# Design of Electric Bike Controller Using Pulse Width Modulation (PWM)

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***Abstract*— As technology continuously evolves and as we move towards the age of Industry 4.0 it is also important to keep up with the pace and move along with the times. Modes of transport through out the ages have also evolved and have become more energy efficient. Bicycles have also evolved throughout the ages and are now electrically powered. The introduction of electric bicycle has led to some of the most interesting applications of electric motors and power electronics. The brushless direct current motor is ideal for this application as its high efficiency , better thermal management, silent operation and reliability. BLDC motors are also attractive in automotive applications as they offer desirable control. The control of these motors can be either sensored or sensor less depending on the application. Another technique that usually accompanies control of brushless dc motors is the utilization of Pulse Width Modulation(PWM). This technique is used to limit the excessive starting current through current chopping and essentially this then controls the speed and the torque of the motor at the shaft. In this project , a prototype electric bike controller will be designed and built. Sensored position control will be used by using hall sensors ,while to vary the speed and torque, PWM shall be used. The focus of this paper was the conversion of the automotive alternator into a BLDC (as AC machines can be converted into DC machines and vice versa) ,insertion of the hall sensors to complete the sensored BLDC design. To ensure success of this project, hall sensors were studied and how the commutation of the BLDC commenced. PWM was used. The last part was to test for the correctness of the switching sequence, the PWM outputs and the characteristics of the BLDC as it shall be ideally used as the electric bike's drivetrain.**

## I. Introduction

Drives are one of the most important and fundamental components in the purely electrical and hybrid automotive industry today. For us to be able to have an electric bike, three things are needed, that is : a controller, a drive circuit and the motor itself. The controller is the brain of the whole system. The main components of the control unit are the microcontroller and hall sensors. There are many microcontrollers that are competent and very useful when it comes to motor control. These include the Microchip Pic and dsPic series, the PSoC, Arm Cortex , Microchip ATmega and the ATmega based Arduino. The microcontroller is responsible for providing the crucial information to the drive circuit with respect to switching and PWM. This information is provided based on the 3digit binary code generated at every commutation step by the hall sensors and by the potentiometer demand setting to determine the required duty cycle. The drive circuit is also known as the power stage of the system. This sole purpose of the drive circuit is to take input DC power and give out AC power to the motor for the motor to rotate. This drive circuit is also known as a 3-phase bridge inverter. The way the inverter takes this DC input is determined by the switching of a pair of MOSFETs per commutation step which is determined by the rotor position as established by the hall sensors.
Finally, the motor receives this AC and a rotating magnetic field in the stator is created. This rotating magnetic field then causes the rotor which could be a permanent magnet or electromagnet to follow this rotating magnetic field. This then causes the shaft of the BLDC motor to rotate.
Below is a simplified illustration of the configuration:

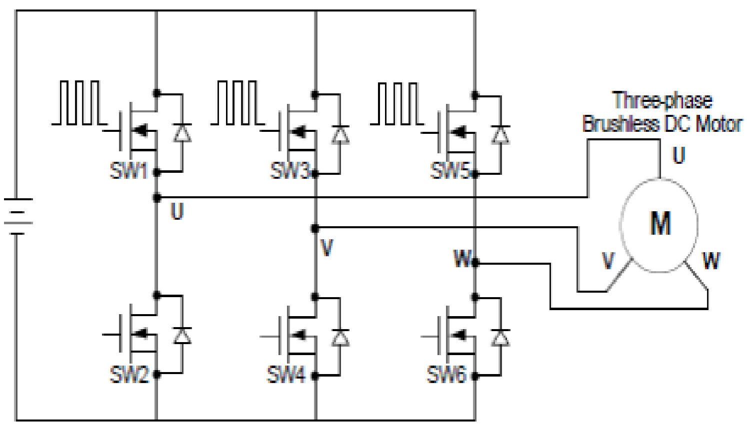



**Figure1 : BLDC Drive Circuit[1]**

The speed and torque of motor is controlled varying the PWM duty cycle between 0-100% whilst the frequency is kept at a constant level. At 0% the speed and torque are at their lowest while at 100% they are at their highest. The

