Loss and Efficiency Analysis of BLDC Motor and Universal Motor by Mathematical Modelling in the Mixer Grinder

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Received: 24 June 2019 / Accepted: 12 July 2021 / Published online: 14 September 2021
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Abstract The typical mixer grinders are universal motor, which operates on alternating current supply because of the higher starting torque characteristics and easy speed control. The absence of brushes in the Brushless DC (BLDC) motor and noise reduction improves its life and makes it perfectly suited for mixer grinder. The mathematical modelling and experimental demonstration of a conventional universal motor and proposed simulated model of BLDC motor was analysed using the MATLAB/Simulink. The loss and efficiency analysis of the permanent magnet BLDC and universal motor in the application of a mixer grinder are presented in this paper.

Keywords BLDC motor · Universal motor · Efficiency · Mixer grinder · MATLAB

Introduction

In a present scenario, the demand for scarce energy resources had necessitated energy-efficient appliances [1]. In all domestic appliances, either universal motor, DC motor, permanent magnet synchronous motor or induction motor is used [2]. In a mixer grinder appliance, a universal motor is used due to its higher starting torque and operating speed than the induction motor [3]. The universal motor operates same as DC series motor. The rotor and stator windings are in series, and the commutator and brush arrangements supply power to the rotor [4]. The design of

the universal motor is cheaper to achieve greater speed for smaller devices [5]. However, the wear-out of the commutator and brush in the universal motor can cause sparking and electromagnetic interference [6]. So, the BLDC motor is suitable for the mixer grinder because of its easy speed torque control and compact size [7]. In a few cases, the quality of the mixing material will affect when the mixer grinder is operated at low speed (3000 rpm), which is possible in the BLDC motor [8]. As the torque vs. efficiency characteristics of the BLDC motor is almost flat, the mixer operating at low speed and part load also save energy [9]. In rural India, the availability of power is poor and the load connected is around 300 W. So the proposed BLDC motor power output was fixed at 200 W and the power input was limited to 250 W. The 200 W output power of a BLDC motor is equivalent to existing 500 W universal motor of the mixer grinder.

This paper contributes in an application of a mixer grinder to the performance and losses analysis of a conventional universal motor and proposed BLDC motor. The proposed BLDC motor has lower power consumption compared to the existing universal motor available in a market.

Mathematical Modelling of a Universal Motor

In a universal motor's mathematical modelling, with the following assumptions voltage equations are given as:

- Magnetic field shows harmonic layout in an air gap;
- Perfect commutating armature; and
- The effect of commutation is ignored [10].

Figure 1 describes the two pole circuit equivalent of a AC universal motor. R_1 is resistance of stator, R_2 is resistance of rotor machine, L_1 is stator inductance, L_2 is

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Fig. 1 AC operating universal motor equivalent circuit

machine rotor inductance, Φ is the magnetic flux in the stator, and u_i is an induced internal armature voltage [11].

Figure 2 represents a DC equivalent circuit of an universal motor. V_t is a supply voltage, E is a back emf, r_a is a resistance of the stator, r_f is the resistance of the rotor, I_a is the current in the armature, I_f is an excitation current, V_f is the excitation voltage, L_{ff} is self-inductance of the rotor, and L_{aa} is self-inductance of the stator. The mathematical modelling equations are given as [12]:

$$I_f = I_a \quad (1)$$

$$V_f = r_f I_a + L_{ff} \left(\frac{dI_a}{dt} \right) \quad (2)$$

$$E = L_{af} \omega I_a \quad (3)$$

$$V_a = r_a I_a + L_{aa} \left(\frac{dI_a}{dt} \right) + E \quad (4)$$

$$V_a = r_a I_a + L_{aa} \left(\frac{dI_a}{dt} \right) + (L_{af} \omega I_a) \quad (5)$$

$$V_t = V_a + V_f \quad (6)$$

$$V_t = I_a (r_f + r_a + L_{af} \omega) + \left(\frac{dI_a}{dt} \right) (L_{ff} + L_{aa}) \quad (7)$$

The mechanical equations of the motor are:

Fig. 2 Equivalent DC circuit in universal motor operation [5]

$$T_e = L_{af} I_a I_f \quad (8)$$

$$T_e = J \frac{d\omega}{dt} + B\omega + T_L \quad (9)$$

$$\frac{d\omega}{dt} = \left(-\frac{B}{J} \right) \omega + \frac{(T_e - T_L)}{J} \quad (10)$$

$$\omega = \int \left(\left(-\frac{B}{J} \right) \omega + \frac{(T_e - T_L)}{J} \right) dt \quad (11)$$

where J is the coefficient of inertia, T_L is a load torque, T_e is an electromagnetic torque, ω is a rotor mechanical speed, B is the coefficient of friction and Ω is angular velocity [13].

