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Experimental Implementation of Speed Stabilizer Based Field Oriented Control of Brushless DC Motor for Scooter Applications

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ABSTRACT- An electric scooter; as one type of Lightweight vehicles technology, is a motorized vehicle designed for short-distance travel and recreational purposes. It is powered by an electric motor and typically has a rechargeable battery that provides sufficient power to operate the vehicle. Electric scooters are similar to traditional scooters but are much quieter, eco-friendly, and more energy-efficient. They are commonly used as an alternative mode of transportation for commuting, sightseeing, and recreational activities. This work presents an experimental implementation of speed stabilizer of electric scooter. In fact, a constant speed function might be required in a specific case in the operation of the scooter. Field-oriented control (FOC) technique is selection to control the velocity of three-phase Brushless-DC motor. 3-phase Brushless-DC motor of the scooter utilizing a PIC16F873A Microcontroller through a Driver circuit. The control algorithm is designed to generate a pulse width modulation (PWM) signal using the PID controller provided with this microcontroller and compare it with the speed sensor return pulse so as to establish and implement a closed feedback system to obtain good stability achievement of the scooter velocity at different load values. The results gained from this work demonstrate the prospect of gaining a broad extent of control scooter speed at different loads with high reliability.

Keywords: BLDC motor, PIC16F873A Microcontroller, FOC method, Gate driver, Speed control.

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1. INTRODUCTION

Pollution caused by emissions from the use of fossil fuels is one of the most important challenges facing contemporary societies. Therefore, the efforts of scientists and researchers have focused in recent decades to search for alternative sources of energy that have a positive impact on the environment. The transportation is one of the most energy-consuming field and therefore one of the most environmentally impactful sectors. Electric and hybrid vehicles are the solutions to reduce emissions from the transportation sector, so competition in the manufacture of these vehicles between companies has reached high levels in recent years [1,2].

One of the most promising technologies in the field of green technology for transportation for short distances is electric motorcycles. This technology has many advantages, especially in crowded areas, as it offers the speed and ease of access to the destination place. In addition, the need of special places for parking and stop is reduced. All this calls for focusing on this technology in terms of scientific and research contributions [3]. Electric scooter which is utilized for movements within short distances includes brushless DC motor (BLDC), batteries and a control system beside the frame and other mechanical parts. The devise is designed in different ratings; i.e. the motor torque, the capacity of batteries and the rider weight and the user could choose the suitable device accordingly [4,5].

The speed of the scooter is an important parameter as it is related to the rider safety. The control system of the scooter regulates the required speed according to rider need. Several control strategies related to the speed regulation of the scooter are presented in the literature [5].

The design of a speed limiter for an electrically assisted kick scooter is presented by (Aida Brankovic, et al., 2015). Initially, a model of the longitudinal dynamics that is control-oriented derived, considering the interaction between the human and the scooter. The next step is to perform a coasting-down experiment for parametric identification. Finally, two distinct speed limiting architectures which are a torque controller with dynamical saturation (DSTC) and a relay-based scheme are

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examined experimentally. The results proved that DSTC is more reliable and effective than relay-based scheme [6].

A control system based fuzzy logic approach of three-wheel scooter for speed control purposes is presented by (Chergui Hicham, et al., 2019). The simulation runs with certain assumptions and at a specific speed. With the use of PI speed controller and the Electronic Differential system, comparative simulation results were presented. The proposed Electronic Differential system responds quickly on both ramp roads and bends. The simulation results show that the recommended electronic differential system operates satisfactorily [7].

Two control strategies of speed limitation are expressed experimentally in. The results conclude that the dynamic saturation torque control strategy is more robust and efficient than Relay based control strategy. To enhance the performance of electric scooter, the control system is improved to be intelligent in [8,9]. In fact, such control system includes power energy management control of the battery in addition to the speed control of the scooter. According to this intelligent system, the rider can monitor the energy of the battery which leads to better use of the scooter. A PID current controller is utilized in the control system of (BMDC) motor of the scooter in. A digital isolator is used to eliminate the effect of the ripple current in the motor. The experimental findings recommended this technique in scooter applications [10,11].

