Brushless Direct Current Motor Efficiency Characterization

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***Abstract*— The use of a compact lightweight efficient propulsion system is one of the main technological requirements for a long endurance electric Unmanned Aerial Vehicle (UAV). Currently the most popular trend is to use a permanent magnet brushless direct current (BLDC) model motor. This type of motor is used because of its efficiency which can be greater than 90% when optimally driven. However the majority of manufacturers do not provide adequate performance response profiles throughout the specified motor applied voltage range. This paper presents a methodology to characterize the BLDC efficiency.**

Keywords—Brushless Direct Current Motor, Permanent Magnet, Unmanned Aerial Vehicle

I. Introduction

Switched reluctance motors were among the earliest electric machines to be developed between the 1830s and 1850s. A reluctance motor develops torque from the tendency of its rotor to move to a position where the inductance of the excited stator winding is maximized. The term switched reluctance does not imply that the reluctance itself is switched, but refers to the switching of the motor stator phase winding currents. This switching is more precisely called commutation, so “electronically commutated reluctance motor” is perhaps an even more precise term to use [1].

The mid 1960s could be said to mark a transition from historical to the modern era of switched reluctance machines. This was brought about by three parallel developments in the industry which started in the late 1960s and early 1970s and gathered momentum since the mid-1980s [1]:

- The development of the power switching devices. These devices facilitated forced commutation and pulse-width modulated current regulators.
- The development of micro-controllers and related digital integrated circuitry capable of implementing more complex control algorithms.
- The development of high-speed computers with advanced programming languages with powerful numerical methods for finite-element analysis and solution of time-stepped differential equations.

According to the National Electrical Manufacturers Association (NEMA), a brushless direct current (BLDC) motor is a rotating self-synchronous machine with a permanent magnet rotor and with known rotor shaft positions for electronic commutation [2]. The BLDC motor control draws a parallel with that of the switched reluctance motor however the main difference is in the use of permanent magnets on the rotor of the BLDC motor.

Two BLDC motor construction types are currently available, namely the sinusoidal and trapezoidal back-emf motors. The control of the sinusoidal back-emf motor is more complex because it requires continuous rotor position feedback and variable PWM to generate average sinusoidal voltages to drive the motor. On the other hand the control of trapezoidal back-emf motors is simpler because only six rotor position detections are required per electrical revolution with positive and negative quasi-square current excitations to drive the motor.

Designers of long endurance electric-propelled UAVs must first be able to identify an efficient BLDC model motor construction design for their intended application. Unfortunately the designer must identify and select more than one competing manufacturer BLDC model motor design. Also the majority of manufacturers do not provide performance response profiles throughout the specified motor applied voltage range. Therefore the purpose of this paper is to provide a simplified characterization system that can be used to determine the performance response profile of any BLDC model motor throughout the applied motor voltage range. Therefore the development and use of a characterization system can eliminate any uncertainty in the efficient performance response between competing manufacturer BLDC model motor designs. To determine the absolute efficiency performance profile will require a complex motor torque measurement system throughout the speed range. However to comparatively determine the most efficient motor design only requires the relative motor efficiency performance response profile. The most simplified approach to determine the relative efficiency performance is to measure the average motor current consumption and RPM response profile throughout the specified motor applied voltage range. The applied voltage to generate the required RPM for a given application for each competing manufacturer BLDC model motor can then be determined from the characterized RPM per Volt response profile. The most efficient BLDC model motor construction design is then determined by comparing the amount of current consumed by each motor from the characterized Amp per Volt response profile. The BLDC model motor that consumes the least amount of current to generate the required RPM will then be the most efficient motor design. Alternatively the characterized RPM per Amp ratio response profile throughout the applied voltage range can also be used to determine the most efficient BLDC model motor. The motor with the highest

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RPM per Amp ratio at the respective applied voltage to generate the required RPM will be the most efficient motor design.

