally. Current variations are also trapezoidal and sinusoidal. The torque in a sinusoidal type motor is smoother. Motors rated at forty-eight volts or less are used in 3D printers [15].

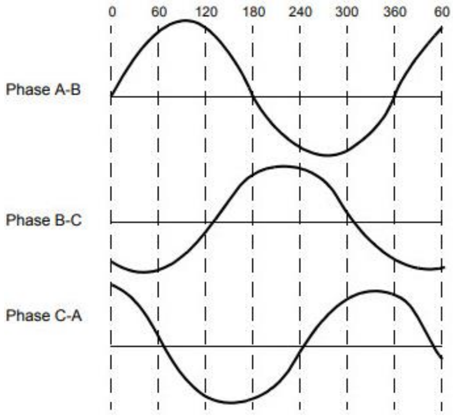

Figure 12. Sinusoidal type back EMF [22]

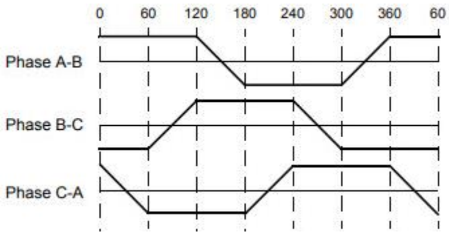

Figure 13. Trapezoıdal type back EMF [22]

4.3. Mathematical modelling of the BLDC motor

Modeling the BLDC motor is essential for its identification and control. The rotor of the BLDC motor consists of a permanent magnet, so it will be modeled as a synchronous motor, however some characteristics are different. The flux linkage of the rotor depends on the material of the magnet [23]. The motor power supply is of the three-phase type, either sinusoidal or another waveform. (7), (8), (9) presents the model for the BLDC motor [24].

$$V_{\mathrm{a}} = R\, i_a + L \frac{di_a}{\mathrm{dt}} \quad (7)$$

$$V_b = R\, i_b + L \frac{di_b}{dt} \quad (8)$$

$$V_{\mathrm{c}} = R\, i_c + L \frac{di_c}{\mathrm{dt}} \quad (9)$$

Where, V_a, V_b, V_c are phase voltage (V), R is armature resistance (Ω), L is a self-inductance (H), and i_a, i_b, i_c are motor input current (A). The (10), (11), (12) presents the expression for the back-EMF which is a function of rotor position.

$$e_a = K_w . f(\theta_e)\omega \quad (10)$$

$$e_b = K_w . f(\theta_e - \frac{2\pi}{3})\omega \quad (11)$$

$$e_c = K_w . f(\theta_e + \frac{2\pi}{3})\omega \quad (12)$$

Where, θ_e is electrical rotor angle, K_w is the back EMF constant of one phase $(V/rad.s^{-1})$ and ω is an electric speed $(rad.s^{-1})$. We represent the electrical angle θ_e of the rotor in function by the mechanical angle of the rotor θ_m multiplied by the number of pairs of poles p as shown in (13).

$$\theta_e = p\theta_m \quad (13)$$

The (14) shows that the total output torque T_e is the sum of the torque for each phase. Therefore, the (15) presents the mechanical part which depends on the load torque T_r (Nm), the moment of inertia of the rotor and the coupled shaft J (kgm^2) and the friction constant B $(Nms.rad^{-1})$.

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} \quad (14)$$

$$T_e - T_r = J\frac{d\Omega}{dt} + B\Omega \quad (15)$$

4.4. Implementation of the BLDC motor

The implementation of the brushless motor model is given in Figure 14. The chosen EMF is of trapezoidal type which allows to modify the value of the electrical angle. The stator is powered by an insulated gate bipolar transistor (IGBT) inverter whose control is a function of the rotor position provided by the encoder. This stator is fed in sequence to determine the rotor position and to know which winding will be fed. The speed loop is equipped with a proportional integral (PI) controller to reduce the static error.