Regarding the speed limiter of the scooter, several research have been carried out to enhance the scooter speed controller through contemporary microcomputers and the power electronic systems. For instance, a combination of high-performance PIC microcontroller and power electronics devices has enabled superior control over the field of scooter speed control. Furthermore, the switching methods used in inverter control technology play a significant role in the expansion and reinforcement of scooter control by decreasing harmonics [12]. In this paper, a Field Oriented Control (FOC) method has been chosen to control the speed of 3-phase BLDC motor of scooter using a PIC16F873A Microcontroller through a Driver circuit. The control algorithm is designed according to pulse width modulation (PWM) theory with the PID controller of the pulse bandwidth equipped with this Microcontroller and compared to the return pulse of the speed sensor in order to create and apply a closed back-feed system for good stability performance of scooter speed at the rider weight of changed. After applying the rider weight to the scooter motor, the PIC16F873A Microcontroller operates on altering the system's speed.

2. SYSTEM DESCRIPTION

The block diagram of the proposed system to stabilize the speed of the 3-phase BLDC motor of the scooter is shown in *figure 1*, that includes the PIC16F873A Microcontroller-based for FOC control process. PIC allows high speed and greater precision control of BLDC motor in a variety of load situation. the PWM switching and PID speed controller was applied to control the motor. FOC is derived from the stator current components over two rectangular- axes realized as direct (d) and quadratic (q), respectively. The main motivation back FOC is that it furnishes accurate speed control in motors with high power-to-weight ratio.

the system contains of the DC power supply (48V,5A), 3-phase voltage source inverter (VSI), 3-phase BLDC motor of the scooter. The control circuit that involves PIC16F873A Microcontroller, and the feed-back sensors circuit. VSI, which is built of MOSFETs VSI is used to manage the flow of DC power source to the load. VSI module consist of the 6 MOSFETs linked, 42 amperes, 100-volt, type IRFP150N. The gate drive circuit is layout using Epitaxial silicon transistor BC327 and switching transistor 2N2222 for the purpose of enhancing the power level of the MOSFET switching pulses of the layout VSI. In fact, the designed gate drive circuit is compatible with the PWM output channels connected to the PIC. The generated signals are exercised to the VSI, that in turn controls the speed of the motor according to the proposed scheme.

Here, FOC method consist of two loops, i.e. the inner loop senses the change of the BLCD motor current through a conditioning current sensor while the outer loop is related to the speed of the BLCD motor. Rotation of a BLDC motor demands feed-back from the proportional rotor position. The most widely used BLDC motor employs Hall-sensors as a exporter of position feedback. Rotation of a BLDC motor demands feed-back from the proportional rotor position. The most widely used BLDC motor employs Hall-sensors as an exporter of position feedback. so as to manufacture on a rotating field (driving torque), the stator phases must be switched on and off sequentially through the six-switches of the 3-phase full bridge converter, according to the position of the rotor. Position signals are returned from the three-Hall sensors as shown in *figure 2* which characterizes the BLDC motor circuit operation.

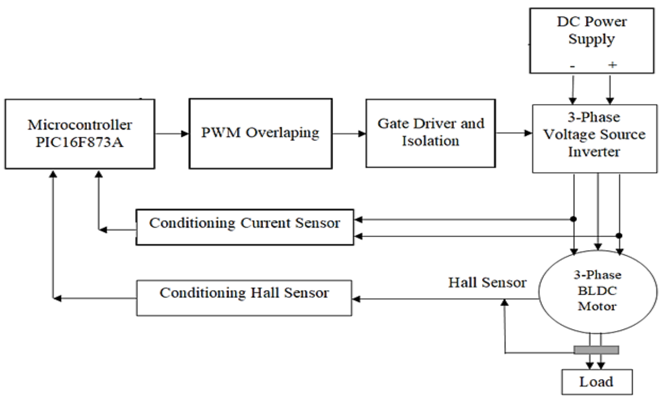

Figure 1. Diagram of the proposed scooter control system

The digital pulses (bit pattern) are supply from the Hall-sensors to the microcontroller. An external interrupt is created on each bit variation at any of the 3-Hall position signal inputs. The bit change interrupt is an inherent feature of the PIC16F873A microcontroller and is very beneficial in designing the algorithm of the motor control. once any bit change happens in any of the Hall input signals, the program fulfilment sequence moves to the interrupt address. Another side of this PIC is that