Losses of Universal Motor Equations

Per slot copper loss:

$$J = \frac{IN}{A} \quad (12)$$

$$P_{Cu,slot} = I^2 R = J^2 A \rho l_{turn} \quad (13)$$

where J is a current density, I is current, A is a slot, L_{turn} is a winding turn length, ρ is the copper specific resistance and N is a number of turns [14].

Hysteresis loss:

$$P_h = k_h B_{max}^n f \quad (14)$$

where k_h is the constant of hysteresis (ranges from 0.1 to 0.6), f is the frequency of flux reversal in the rotor (50 Hz), B is a maximum flux density (2–4 Tesla) and n is a material-dependent exponents ranges from 1.5 to 2.5.

Eddy current losses:

$$P_e = k_e B^2 f^2 m \quad (15)$$

where k_e is the Eddy current constant (almost equal to 1, i.e. 0.8), f is the frequency of flux reversal in a rotor (50 Hz) and B is a maximum flux density (2–4 Tesla).

The square of frequency influences the eddy current losses, and hysteresis losses rise linearly with the frequency.

Field copper loss:

$$P_{fieldcu} = I_{se}^2 R_{se} \quad (16)$$

where I_{se} is the field winding current in series and R_{se} is the field winding resistance in series [15].

Mathematical Modelling of a BLDC Motor

Considering a cylindrical stator and rotor in three phases, with windings a , b and c . The rotor consists of a permanent magnet with air gap uniform as stator consists of three phase bounded by star connected [16]. For phase a , phase b and phase c , the dynamic equations are:

$$V_{an} = R_S i_a + L \frac{di_a}{dt} + M \frac{di_b}{dt} + M \frac{di_c}{dt} + e_a \quad (17)$$

$$V_{bn} = R_S i_b + L \frac{di_b}{dt} + M \frac{di_c}{dt} + M \frac{di_a}{dt} + e_b \quad (18)$$

$$V_{cn} = R_S i_c + L \frac{di_c}{dt} + M \frac{di_a}{dt} + M \frac{di_b}{dt} + e_c \quad (19)$$

where M is armature mutual inductance, R is armature resistance, V_{an} , V_{bn} and V_{cn} are the voltage of the terminals, L is armature self-inductance, and i_a , i_b and i_c are input currents of the motor [17].

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (20)$$

The rotor position function in a BLDC motor is related to the back emf. Each back emf phases has a difference of 120° angle of phase [18]. Hence, the equations for each phase are:

$$e_a = K_a f_a(\theta) \omega_r \quad (21)$$

$$e_b = K_b f_b\left(\theta + \frac{2\pi}{3}\right) \omega_r \quad (22)$$

$$e_c = K_c f_c\left(\theta - \frac{2\pi}{3}\right) \omega_r \quad (23)$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_s \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (24)$$

The total torque is given as:

$$e_a = K_a \omega_r \quad (25)$$

$$P_m = e_a i_a + e_b i_b + e_c i_c \quad (26)$$

$$T_e = \frac{P_m}{\omega_{rm}} = \frac{(e_a i_a + e_b i_b + e_c i_c) P}{\omega_r} \frac{1}{2} \quad (27)$$

$$T_e = \frac{P(K_a i_a + K_b i_b + K_c i_c)}{2} \quad (28)$$

Mechanical part:

$$T_e - T_L = J \frac{d\omega_{rm}}{dt} + B \omega_{rm} \quad (29)$$

$$\frac{d\omega_{rm}}{dt} = \frac{P}{2J} \left(T_e - T_L - \frac{2B}{P} \omega_r \right) \quad (30)$$

where T_L is a load torque, J is a current density, T_e is an electromagnetic torque and B is a flux density [7].

Losses Equations of the BLDC Motor

Hysteresis loss:

$$W_h = k_h B_{\max}^\alpha f \quad (31)$$

where f is the frequency of flux reversal in the rotor (50 Hz), $B_{\max}$ is the maximum flux density (0.638 Tesla), k_h is the hysteresis constant (ranges from 0.1 to 0.6) and α is the constant (1.5–2.5).

Copper loss:

$$W_{cu} = I_{rms}^2 R_a \quad (32)$$

where I_{rms} is the current RMS value and R_a is the armature resistance.