## II. Methodology

The first step in this project was to derive a system block diagram to show how the various subsystems interact with each other. The block diagram is illustrated below:

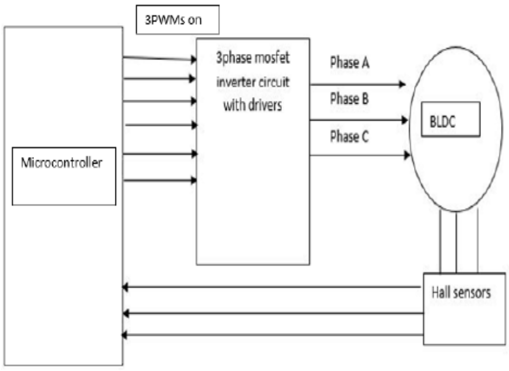



**Figure2 : Block diagram of the whole system**

The microcontroller reads the 3 states of the hall sensors and based on the instructions set by the designer a 3digit binary code is generated which is then sent to a lookup table. In this lookup table there are different pair combinations of MOSFETs that must switch on based on the binary code.

A table was lookup table was generated to facilitate clockwise commutation of the BLDC. Th high-side switch perform PWM while the low-side switches are either on or off.

| STEP | Hall Effect sensors | | | MOSFET switching | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | HALL 1 | HALL 2 | HALL 3 | Drive SW1 | Drive SW2 | Drive SW3 | Drive SW4 | Drive SW5 | Drive SW6 |
| 1 | 1 | 0 | 1 | pwm | 0 | 0 | 1 | 0 | 0 |
| 2 | 0 | 0 | 1 | pwm | 0 | 0 | 0 | 0 | 1 |
| 3 | 0 | 1 | 1 | 0 | 0 | pwm | 0 | 0 | 1 |
| 4 | 0 | 1 | 0 | 0 | 1 | pwm | 0 | 0 | 0 |
| 5 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | pwm | 0 |
| 6 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | pwm | 0 |

**Table1 : Lookup Table for Commutation**

From the above table the logic of the code was built such that when the rotor's position is sensed, the condition obtained is compared against the lookup table and then the respective MOSFET gates are triggered.

Once this was done the next step was to modify the automotive car alternator as a sensored BLDC motor and build the drive circuit. This was done as shown below:

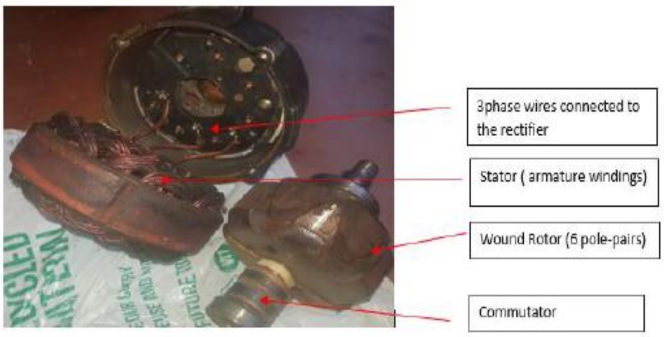



**Figure3: Alternator configuration**

The alternator was then modified by placing small permanent magnets at the end part of the rotor so that the position could easily read.

This is shown below:

**Figure4 : Permanent Magnet Placement on rotor base**

And finally, for the modification to a BLDC motor to be complete, hall sensors had to be inserted inside. This was done by spacing them 20°apart from each other.

The figure below shows this :

**Figure5: Hall sensors embedded inside the machine**

Once the alternator was successfully modified into a BLDC sensored motor, the next step was to construct the drive circuit as was designed and shown below.