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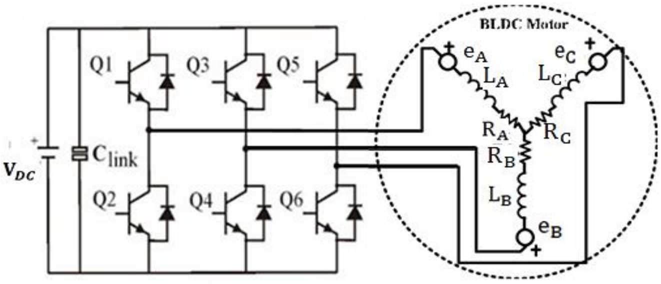
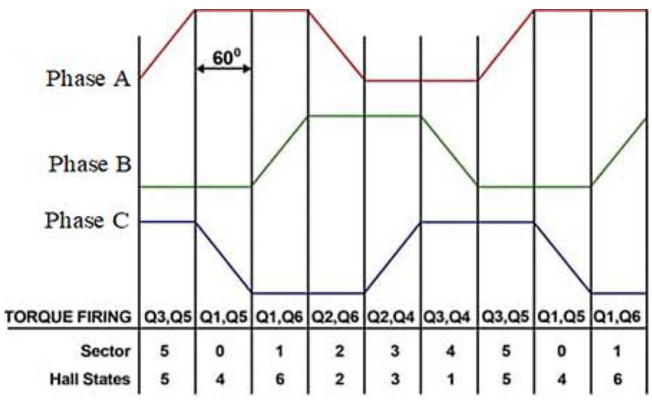
it has 8 set up PWM signals, out of which 6 PWM signals are wanted to operate the gates of the 3-phase VSI. This inverter directly operations the 3- phases of a BLDC motor. relying on the rotor position, the PWM channels are driven. The BLDC motor is connected in a star shape. As a result, this motor can be related to a 3-legged VSI. The BLDC motor is use for check various loading conditions.

3. MODELING OF BLDC MOTOR FED BY 3- PHASE INVERTER

The combination of BLDC motor fed by a three-phase inverter is shown in *figure 2(a)*. The BLDC motor is running and controlled by an inverter, and the power is transferred from the DC- power supply to the BLDC motor by the switching and series connection process of the 3-phase inverter. As shown in *figure 1(b)*, the six-step commutation acquired from experiments. For every step, two windings are activated. The VSI consists of 3 half bridge MOSFETs as a switching phases a, b and c. The switches Q1, Q2, Q3, Q4, Q5 and Q6 of VSI will be activated by PWM signal provided by the gate driver circuit [13,14].



(a) Equivalent circuit



(b) Six Step Commutation

Figure 2. Model of BLDC motor fed by 3 phase inverters

The equivalent circuit of BLDC motor composed of a series resistance, a DC source and a created voltage that displays the DC source. As explained in Figure 2(a), Since the BL-DC motor is a changing speed device, the input voltage must be controlled to match the voltage and current to the required speed and load. The terminal voltage applied to the motor is determined by [15,16]

A BLDC motor contains permanent-magnets on the side of the rotor and 3-stator windings. Because the stainless steel and magnetic retaining sleeves have high resistance, the currents generated by the rotor can be neglected and the damper coils cannot be modelled. Therefore, the circuit equations for the 3 coils in phase variables are [17]

$$V_A = Ri_A + L\frac{di_A}{dt} + e_A \tag{1}$$

$$V_B = Ri_B + L\frac{di_B}{dt} + e_B \tag{2}$$

$$V_C = Ri_C + L\frac{di_C}{dt} + e_C \tag{3}$$

The matrix from the phase voltage equation of brushless DC motor can be shown as [18]