II. THE BLDC MOTOR MODEL

Currently the use of rare-earth Neodymium-iron-boron magnets has dramatically improved BLDC motor torque production. The high remanence and coercivity of these magnets has also allowed reductions in the BLDC motor frame size for the same output torque compared to motors using other PM materials [4]. Stronger PM materials will generate a larger back-emf voltage that opposes the applied voltage and effectively reduces the motor speed range. However, to regain the lost motor speed the generated back-EMF voltage can be reduced by decreasing the number of stator phase coil windings. With fewer winding coil turns more space is available that is then filled up by using thicker wire resulting in a lower winding coil resistance thereby further increasing motor efficiency and even the current rating at the same time. Also by star connecting the BLDC motor three phase windings, higher torque production is generated because two winding coils are always energized at any given time. The overall BLDC model motor torque production and efficiency is further improved by the following design enhancements:

- Significant torque production is achieved with longer uniform rectangular magnetic flux distribution in the air gap generated by surface-mounted radial PMs as in a trapezoidal BLDC motor design.
- The air gap should be reduced in order to more effectively utilize the magnetic field.
- Greater uneven magnetic attraction is generated by winding concentrated phase winding coils in stator slots with salient poles.
- Higher permeability and/or thicker bell housing material will improve BLDC motor efficiency by avoiding magnetic flux penetration wastage.
- Greater output torque production is developed by using longer PMs with longer stator stacks.

A three phase voltage source inverter is the most widely used drive strategy due to cost saving, weight, dynamic performance capabilities and ease of control [7], [15]. The excitation switching is normally set to commutate around the peak of the torque angle curve. Therefore the optimal inverter gate firing sequence will inject rectangular current pulses in each phase that coincides with the 120° electrical flat crest of the generated back-emf waveform [8]. The 60° period is designated as the “silent phase” and is used in “sensor-less” trapezoidal BLDC motor drive control. During this 60° period the generated phase winding back-emf voltage is sensed in order to determine the angular rotor position. The drive scheme of a trapezoidal BLDC motor is simplified because only six detected commutation points are required in a 360° electrical cycle [9]. The waveforms are shown in Figure 1.

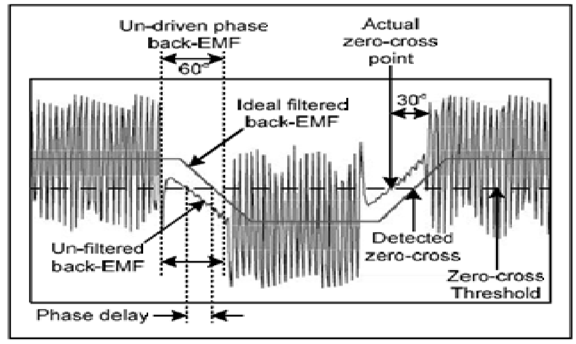

Fig. 1. Actual and ideal filtered back-EMF generated waveforms [12].

The phase winding commutation position is optimal when the un-energized phase back-emf generated voltage is symmetrical thereby ensuring optimal torque production and efficiency. Therefore appropriate adjustment of the phase winding current pulse position will ensure optimal torque and efficiency throughout the BLDC motor speed range [10]. The third harmonic sensing method provides a wider speed range, does not introduce much phase delay and requires less filtering than the terminal voltage sensing method. However open loop drive for BLDC motor start-up is still required since the generated back-emf is zero at standstill [11], [13], [14].

III. CHARACTERIZATION SYSTEM DESIGN

Based only on given motor specifications, it is very difficult to compare the efficient performance response profile between different competing manufacturer BLDC model motor designs. However the performance of a given BLDC model motor relies in part on the combined motor and speed drive controller characteristics. The unknown speed drive controller characteristics can be avoided by using an adjustable speed drive controller to optimally drive and test the different manufacturer BLDC model motors. The BLDC model motor is driven optimally by verifying that the generated phase back-emf trapezoidal waveform is symmetrical throughout the tested BLDC motor speed range. A vertically symmetrical trapezoidal back-emf waveform generation is achieved by appropriately adjusting the motor phase current pulse excitation position at each applied BLDC motor voltage test point. The manufacturer BLDC model motor characterization system proposed is illustrated by a block diagram shown in Figure 2.