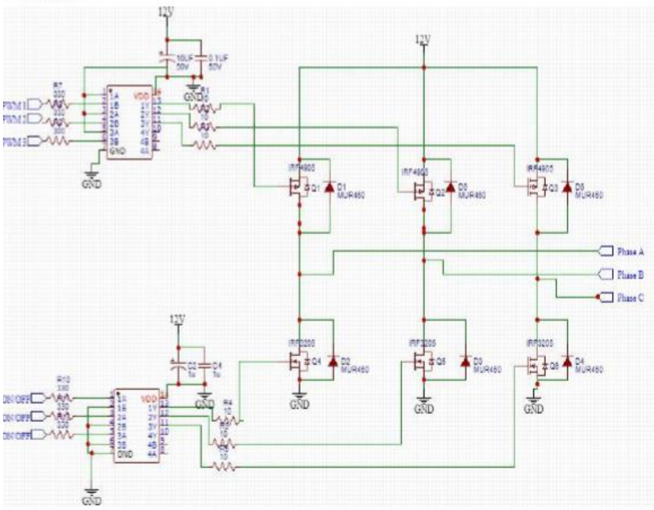


**Figure6 : Design of Power Stage**

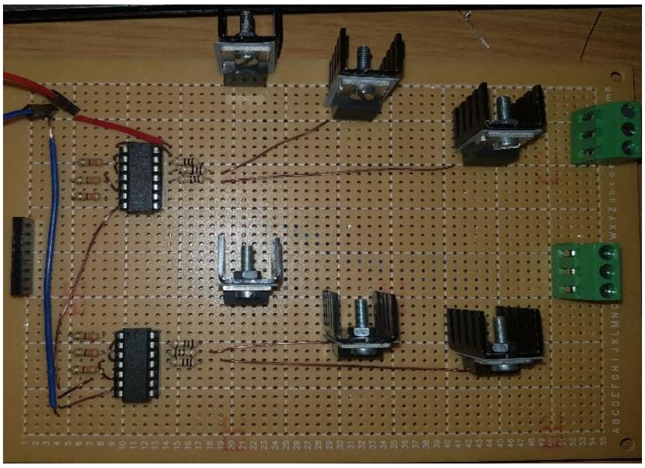


**Figure7 : Power Stage**

The images above show the driver circuit that was designed and constructed using the TC4469 drivers and IRF4905 and IRF3205 MOSFETs. The supply voltage is 12V while the voltage provided at the driver inputs in 12V. Six Power rectifiers were soldered in between the drain and source of each MOSFET to improve current recirculation within circuit during switching.

Finally, the last step was put together the whole system as one and begin testing of the controller and  BLDC. The image below shows the circuit of everything connected and put together.

**Figure8 :  Set-Up**

## III. Experiments and Performance

***<u>Experimental Observations:</u> Checking the correctness of the switching sequence based on the lookup table designed***

An LED experiment was conducted to check the correctness of the switching sequence based on the lookup table designed. 6 LEDs were mounted on the breadboard to simulate the 6 MOSFETs, the shaft of the motor was then rotated and every 18 or so 20° mechanically, a pair of LEDs switched on according to the lookup table. This was true for all the 6 commutation steps.

Below show the results of this :

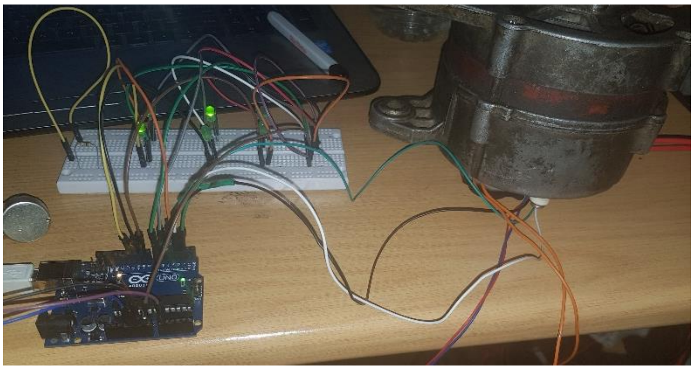


**Figure8 : LEDs simulating Phase A low and Phase B high both on**

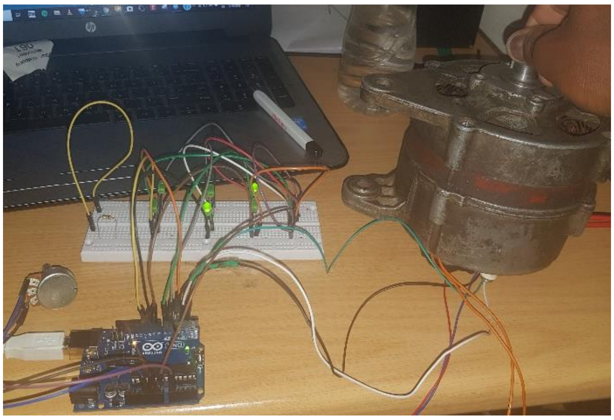


**Figure9 : LEDs simulating Phase C high-side and Phase B low-side both on.**

Thus, from the experiment above it was shown that the switching sequence is correct.