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} R_A & 0 & 0 \\ 0 & R_B & 0 \\ 0 & 0 & R_C \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_A & L_{BA} & L_{CA} \\ L_{BA} & L_B & L_{CB} \\ L_{CA} & L_{CB} & L_C \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \tag{4}$$

Based on the *equation (4)*, It has been assumed that the stator resistance of all the windings is equal. Assuming further that there is no change in the rotor reluctances with angle, then [18,19]

$$L_A = L_B = L_C = L \qquad L_{AB} = L_{BC} = L_{CA} = L$$

Hence,

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} R_A & 0 & 0 \\ 0 & R_B & 0 \\ 0 & 0 & R_C \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \tag{5}$$

Where V_A, V_B, V_C is a phase voltage A, B, and C. R is a stator resistance. L_A, L_B, L_C are self-inductance of A, B, and C phases. L and M is self-inductance and mutual inductance. i_A, i_B, i_C is phase current A, B, and C. e_A, e_B, e_C is phase back emf voltage A, B, and C.

The electromagnetic torque of brushless DC motor can be shown as

$$T_E = \frac{e_A\, i_A + + e_B\, i_B + e_C\, i_C}{\omega_M} \tag{6}$$

Where, T_E is electromagnetic torque of brushless DC motor and ω_M is angular velocity of rotation in radians per second.

The equation to calculate the motion in order to build a complete mathematical model of electromechanical system can be shown as

$$T_E - T_l = J\frac{d\omega_M}{dt} + B_u\omega_M \tag{7}$$

Where, J is an engine moment of inertia, T_L is the load torque and B_u is the coefficient of viscous friction.
The electrical position of the rotor and the rotor speed are related to [20].

$$\frac{d\theta_R}{dt} = \frac{P}{2}\omega_M \tag{8}$$

Research Article | Volume 12, Issue 3 | Pages 919-925 | e-ISSN: 2347-470X

Where, P is the number of poles and θ_R is the position of the rotor with relative to d-axis in rads. The equations discussed a above used to are to evolve the parameter blocks.

In this proposed electric scooter system, BLDC motor specifications are listed in *table 1*.

Table 1. Parameter values of the BLDC motor

Parameter	**Value**
Operating Voltage	DC 24V/36V
Power	Max 250 W
Speed	Max 900(r/min)
Current Limit	2 Amps
Torque of the wheel motor	7.86 N.m
Tire	Solid Rubber Tire
Wheel Weight	3.35kg
Sensors	5V Hall Effect Sensors

4. EXPERIMENTAL IMPLEMENTATION

The main purpose of the proposed control system as shown in *figure 1* is to achieve a constant speed of e-scooter at variable load values. The experimental implementation of the proposed system is shown in *figure 3*, that includes a PIC16F873A Microcontroller kit which is coded to generate the required PWM signals, a gate driver circuit, a BLCD motor and VSI in addition to other devices and measurement meters. The FOC control approach is utilized in this paper.

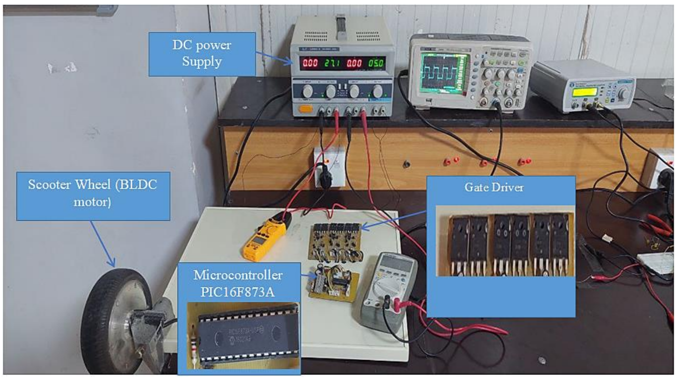


Figure 3. Experimental implementation of the proposed system

When the power is turn on, the dc-voltage of VSI is determined to 27 V. The PIC16F873 kit provides six-PWM signals to the MOSFETs gates. This signals pass through the gate drives to the MOSFET gates in the inverter to supply the BLDC motor with the power it demands. Then the motor starts to run at its requisite speed. But its speed reduces when it is loaded. consequently, an speed sensor detects the lowering in speed and emits it to the PIC16F873. Now, the PIC16F873 implements the program and outputs the BLDC motor unit signal. As a result, the voltage necessary to maintain the base speed will raise. So, the speed of the motor remains constant after the load is placed. In this way, speed control of the BLDC motor is achieved.