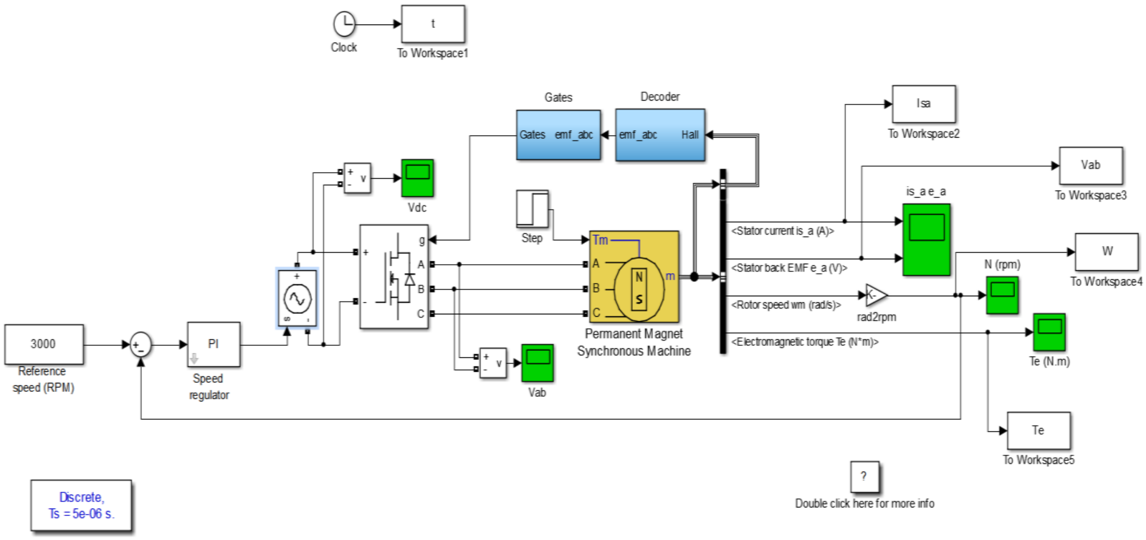

Figure 14. Brushless DC model

4.5. Simulations results

The Figure 15, Figure 16, Figure 17, and Figure 18 show results of simulations of a BLDC motor with the following parameters wich has the same carachteristics used in 3D printer: V = 24 V, R = 1.5 Ω, L = 1.8 mH, J = 1.123 10^{-5} kgm^2, T = 0.71 Nm. Theoretically, the trapezoidal back EMF shape is driven by rectangular stator currents as shown in Figure 15, which causes a constant torque. However, in practice, the torque exhibits ripple as shown in Figure 16 as well as counter EMF.

Figure 17 shows an example of speed characteristics. The motor can run up to maximum speed, but the torque starts to drop. The speed increases linearly at 6000 rpm after 25 ms. The selection of the powered windings depends on the position of the rotor, and can be defined in different ways, the rotor angle increases at 0.6 ms as shown in Figure 18, the rotor angle increases at 0.6 ms as shown in Figure 18.