***Experimental Observations:*** ***Testing PWM of the gate pulses of the MOSFETs***

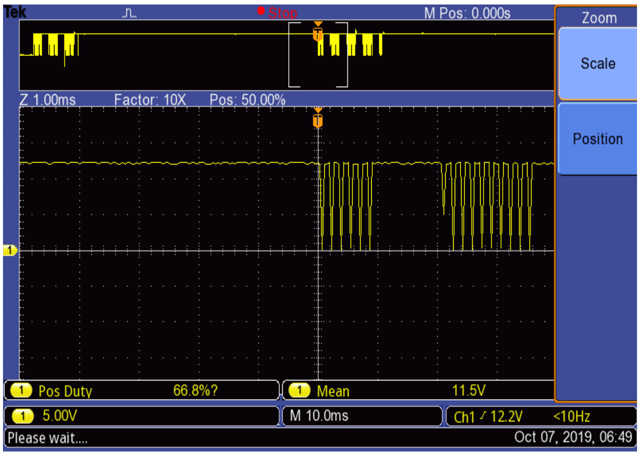



**Figure10 : Gate Pulse(PWM) of high-side MOSFET**

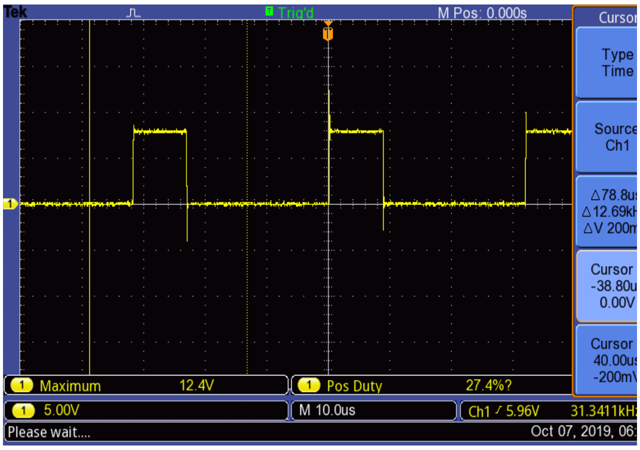
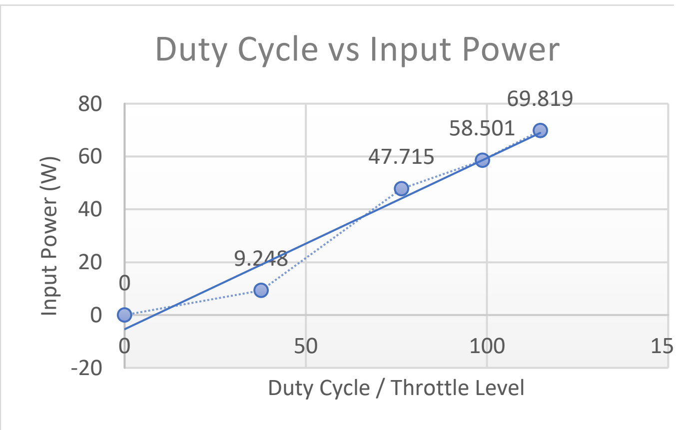