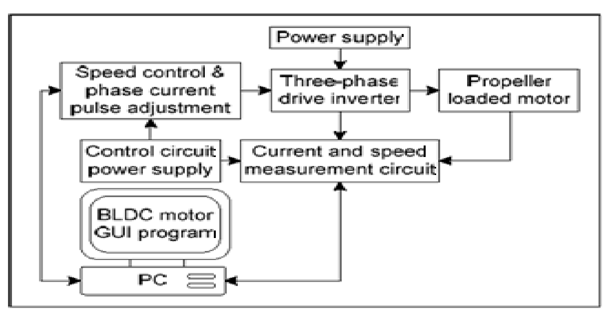

Fig. 2. BLDC motor characterization system [12].

Figures 3, 4 and 5 illustrate detailed schematics used for implementation of the BLDC motor characterization system.

At each applied voltage test point the average motor current and the propeller RPM speed is measured and recorded by the GUI characterization program. The following control and measurement circuits are required:

- A three-phase inverter circuit that is powered by an accurate high current DC/DC converter fixed voltage supply source to drive the BLDC model motors.
- A drive control circuit that controls the three-phase inverter circuit to provide variable applied average motor voltage and an adjustable phase current pulse position excitation.

A circuit that measures the BLDC model motor average current consumption and the propeller RPM speed at each applied voltage test point.

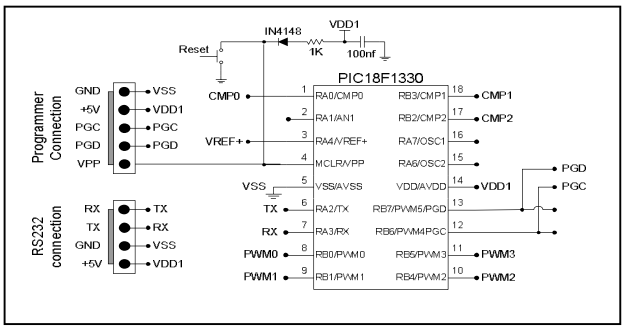

Fig. 3. PIC18F1330 programming, RS232, PWM and comparator [12].

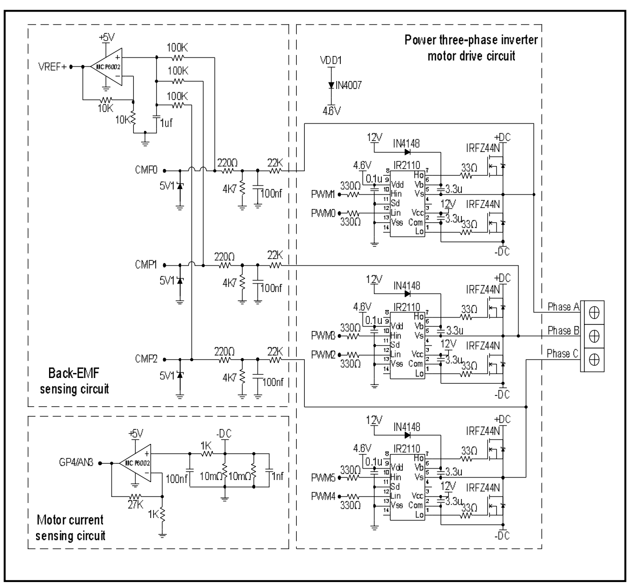

Fig. 4. Three-phase inverter, motor current and back-emf sensing circuit [12].

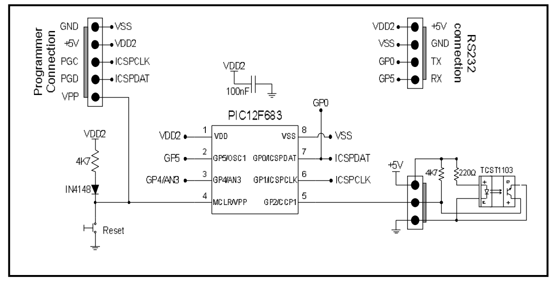

Fig. 5 PIC12F683 microcontroller motor current and speed measurement [12].