5. RESULTS AND DISCUSSION

The proposed speed stabilizer of scooter is implemented experimentally with and without the designed controller on the foundation of constant speed for variable load states. The measurements of the system include the duty cycle (D) that produced by the controller, the drawn current by the motor which analogue the load torque, and the shaft speed of the motor in (rpm) as follows,

5.1. Without the proposed controller

The measurements of the system without the created controller are summarized in *table 1*. Through the control process, PWM pulses are created which involves getting a reference voltage by facilitating the PWM case. *Figures 4(A) - 4(F)* show variation in duty cycles of modulated pulses beneath variation loads in a controller that modulates the duty cycle of the PWM control signal that obtain the desired speed.

- Test 1 as displayed in *figure, 4(A)* and *table 2*. It displays the natural running of the engine by a velocity of 370 rpm no-load, it may be visible that the pulse value is around 35% (PWM signal period is around 500×10^(-6) ON, 500×10^(-6) OFF) and the pulled current is around 0.5 Amp.
- Test 3 displays the second loading case of the engine as displayed in *figure, 4(B)* and *table 2*. Now, we notice that when a load is applied to the engine, the motor velocity decreases to 368 rpm, and the drawn current value becomes around 0.57 A, *i.e.* an increase comparison to the absence of load, as shown in Test 1. It can be noted that the pulse value is around 43% (PWM signal period is around bout 670×10^(-6) ON and 330×10^(-6) OFF).
- Test 4 displays the third loading case as displayed in *figure 4(C)* and *table 2*. Here we notice that while the load value is raised, the velocity drops to 358 rpm and the drawn current becomes around 0.91 amps, *i.e.* an increase comparison to the no load-test. It can be noted that the pulse value is around 50% (PWM signal period is around 700×10^(-6) ON and 300×10^(-6) OFF).
- *Test 5* shows the fifth loading case as shown in *table 2* and *figure 4(d)*. It is noted here that if the load on the motor increases, the speed decreases to 351 rpm with the value of the current drawn reaches 1.11 amps, *i.e.* an increase compared to the no-load test. The pulse value is around 55% (the period of the PWM signal is 730 µs in ON mode, and 270 µs in OFF mode).
- *Test 6* shows the sixth loading case as shown in *table 2* and *figure 4(e)*. Here we notice that if a load is applied to the motor, the speed of the motor reduces to 347.5 rpm and the value of the current drawn reaches 1.2 amp, i.e. an increase compared to the no-load test. The pulse value is around 65% (the period of the PWM signal is 820 µs in ON mode and 180 µs in OFF mode).
- *Test 7* shows the seventh loading case as shown in *table 2* and *figure 4(f)*. It is notice here that if the load on the motor increases, the speed reduces to 344 rpm and the value of the current drawn reaches 1.31 amps, i.e. an increase compared to the no-load test. The pulse value is around 70% (the period of the PWM signal is 870 µs in ON mode and 130 µs in OFF mode).