Eddy current loss:

$$W_e = k_e B_{\max}^2 f^2 \quad (33)$$

where k_e is the eddy current constant (almost equal to 1, i.e. 0.8), f is the frequency of flux reversal in a rotor (50 Hz) and B is the maximum flux density (0.638 Tesla) [20, 21].

Simulink Model of an Universal Motor

Table 1 presents Simulink model specification of an AC operating universal motor. The conventional mixer grinder of 600 W power rated with voltage of 230 V AC and rated speed of 20,000 rpm was considered. The operating torque is based on the size of a jar (0.4 Litre, 1.3 Litres and 1.8 Litres) and the materials used. As per the market available mixer grinders, the required torque is in the range of 0.2–0.4 Nm. Figure 3 demonstrates Simulink model of an universal motor in state of AC operation.

Table 2 depicts parameters of Simulink model of a DC operating universal motor. A mixer grinder speed of 20,000 rpm, 600 W rated power, current of 2.73 A and voltage of 220 V DC was considered. Figure 4 depicts the Simulink model of a DC operating universal motor. Due to the presence of resistance, the current gets restricted, and there is no effect of saturation.

Figure 5 shows the load torque vs. speed characteristics of AC and DC operating the universal motor. For different speeds, the load torque at DC operating condition was more than the AC operating condition. Due to the presence of reactance in the AC operating condition of the universal motor, there was a drop in the speed curve.

Table 3 presents a Simulink model parameters of BLDC motor. A mixer grinder with a speed of 10,000 rpm, 200 W rated power and voltage of 48 V was considered. Figure 6 shows the Simulink model of a BLDC motor.

Table 1 Specifications of the AC universal motor Simulink model [5]

Rated power	600 W
Voltage input	230 V AC
Current	2.61 A
Speed	20,000 rpm
Stator resistance	2.04 Ω
Rotor resistance	1.6 Ω
Self-inductance of rotor	87 mH
Self-inductance of Stator	73 mH
Mutual inductance	2.86 mH
Friction coefficient (B)	1.687e–5 Nms
Inertial coefficient (J)	3.23e–4 kg m ²

Fig. 3 Simulink model of an AC operating universal motor**Table 2** Specifications of the DC universal motor Simulink model [5]

Rated power	600 W
Input voltage	220 V DC
Current	2.73 A
Speed	20,000 rpm
Stator resistance	2.04 Ω
Rotor resistance	1.6 Ω
Self-inductance of rotor	87 mH
Self-inductance of stator	73 mH
Mutual inductance	2.86 mH
Friction coefficient (B)	1.687e–5 Nms
Inertial coefficient (J)	3.23e–4 kg m ²

Fig. 4 Simulink model of the DC operating universal motor

Figure 7 represents the load torque vs. speed characteristics of a 48 V BLDC motor. The torque decreases with an increase in speed. It can be observed that the starting torque was higher in the BLDC motor than in the universal motor.

Figure 8 shows the efficiency vs. speed characteristics of AC and DC operating the universal motor and BLDC motor for different speeds. It can be seen that the efficiency of an AC operating universal motor is 52.16%, and the DC operating universal motor efficiency is 54.5%, while that of the 48 V BLDC motor is 81.15%. The efficiency of 48 V BLDC motor is higher than 230 V AC and 220 V DC operating universal motor.

Losses Analysis of the Universal Motor and BLDC Motor

Efficiency is the ratio of power output to power input, depending on the different power losses, i.e. iron loss, ventilation loss, copper loss, friction loss, mechanical loss and so on. The losses in the 230 V and 220 V universal motor and 48 V BLDC motor are depicted in Tables 4, 5 and 6.

Tables 4, 5 and 6 show that the losses in the 48 V BLDC motor are lesser than those in the 230 V AC and 220 V DC universal motor. The loss in the 220 V DC universal motor is lesser than in the 230 V AC universal motor.

Philips HL 1643/04 model is configured to prove experimental. The model specifications are 600 W, 230 V and speed of 20,000 rpm. The energy and power quality

Fig. 5 Load torque versus speed characteristics of AC and DC operating a universal motor

Table 3 Parameters of BLDC motor's Simulink model

Power	200 W
Voltage input	48 V
Rated speed	10,000 RPM
Resistance of stator (R_s)	0.06 ohms
Inductance of stator (L_s)	0.006 mH
Coefficient of friction (B)	0.0682e-3
Number of poles (P)	4
Inertial coefficient (J)	21.5e-3 J/kgm ²

Fig. 6 Simulink model of 48 V BLDC motor

analyser of the Flux 435 series II is used to take the readings as depicted in Fig. 9.