**Figure11 : PWM at 31kHz**

***Performance Results 1:*** ***Input Power***

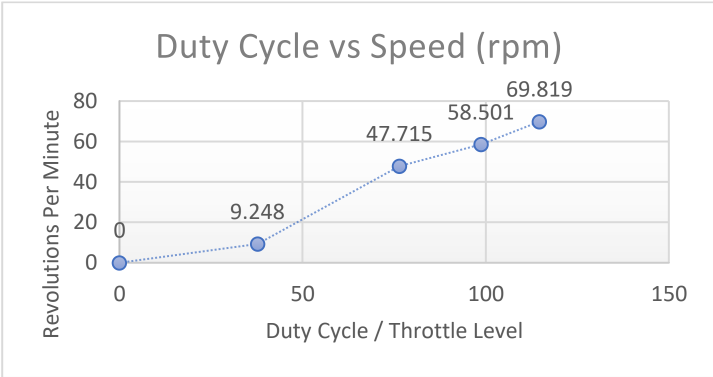
| Throttle Level | Voltage (V) | Average Current (A) | Input Power (W) |
|---|---|---|---|
| 0 | 12 | 0 | 0 |
| 25 | 12 | 3.2 | 12.32 |
| 50 | 12 | 4.33 | 53.34 |
| 75 | 12 | 5.48 | 67.51 |
| 100 | 12 | 6.79 | 83.65 |




From the above graph the Input power is directly proportional to the duty cycle. This was to be expected as the essence of PWM is to reduce input power levels as per duty cycle setting by the designer. Thus, at no load it was clear to see that the power consumed by the motor was approximately **83.65W.**

***Performance Results2 :Revolutions Per Minute***

| Duty Cycle / Throttle Level | Frequency of electric field $F_{motor}$ (Hz) | Speed of rotating field $n_s$ (rpm) | Speed of shaft at no load n (rpm) |
|---|---|---|---|
| *0* | 0 | 0 | *0* |
| *25* | 38.1 | 2160 | *360* |
| *50* | 73.2 | 4380 | *730* |
| *75* | 95.4 | 5724 | *945* |
| *100* | 109.5 | 6570 | *1095* |




From the graph above, the increase in speed takes a linear form up until around the 50% duty cycle setting. From about 60% this linear relationship is lost and as the graph start to curve as we it approaches at 100%. In my opinion this is because of the way the hall sensors were mounted in in the alternator such that low speed the relationship is linear but as speed tend to increase the errors such as incorrect angles (even being off the hall sensor spacing angle by as little as 2° compromises the speed as the duty cycle approaches 100%)

***Performance Results 3 : Torque***

We know that $\omega = \frac{2\pi n}{60}$ were n is the speed thus:

| Duty Cycle | RPM | Angular velocity ($rads^{-1}$) |
|---|---|---|
| 0 | 0 | 0 |
| 25 | 360 | 37.699 |
| 50 | 730 | 76.445 |
| 75 | 945 | 98.690 |
| 100 | 1095 | 114.668 |

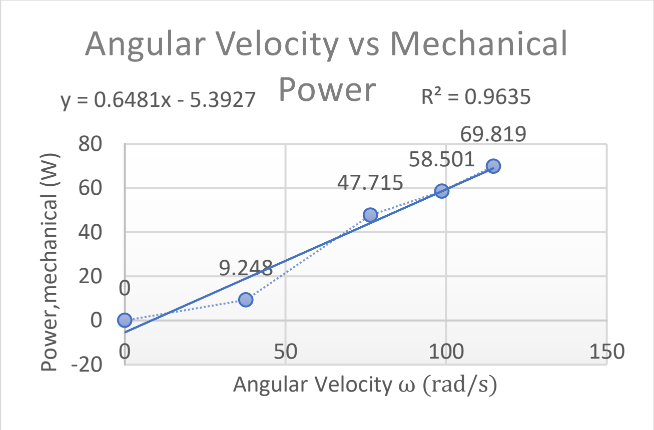
The per phase resistance was then measured by an RLC meter and was found to be 0.1Ω. Thus:

$P_{mech} = P_{in} - P_{statot-loss}$ were $P_{stator-losses} = 3I^2R$

| Duty Cycle/Throttle | $P_{in}(W)$ | $P_{stator-loss}$ | $P_{mech}$ |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 25 | 12.32 | 3.072 | 9.248 |
| 50 | 53.34 | 5.625 | 47.715 |
| 75 | 67.51 | 9.009 | 58.501 |
| 100 | 83.65 | 13.831 | 69.819 |

It is clear now that from this information that has been deduced empirically, other important parameters can be determined as well. The average torque can be found by making use of the following relationship in the equation below:

The equation $P_{mech} = \tau\omega$ suggests that there is a linear relationship. Thus, rated torque can be deduced.