Figure 6 shows the experimental setup for efficiency characterization for BLDC.

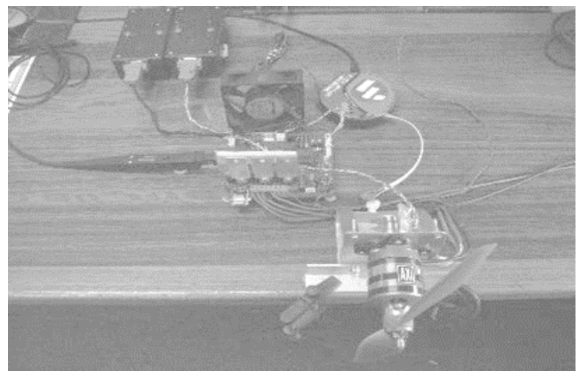

Fig. 6. Experimental set up [12].

The steps to characterize each selected BLDC model motor are as follows:

1) Drive the BLDC model motor at each selected voltage test point to determine the optimal current pulse excitation position that generates a symmetrical back-emf phase waveform.
2) Generate a characterization sequence test with the selected voltage test points and corresponding optimal current pulse excitation positions by using the GUI program.
3) Run the GUI program characterization sequence test to measure and capture the average motor current and shaft speed at each voltage test point.
4) Tabulate and/or graph the measured characterization sequence test results for each selected BLDC model motor manufacturer design, in order to compare the efficiency performance response profiles throughout the applied voltage range.

Steps one to three must be repeated to characterize each selected manufacturer's BLDC model motor design before comparing characterization measurement results.

IV. BLDC COMPARISON RESULTS

Since the relevant application in this case is the use of a BLDC to power an Unmanned Aerial Vehicle (UAV) the load employed was a propeller.

Three well-known manufacturer BLDC model motors were selected for efficiency performance response profile comparison. The objective is to determine by comparing the individually characterized performance response profiles, which BLDC model motor construction design is the most efficient throughout the specified applied voltage range. The results obtained for each BLDC model motor are shown in Figures 7, 8, 9, 10 and 11 respectively.

In Figure 7, the speed response profile of all three BLDC model motors is almost linear with respect to a linear increasing applied motor average voltage.

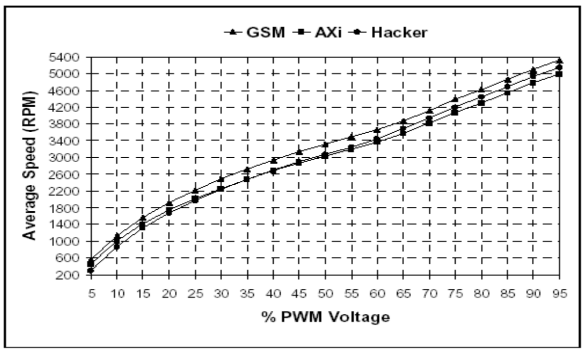

Fig. 7. BLDC motor speed with 16x10 propeller [12].

As clearly observed in Figure 8, all three BLDC model motors selected have an exponential current consumption response profile which is expected when a propeller load is being driven. By using this approach the actual torque generated by each motor is not required in order to determine which motor is the most efficient.

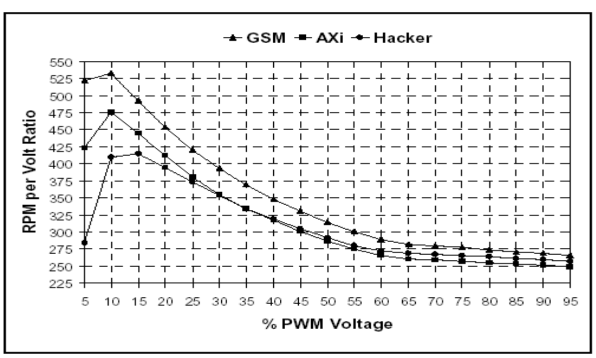

Fig. 8. Current consumption with 16x10 propeller [12].