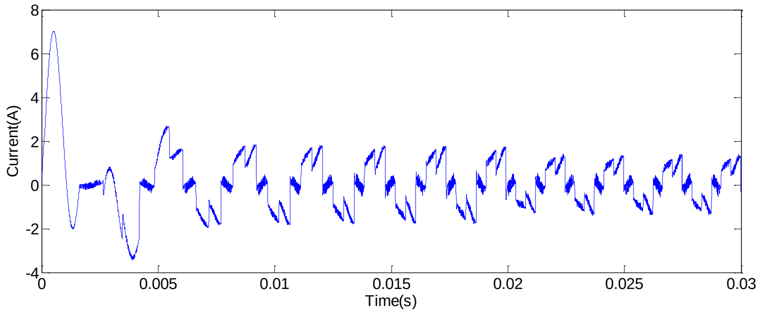

Figure 15. Currents of the BLDC

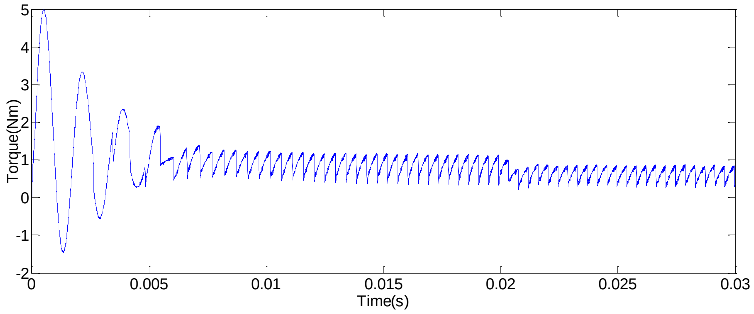

Figure 16. Electromagnetic torque of the BLDC

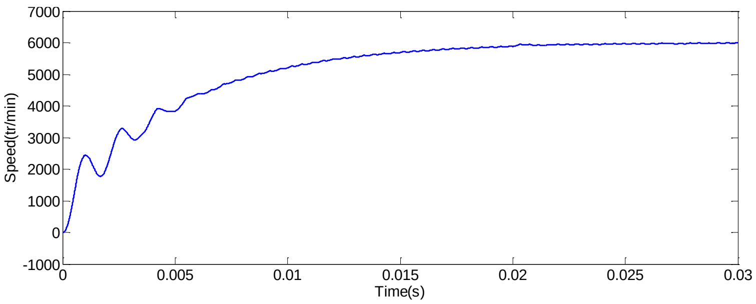

Figure 17. Speed characteristics of the BLDC

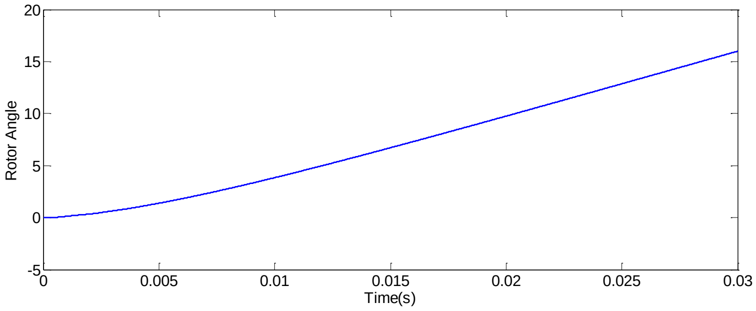

Figure 18. Rotor position of BLDC motor

5. STEPPER MOTOR

5.1. Principal of a stepper motor

A stepper motor converts electrical energy in the form of current pulses into rotational movement of the rotor. There are 3 types of stepper motor [25]: a) permanent, b) hybrid, and c) variable reluctance. In the case of 3D printers, there is a wide variety of desired features and characteristics. The rotor teeth are attracted by the excited phase of the stator. The excitation of a phase is given by a stepping pulse. We can increase the number of steps of the rotor when we excite two phases at the same time [26].

5.1.1. Hybrid stepper motor

The stator and rotor of hybrid stepper motors consist of salient poles. The stator poles support the coils through which the motor is supplied. The rotor is composed of a permanent magnet with several pairs of poles [27]. The Figure 19 shows the two-phase hybrid stepper motor. This motor consists of a stator which is made up of windings and the rotor which is made up of permanent magnets.

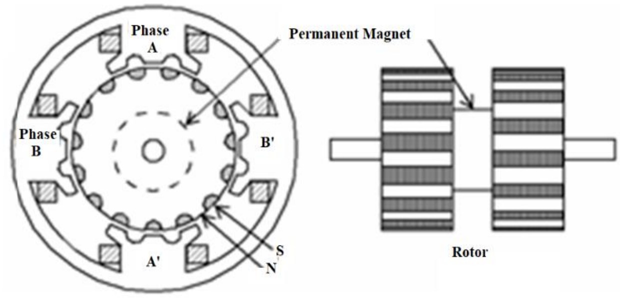

Figure 19. Hybrid stepper motor [27]

5.1.2. Variable-reluctance stepper motor

The variable reluctance stepper motor is an energy conversion device with good energy efficiency. It works on the principle of reluctance. Figure 20 shows that the stator and rotor of variable reluctance stepper motors consist of salient poles. The phase number represents the number of poles of the stator [28]. The stator poles are excited with three-phase or single-phase supply and the rotor is either made of permanent magnets or excited with single-phase supply to obtain the rotor magnetic field.

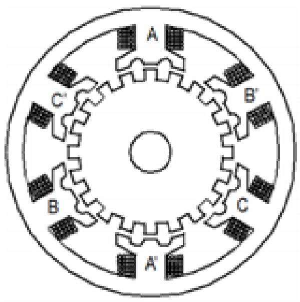

Figure 20. Variable-reluctance stepper motor [28]

5.1.3. Permanent magnet stepper motor

The stator of permanent magnet stepper motors consists of poles that carry coils. The number of poles in the stator determines the number of phases of the motor. The number of pole pairs in the rotor are produced from permanent magnets [29].

5.2. Mathematical modelling of hybrid stepper

The stepper motor is modeled by an electrical and a mechanical part. The single-phase electrical part of hybrid stepper motor is represented by an equivalent circuit R_a and $L_a(\theta)$ which depends on its position. As shown in Figure 21 reluctance stepper motor wich is used in the 3D printer. We represent also the electrical and mechanical mathematical model of the Hybrid stepper motor.