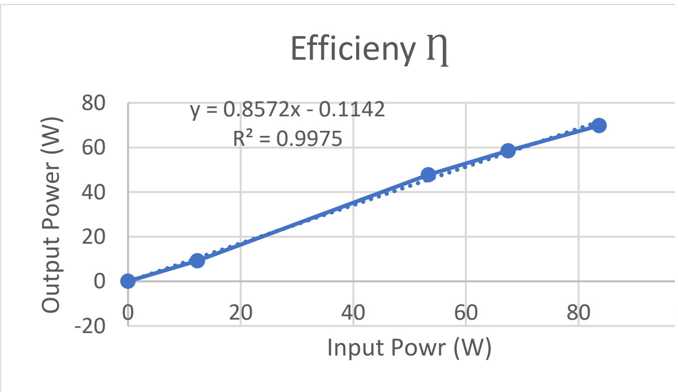

The graph above shows the relationship between the angular velocity and the mechanical power. It can be noticed that from the graph , theR^2 value is 0.9635 which is closer to 1 that this suggest a linear relationship. Again, by looking at the gradient we can conclude that at no load, the rated torque is **0.6481Nm**. However, one should also note that this value isn't overly accurate as other losses which couldn't be obtained via lab experiments were neglected. So, a rule of thumb would be assuming that the real value of torque is 70% of this calculated value.

Thus

Torque = 0.70*0.6481 = **0.4537Nm**

***Performance Result 4 : Efficiency***

In Power Electronics, efficiency is one of the most important factors in any design. It shows the power. Again, to calculate the efficiency, it was done under no load to the shaft (rotor acting as load). Since the input power was determined earlier and the mechanical power (output power) were determined it is easy to calculate the efficiency. A more elegant way to do this is to plot the graph that pits input power against output power.




The graph above has $R^2$ value of 0.9975. This is very close to 1 therefore this graph suggests a linear relationship. The efficiency is therefore the gradient which is 0.8572. However, since some loses couldn't be deduced a fudge factor of 0.95 was used to compensate for this.

Thus Ƞ =0.95*0.8572 =0.81434 = **81.4% .** This is reasonably acceptable as most motors are in and around this efficiency.

## IV. DISCUSSION

The performance analysis was performed via the plotting of graphs. The speed, torque and efficiency of the motor were determined as a result of this. In order to find the input current drawn at different duty cycles, a shunt resistor was used. It was connected in series with the battery and the voltage drop as a result was measured for each duty cycle setting thus determining the current at each setting. To measure the speed thus the rpm of a motor the following equations were used:

$F_{motor} = \frac{1}{T_{motor}}$ , were F being the frequency of the rotating magnetic field in the stator measured between 2 phases and T is period of this frequency.

$n_e = f_{motor} * 60$ were

$n_e$ = speed of rotating field

$n = \frac{n_e}{p}$ were n being the mechanical rpm's while p is the number of poles of the motor.

Results for the rpm were taken at different duty cycle settings.

## V. CONCLUSION

From the experiments , test performance results and motor characteristics that were obtained above, it can be seen that the motor controller is working the way it is intended with respect to PWM and the first quadrant of motor control. Some were graphs plotted to interpret and further affirm the attractiveness of using PWM and how PWM is used as a current chopping technique. Thus, in closing the project was a success as the primary objective of building an electric bike controller using PWM was achieved.


## ACKNOWLEDGMENTS

I would like to thank my supervisor and study leader Dr Pentz who guided me throughout the year throughout the life cycle of this project. I feel very blessed and lucky to have been under his guidance and tutelage as throughout the year I learnt a great lot from him, things that I wouldn't have otherwise learnt in the classroom. I would also like to thank my parents for supporting and encouraging me all the time throughout my academic career. Big thank you to you all!!!


## REFERENCES


[1] Honeywell, Application Note, "Magnetic Position Sensing in Brushless DC Electric Motors''