OPTIMAL DESIGN OF ELECTRIC BICYCLE

(ELECTRIC BICYCLE MOTOR)

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ABSTRACT

The creation of Electric Bicycle gives many advantages in our lives. This thesis is focused on the type of motor that used on the electric bicycle, the type of motor that were used on the electric bicycle is Brushless DC (BLDC) motor. The BLDC motor provides many advantages to the electric bicycle, it provide lots of benefits to the user. It is not only for electric bicycle it can be used to lot of machines. By the way, the characteristic of BLDC motor make it majorly being used around the world, this is because it has high efficiency, long life duration and more durable compared to other motor. The BLDC motor were widely been used on most type of the electric bicycle which is most compatible with it. The used of BLDC motor on the bicycle give the bicycle maximum performances and can travel longer with certain level. Analysis that was done to this type of motor is to determine either this motor suitable for the electric bicycle or vice versa. The criteria that were analyze are, torque, speed, power, current and efficiency.
ABSTRAK

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Electric bicycle is a vehicle empowered by electric motor in order to move. It is also known as e-bike. For the power source of the electric motor, certain country used different power, because it is depends on the Law of the country. Basically, rechargeable batteries that used for the e-bike is 15 to 20mph which is can travel 24 to 32km/h. The invention of the electric bike is as a proof that the engineering field keep advancing, the invention of the electric bicycle make it replacing the old bicycle in the market.

Although the electric bicycles are using electric motor, it still called as bicycle rather than motorcycle. This is because it identity as bicycle is still fixed which is most of it part are belong to bicycle. So, it not included in transportation law which require the certification and operation as on good motor vehicle. It is not need to have license to ride the electric bicycle.

The electric bicycle is not a fully motorized vehicle, it’s just semi motorized bicycle, which is still have pedal, gearing, brake, and frame design and so on. This electric bike use NiMH which is a common power supply used on the electric bicycle. This kind of the battery is rechargeable and a lighter and denser capacity batteries which is make it the designing of an electric bicycle more handful and easier. The electric bicycle is not like a motorcycle in many concept, either it design or it power supply. Besides that, the electric motor is also used lower power compared to motorcycle which is the bicycle still need the rider to pedal the bicycle. There is some type of electric bicycle that commonly used by all the people in term of weight and frame material type.

Weight of the bicycle also plays an important role in the speed of the bicycle. The weight of the bicycle depends on the purpose of the bicycle been used, it is
either for competition so there is few of common weight that been used for the bicycle. On the older bicycle, the weight of the bicycle is about 35 or 40 pounds, this kind of weight was back older day before the technology of the bicycle still not growing. Now, the weight of the bicycle was improved, the weights of the bicycle have been reduced about to 15 and 25 pounds. The improvement of the weight of the bicycle is for the purpose of bicycle handling and speed of the bicycle.

Next is frame of the bicycle, there is few of material that is popular to develop the bicycle frame, it purpose is to make the bicycle lighter and strong frame. The type of materials that commonly used to develop bicycle frame are Carbon fiber, Steel, and Titanium.

Most popular material used in develop bicycle frame is carbon fiber, the term of carbon fiber describe this material have various different composites that include different polymers, carbon and graphite that are link by an epoxy-resin matrix which is sometimes containing metals or ceramics. This carbon fiber is one the advanced composites which offer great possibilities for light weight and high-performances in many way, this is because layer of composite can be insert only where it needed to be placed. Fiber also called whiskers of material used to stabilize dynamic forces due to different degrees and direction on different part of the bicycle frame.