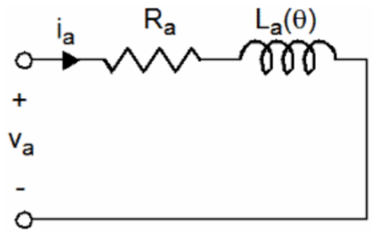

Figure 21. Electrical model of stepper motor

Where R_a and L_a are the resistance and the inductance of the phase a winding [26]. In this case the inductance L_a approaches a sinusoid and it depends on rotor position as shown in the (16).

$$L_a(\theta) = L_0 + L_1 \cos(N_r\theta) \quad (16)$$

L_1 is the inductance variation, L_0 is the average inductance and Nr is the number of rotor teeth. The (17) presents a total electromagnetic torque T_e created by the stepper motor:

$$T_e = \sum_{x=1}^{m} 0.5\, i_x^2 \frac{dL_x}{d\theta} \quad (17)$$

We have, i_x is the current per phase, m is the phase number and L_x presents the inductance per phase. The (18) presents the mechanical torque.

$$T_e = T_r + J\frac{d\Omega}{dt} + B\Omega \quad (18)$$

T_r is load torque, J is inertia of motor and load, and B is total friction of motor and load.

5.3. Implementation of the stepper motor

The implementation of the stepper motor on Matlab Simulink is given by Figure 22. The stepper motor studied is of hybrid type which is composed of several blocks. The hybrid stepper motor model is established by entering the motor parameters in the simulation. We have chosen a motor with the following characteristics for using in 3D printer: V = 24 V, R = 0.63 Ω, L = 1.03 mH, Step: 1.8°, J = 82 10^{-9} kgm^2, T = 0.15 Nm.

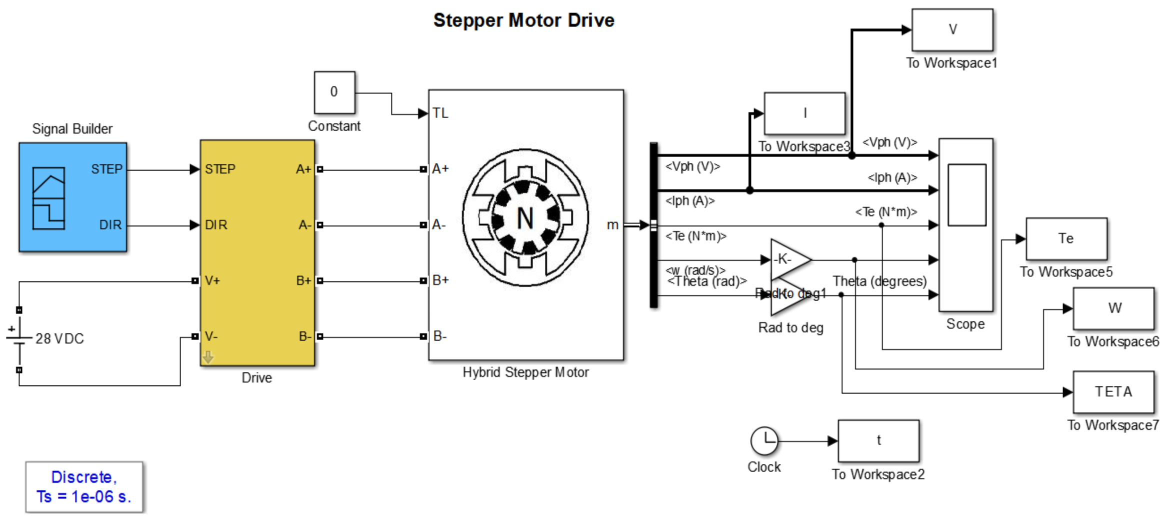

Figure 22. Hybrid stepper motor model

5.4. Simulations results

At first the stepper motor is simulated with no load, Figure 23 shows the square waveform of the obtained current using the current amplitude and step specified in the parameters. The motor is supplied with a voltage of 24V. We find that the speed of the stepper motor reaches 3000 tr/min as shown in Figure 24.