In Figure 9, the RPM per volt response profile of all three BLDC model motors is higher at the lower applied voltage range and reduces towards the higher applied motor voltage range. This RPM per volt response profile reveals that the given manufacturer RPM per volt number must be an average result for a specified 16x10 propeller load. For example, the Hacker manufacturer specified RPM per volt number is 300 and the measured overall average calculated RPM per volt number is 309.

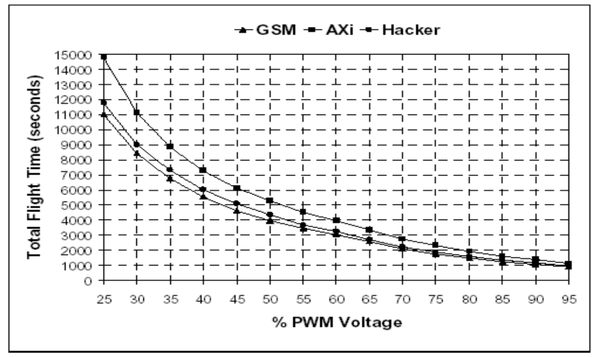

Fig. 9. RPM per Volt ratio with 16x10 propeller [12].

In Figure 10, the RPM per Amp response profile reveals that the AXi motor has the highest efficient performance response profile because of the higher RPM per Amp developed throughout the applied voltage range. At 40% of the applied voltage the Hacker motor efficient performance reaches and then slightly exceeds that of the GSM motor towards the higher applied voltage range. The amount of cogging torque force experienced can be easily determined by manually rotating each BLDC model motor.

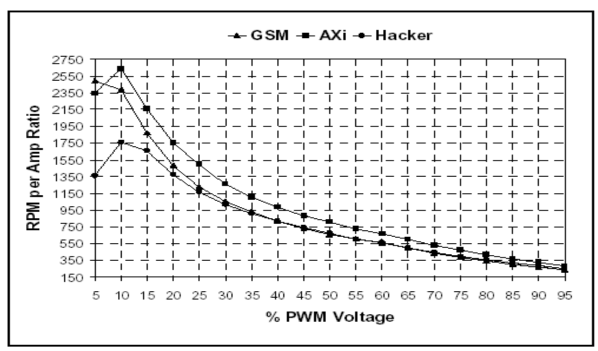

Fig. 10. RPM per Amp ratio with 16x10 propeller [12].

The cogging torque force of the AXi motor is much higher than that of the GSM motor. Therefore the extra cogging torque force of the AXi motor must first be overcome at motor start-up. This explains why the AXi motor RPM per Amp response rapidly increases from 5% to 10% of the applied voltage resulting in a transition above that of the GSM motor RPM per Amp response. Also at around about 75% of the applied voltage both the GSM and the AXi motors both generate an additional rotational mechanical vibration noise. This mechanical vibration is speed dependent because above 75% of the applied voltage the vibration stops. However the Hacker motor runs more quietly and does not experience any additional rotational mechanical vibration which is probably due to the larger bearings used on the rotor shaft assembly. The RPM per Amp response profile is the most appropriate method to compare BLDC model motor efficiency performance, because both the motor RPM and current consumption results are taken into consideration.

Finally in Figure 11, the Amp per volt response profile reveals that the GSM motor consumes the most current per volt followed by the Hacker and then the AXi motors.

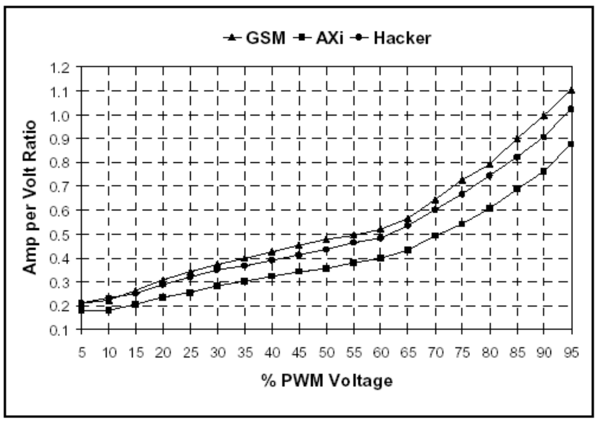

Fig. 11. Amp per Volt ratio 16x10 propeller [12].