Next is steel, which also commonly used to develop the bicycle frame. Steel is the material which used for many bicycle frames. Lots of bicycle designers have used their many years experience in refining the design of steel bicycle. Steels offers a comfortable ride and frame made up from steel can act as a spring to store energy when the rider causes the frame to flex at different parts of the pedals stroke. The stored energy by the steel can be released and converted to forward motion another part of the pedal stoke. Steel frame can be repaired with low cost and when there is damaged, steel bicycle can show or reveal frame stress injuries before the frame break. Steel bicycle frame break slowly compared to aluminum frame which break suddenly when there is failure on the frame. Most of the high quality bicycle frames are made of steel tubing which has been alloyed with chromium and molybdenum, sometimes also alloyed with manganese and molybdenum.
Beside than Carbon fiber and Steel frame, Titanium also one of the popular material used to develop bicycle frame. The characteristic of the Titanium as bicycle frame is almost similar to steel but it have more advantages than both carbon fiber and steel. Titanium is lighter than the carbon fiber and steel, also the strength to overcome the stress by force or impact is higher than steel and fatigue life of the titanium is more than steel. Even though titanium wins all aspect for develop the bicycle frame, but the cost to develop frame from titanium is higher than steel and carbon fiber.

### 1.2 Problem Statements

This project is proposed in order to design the electric bicycle that use for the travelling and can be used in long distance. The designing of the electric bicycle is included of the frame design, motor control and gearing system design and the riding comfort for the rider. The design is done in group but with separate task and objective, which is each of people done different part for the electric bicycle. In this proposal, the motor control and gearing system design will be proposed.

The motor that would be used for the gearing system need to be done research and analysis so that the suitable motor for the electric bicycle can be choose. Research and analysis for the motor is needed because it one of the main component of the electric bicycle in order to move. The limit of the motor that would be used in the project also must be noted, because it will tell how much the load or speed the motor can withstand when heavy duty task are applied on the bicycle. The torque of the shaft also must be calculated which is will be used as the reference of the motor speed on the gearing system.

The type of motor that will be used for the electric bicycle is one of the important thing or element that can influence the speed, duration of the electric bicycle can move with the assistant of electric bicycle that was chosen. Besides that, the type of motor that were be used also important in selection of power supply. This is because; each motor has its own specific power or voltage that the motor used. Even the same type of motor, it power usage still has differences because of it differences in specification. All the motor that will be compared and analyze is DC motor which is

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suitable for electric bicycle design, because the power source of the motor is will be battery.

By the way, the position of the motor also must be done a research and analysis; it cannot put the motor on the electric bicycle without do analysis the effect of the motor position to the electric bicycle speed and rider comfort. The position is consider either embedded at the rear tire, front tire, near the pedal and on the tire with shaft drive the tire by direct contact.

1.3 Objective

The aim for this project of making the electric bicycle which is included the designing of the frame, comfort, the way of powered and controlled it. Hence, my objective for this project is:

i. To choose a motorize system for the electric bicycle which is can use minimum of power supply during travelling.

ii. To select the type of motor for electric bicycle that can compatible with the bicycle.

iii. To state position of the motor, so that the rider comfort can be optimize.

1.4 Scope of Study

In my part/ project task, there is three scope of being studied. They are:

i. Choosing motorized system that involves with mechanical part and electrical field, which is known as power drive system. It is studies of how we use or applied the electric motor in the gearing system.

ii. Selecting the type of motor that suitable for the electric bicycle.

iii. Decide the suitable position of the motor, it is to make sure the comfort for the rider is optimize.
1.5Conclusion

This chapter discuss about the background of the electric bicycle which included the problem statement for this project that related to motor that suitable for the electric bicycle. Included in this chapter is objective and scope of study for this project which used as a guide for completing the project.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Electric bicycle is a vehicle that known or called as e-bike, it is a bicycle which is assist by the electric motor to set this vehicle in motion. The bicycle use electric dc motor which is receiving power supply from rechargeable batteries. Within batteries powered the motor, the bicycle can travel up to 15 and 20 mph, but this range depends on the batteries and the motor power limit which is each of the components has their own specifications and limitation. The electric bicycle is not restricted or bend to the motorist vehicle law even though it is power by motor, it still considered as bicycle which is the identity of the bicycle is still fixed on it. [1]