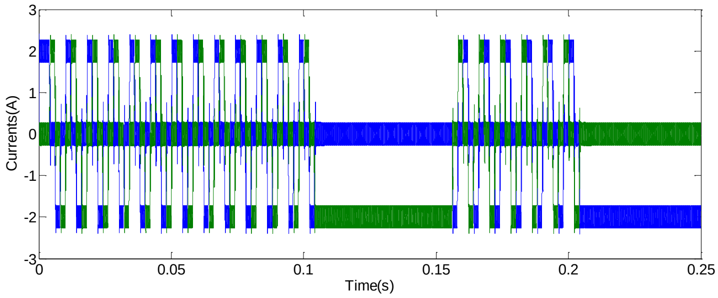

Figure 23. Current of hybrid stepper motor

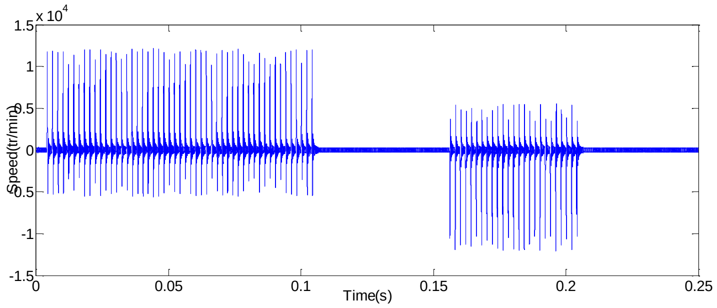

Figure 24. Speed of hybrid stepper

The Figure 25 presents the variation of the torque with no load and when the load is applied. The rotor position of of stepper motor is determineted directly from the flux, which can be all so calculated form phase current and stator voltage. The initial position of the rotor is determined from four impulses. This parameter is essential for the high performance of the 3D printer. When the phases are supplied, the current reaches a peak. Figure 26 represents the real rotor position estimed from incremental encoder is represented in Figure 26. The rotor position increase at 5 ms.

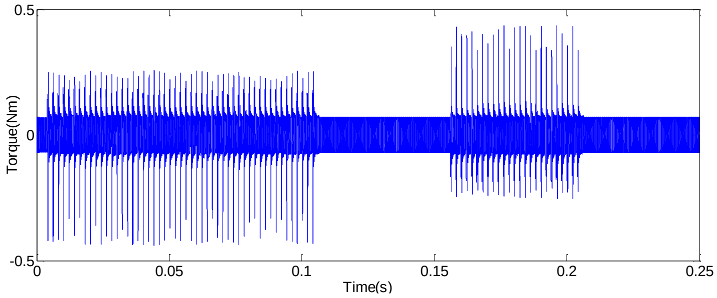

Figure 25. Torque of hybrid stepper motor

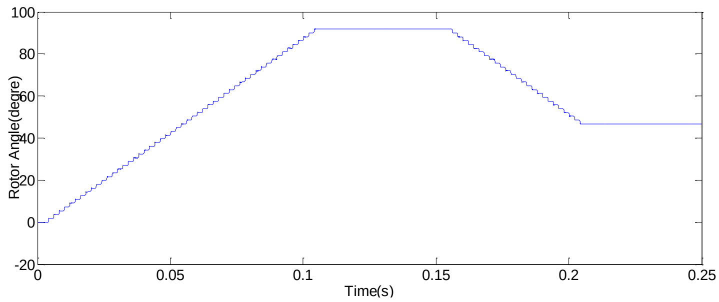

Figure 26. Rotor position of stepper motor

6. COMPARISON STUDY

The new in this article is the full comparison between PMSM, BLCD, and stepper motor for a great performance of 3D printers.This comparison is established on the modelling of each type of motor and also based on the simulation results found for the nominal torque, the current, the maximum speed, acceleration and rotor position. For a good choice of motor, different comparisons are summarized in the Table 1. The simulations result show the guarantees the start-up of each motors in the desired direction when they used in 3D printer. The obtained results are good in PMSM motor, because it is precise and has a quick response then stepper motor and BLDC motor.

Table 1. Comparison study

Comparison criteria	PMSM	BLDC	Steeper motor
Currents	The starting current is seven times the nominal value	– BLDC does not require any special starting circuit – The starting current is not so high compared to the rated current	The starting current is higher then the nominal value
Speed/ acceleration	– PMSM machine offer the best and high dynamic performance – Short acceleration response	– Acceleration isn’t ideal for high-speed applications as 3D printer – In higher power ratings, is interesting in terms of dynamics	Stepper motors aren’t great for dynamic applications
Rotor position	– Rotation angle of the motor varies linearly with the input pulse – Rotor position response is good and fast	– Rotation angle of the motor varies linearly with the input pulse – Rotor position is not fast	Precise positioning and repeatability of movement
Electromagnetic torque	– PMSM motor effectively reduces the torque ripple – Up to the rated speed, the motor is characterized by a constant torque	BLDC present high torque ripple	Stepper motor gives better torque

7. CONCLUSION

The 3D printer has led to increased usage in different fields, and its low cost makes it more affordable to use. One of the most critical components for building a 3D printer is the electric motor. This article has studied the technologies of electric motors used for 3D printers. Their characteristics, the modelling procedure are represented, and simulations results are discussed. A comparison between motors technologies is shown. The BLDC motors are particularly attractive for high-speed applications. However, using them to position oneself would be uninteresting. Stepper motors are great for open loop positioning. However, use them to drive loads with limited maximum speed. The PMSM have an important role in high performance drive systems, they are perfectly suited for precise positioning. The objective of this article is to offer a clear roadmap for the applications of electric motors in 3D printers.

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