Comparison of proposed simulated 48 V BLDC motor and experimental conventional mixer grinder is presented in Tables 7 and 8. Compared to the proposed system, the amount of distortion is high in the existing one. When the

Fig. 7 Load torque versus speed characteristics of 48 V BLDC motor

Fig. 8 Efficiency versus speed characteristics of a universal motor and BLDC motor

Table 4 Universal motor of 230 V AC operating losses

Percentage of losses in universal motor 230 V AC	Loss wattage in 230 V AC universal motor
Efficiency = 52.16%	Rated power = 500 W
Field winding = 8.4%	Field winding = 42 W
Armature copper = 14.4%	Armature copper = 72 W
Stray load = 2.14%	Stray load = 10.7 W
Mechanical = 3.62%	Mechanical loss = 18.1 W
Hysteresis = 9.3%	Hysteresis = 46.5 W
Eddy current = 8.07%	Eddy current = 40.35 W
Brush + friction + ventilation loss = 1.91%	Brush + friction + ventilation loss = 9.55 W

crest factor is 1.42, no distortion exists, and if the crest factor is greater than 1.8, then high distortion occurs. The total harmonic distortion of a voltage and current is high in the conventional compared to the proposed system. So, it can be concluded that the proposed 48V BLDC motor has a

Table 5 Losses of 220 V DC universal motor

Percentage of losses in 220 V DC universal motor	Wattage of losses in 220 V DC universal motor
Efficiency = 54.5%	Rated power = 500 W
Armature copper = 14.3%	Armature copper = 71.5 W
Field winding = 8.2%	Field winding = 41 W
Stray load = 2.09%	Stray load = 10.45 W
Mechanical = 3.21%	Mechanical = 16.05 W
Hysteresis = 9.21%	Hysteresis = 46.05 W
Eddy current = 7.17%	Eddy current = 35.85 W
Friction + brush + ventilation loss = 1.32%	Friction + brush + ventilation loss = 6.6 W

Table 6 Losses of 48 V BLDC motor

Percentage of losses in 48 V BLDC motor	Wattage of losses in 48 V BLDC motor
Efficiency = 81.15%	Rated power = 200 W
Resistive loss = 0.5%	Resistive loss = 1 W
Winding loss = 3.76%	Winding loss = 7.52 W
Mechanical loss = 2.02%	Mechanical loss = 4.04 W
Stray load loss = 1.57%	Stray load loss = 3.14 W
Eddy current loss = 4.35%	Eddy current loss = 8.7 W
Hysteresis loss = 6.15%	Hysteresis loss = 12.3 W
Friction loss = 0.5%	Friction loss = 1 W

Table 7 Comparison of proposed simulated BLDC motor and experimental conventional mixer grinder under no-load condition

No-load condition	Experimental conventional mixer grinder (600 W)	Proposed mixer grinder simulated (200 W)
Amount of distortion (crest factor)	Cf = 2.38	Cf = 1.42
Total harmonic distortion	Voltage = 5% Current = 20.2%	Voltage = 3.35% Current = 3.25%

Table 8 Comparison of proposed simulated 48 V BLDC motor and experimental conventional mixer grinder at load condition

With load	Experimental conventional mixer grinder (600 W)	Proposed mixer grinder simulated (200 W)
Amount of distortion (crest factor)	Cf = 2.06	Cf = 1.38
Total harmonic distortion	Voltage = 4.8% Current = 15.3%	Voltage = 3.15% Current = 3.05%

Conclusions

In a MATLAB/Simulink, a proposed BLDC motor and existing universal motor for the application of a mixer grinder were simulated according to the specifications. The comparative efficiency and loss analysis were determined for the experimental convectional universal motor and BLDC motor. The starting torque in the BLDC motor can be observed to be higher than in the universal motor. Due to the absence of brushes friction, the 48 V BLDC motor had a higher efficiency than the universal motor working 230 V AC and 220 V DC. The losses in the 48 V BLDC motor were lesser than in the universal 230 V AC motor and the universal 220 V DC motor. In an existing system, the total harmonic distortion and crest factor are higher than the proposed system.

Fig. 9 Experimental test of the conventional mixer grinder

reduced amount of distortion than the existing in the application of a mixer grinder.

Acknowledgements The authors would like to acknowledge Manipal Institute of Technology, MAHE, Manipal, India for their support of the research work.

Funding Open access funding provided by Manipal Academy of Higher Education, Manipal.

Conflict of interest The authors declare there is no conflict of interest.

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