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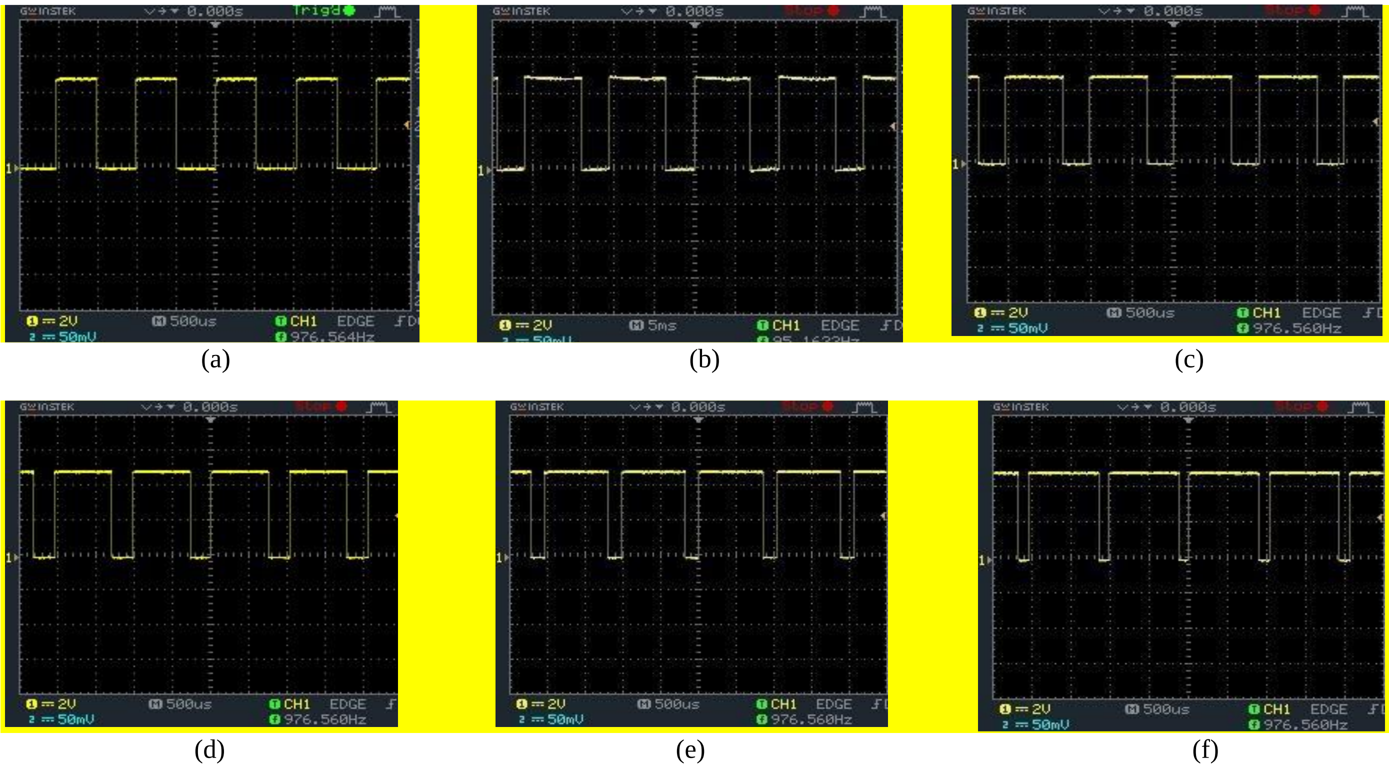

Figure 4. Different duty cycles under the different loads (a) no load, (b) load 2, (c) load 3, (d) Load 4, (e) load 5, and (f) load 6 are applied on the motor

Table 2. The practical results drawn current as torque with the speed of Scooter or BLDC Motor without controller

No. Test	Current I(Amp)	Duty Cycle %	Speed(rpm)
1	0.5	35	370
2	0.57	40	368
3	0.7	43	364
4	0.91	50	358
5	1	55	354.5
6	1.11	60	351
7	1.2	65	347.5
8	1.31	70	344

5.2. With the proposed controller

Table 3 shows the response speed of the system to the FOC control planner and changes in the cyclic time of the PWM while the controller is in place through the different loading process. The speed control group used to manage the process of keeping the speed constant at 370 rpm adjusted the duty cycles through the eight test stages, based on the loaded conditions, accordingly shown in *table 3*. It can be noticed that the controller senses the load change and stabilize the duty cycle (D) at the designated value of 35% that reflects the scooter speed of 370 rpm. For instance, when the motor is loaded to draw 0.5 A, a 35% duty cycle is produced by the controller accordingly. If the load is increased and the motor draw a current of 1 A, the controller will process this change and re-correct the value of duty cycle at 35% and the speed will be stabilized at 370 rpm. So, the duty cycles were adjusted compared to that in the load case shown in *table 2*.