However the Amp per volt response profile does not take the generated RPM into consideration and is therefore not an adequate efficiency performance comparison test. The compared overall average results also reveal that the AXi motor is the most efficient even though the GSM motor generates a higher overall RPM while the Hacker motor generates a lower overall RPM. The average maximum UAV flight time at each throttle setting can also be calculated for a given battery capacity with the BLDC model motor driving the specified 16x10 propeller load.

Comparing these results will also reveal the amount of UAV flight time gained by selecting a more efficient manufacturer BLDC model motor design. The average flight time in seconds at each applied throttle voltage setting can be calculated for the GSM, AXi and Hacker motors respectively. Let us assume the flight time calculation is based on a 5500mAh battery capacity and the average measured motor current consumption at each applied throttle voltage setting. The 5,5Ah capacity is converted to ampere seconds when multiplied by 3600 seconds. The (5,5Ah x 3600s) = 19800As is equivalent to the total battery charge in coulombs ($Q = I_{AVE} \times t$) available. The average flight time can then be determined by dividing the total battery charge available by the average current consumption at each applied throttle voltage setting. However a Lithium-polymer battery exhibits a specific discharge profile where the voltage level also drops as the battery charge is decreasing. Therefore the average flight time calculation assumes that a fixed voltage at each throttle setting is constantly applied and the average motor current consumption remains constant. Therefore these results represent the absolute maximum flight time and can be comparatively used to determine the extra flight time acquired by using a more efficient BLDC model motor. In Figure 12, the total flight time response profile at the different applied voltage throttle settings clearly indicates that the AXi motor will ensure longer UAV flight times. For example at 50% of the throttle voltage setting the average flight time difference between the AXi and the GSM motor will be (5294 sec – 3952 sec) = 1342 sec, i.e. 22 min and 22 sec. The AXi motor speed may be lower at 50% of the throttle voltage setting compared to the GSM motor. This may require increasing the AXi motor applied voltage to increase its speed to match that of the GSM motor. However the AXi motor still has the most efficient RPM per amp response profile.

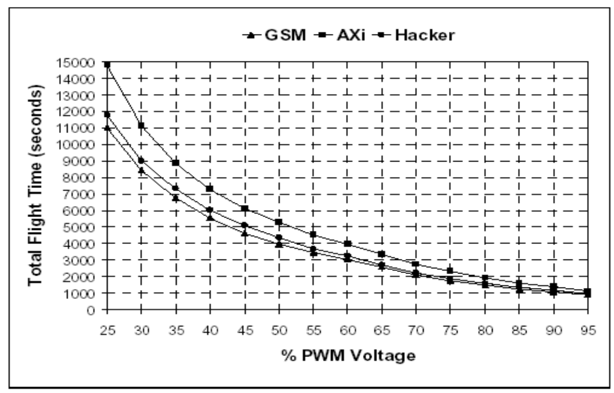

Fig. 12. Flight time comparison response profile [12].

V. Conclusions

The scope of this investigation has only focused on the efficiency performance response profile comparison between competing BLDC model motor manufacturers. The quality of the materials used in the construction of these motors has not been considered. This type of construction quality investigation will require endurance accelerated life tests that consist of extreme temperature cycling, humidity, vibration shock testing, etc. The test results obtain from the proposed characterization system has however revealed that the AXi motor has the most efficient performance response profile out of all the selected manufacturer BLDC model motor construction designs. Clearly this graphical efficiency performance response profile comparison test provides an adequate simplified solution to determine the most efficient BLDC model motor construction design. Currently BLDC model motor manufacturers do not provide similar performance response profiles to assist UAV enthusiasts in not only selecting the most efficient motor but also optimal drive throttle voltage settings. By using the motor characterized response profiles, the lowest throttle setting that develops adequate thrust can now be determined thereby extending UAV flight time.

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