Table 3. The practical results drawn current as torque with the speed of Scooter or BLDC motor with controller

No. Test	Current I(Amp)	Duty Cycle %	Speed(rpm)
1	0.5	35	370
2	0.57	35	370
3	0.7	35	370
4	0.91	35	370
5	1	35	370
6	1.11	35	370
7	1.2	35	370
8	1.31	35	370

Figure 5 shows the speed of response when applying different loads in the absence of a controller. it can be clearly concluding the inverse relationship between the speed of the motor and the current drawn by the motor because of changing the duty cycle. We note that increasing loads guides to higher values of the pulled currents. The speed deviation increases with increase of the load, which leads to a raise in the pulled current.

Figure 6 shows the velocity response when different loads are applied to the motor according to the controller. It can be clearly seen that the increasing of the load on the motor that leads to higher values of the drawn current will not affect the values of PWM and hence the speed of the motor (We notice a constant speed at 370 rpm) due to the successful operation of the proposed controller.

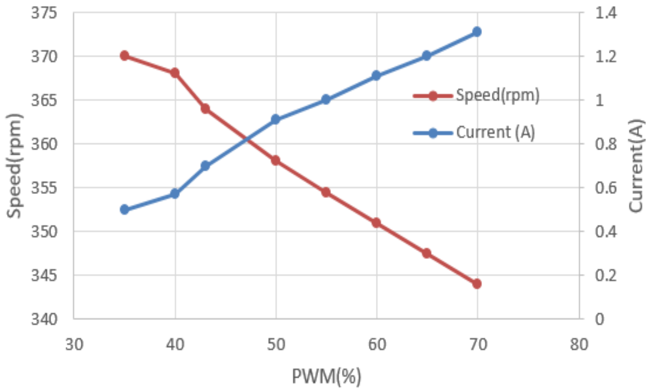

Figure 5. motor speed and motor current vs. duty cycle (without controller)

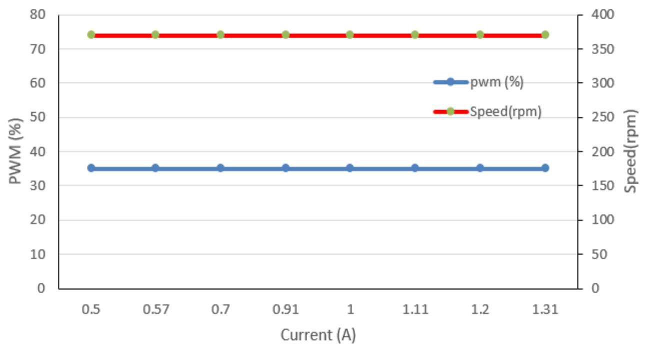

Figure 6. motor speed and motor current vs. duty cycle (with controller)

6. CONCLUSION

An experimental speed stabilizer implementation for an electric scooter is presented in this article. In fact, under certain situations, the scooter's functionality may call for a constant speed feature. The scooter's three-phase brushless DC motor speed was selected to be controlled via a driver circuit and a PIC16F873A microcontroller using the Field Oriented Control (FOC) approach. In order to create and apply a closed back-feed system for good stability performance of scooter speed at various load values, the control algorithm is designed to produce a pulse width modulation (PWM) signal with the PID controller of the pulse bandwidth equipped with this Microcontroller and compare it to the return pulse of the speed sensor. The results proved that the speed control toolkit used to manage the process of maintaining constant motor speed with variable loads has achieved the desired goal of the presented research. In the tests conducted, starting with no load of the motor, we note that increasing the loads leads to higher values of the drawn currents (0.5, 0.7, 0.91, 1.11, and 1.31) amperes. In other words, it is observed that the gradual increase in the duty cycle of the square wave generates the width (35, 43, 50, 60, 70) % proportional to the increase in the load value, and thus the stability of the speed the motor was kept constant (370 rpm) regardless these changes in different loads.

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