The electric bicycle is a free from pollution, this is because it using electric source, rather than gasoline, it will cause pollution to environment, and it will be more similar to a motorcycle. Hence, the using of dc motor that power by batteries is used on the electric bicycle. The electric bicycle is still used pedal to for pedaling, it just adding the motor, batteries, electronic components and throttle for speed. This add up is for assist the rider in certain condition which is when pedaling away up the high slope, more power are needed, so the motor can assist the rider by provide pedaling power to the rider during pedaling up the high slope. [2]

The electric bicycle can be separate in few parts in context of its components and design consideration in order to produce a good electric bicycle, first is the motor and motor control part which related to the electric bicycle motion that assist by the motor, it all about type of the motor that efficient and most suitable for this kind of bicycle. Second is electric and electronic part where this part is about the circuit of the motor control system, like the connection of the battery, motor interface by the gear and regenerative brake of the motor. Then, other part is frame design part and the rider comfort consideration of design which related to rider comfort during riding the bicycle; it is including the type, height, design and weight.
of frame that used to build the electric bicycle. By the way, type of material and position of the seat also play important role for the rider comfort, this because seat of the bicycle can effect rider heath and body, if the seat were design with consideration of rider health by design the seat with safety material that can reduce impact during pass through the bump, then it can at least guaranty rider health when riding the bicycle. But, in this report, the motor components are only focused. This is because this project focuses on this part of the electric bicycle. Hence, the consideration that will be included for the motor are, torque calculation, type of motor, motor power and etc. [2]

2.2 Motor

2.2.1 Type of motor used

The motor that was chosen for the electric bicycle is the Brushless DC (BLDC) motor. BLDC motor is also known as electronically commutated motor (ECM). The BLDC motors are powered by DC electric source in order to function. The source is supplied via integrated inverter or more known as switching power supply. The integrated inverter is functioning by produce AC electric signal to drive the motor [2].

The BLDC motor was chosen because this type of motor has many advantages compared to other motor. The most obvious advantage of BLDC motor is, it has less brushes and physical commutator. From this, it make less of the part that will wear out or break and need to be placed compared to brushed motor. Also, BLDC motor is more reliable; last longer and more efficient than other motor. BLDC motor can operate with less noise and electromagnetic interference compared to brushed motor. By the way, excellent efficiency and reliability that offers by BLDC motor follows with its low weight and can be obtain in many size, make this kind of motor most suitable choice for many application, especially for the electric bicycle.

The motor part for the BLDC motor is commonly a permanent magnet synchronous motor, also can be a switched reluctance motor or induction motor. Even though Brushless DC motor is described as stepper motor, this nickname not suitable for BLDC motor that designed specifically to be operated in a mode where
they commonly stopped with the rotor in a defined angular system or specific angle. [2]

The basic construction of Brushless DC motor are likely similar to the AC motor which is known as the permanent magnet synchronous motor. In Figure 1 is showing the structure of the 3-phase brushless DC motor. The winding of the stator of BLDC motor is similar to AC motor that have polyphase, the number of permanent magnet consist of one or more than one poles. The differences of BLDC motors from the AC synchronous motor are in the way it does detect the position of rotors in order to produce signaling to control the electronic switches which is shown in Figure 2. Also, the common position or pole sensor is called Hall element.. [3]

When the BLDC motor is compared to others motor, there is several advantages that are shown by the BLDC motor, these advantages are:

i. Better speed versus torque characteristic
ii. High dynamic response.
iii. High efficiency
iv. Long operating life
v. Noiseless operation
vi. High speed ranges

Also, the ratio of torque that delivered to the size of motor is possibly higher which is making the BLDC motors application is useful when the space and weight are mention. [4]

Figure 2.1: BLDC motor part layout. [3]
Figure 2.2: Brushless DC motor: Permanent magnet ac motor + Electronic commutator [3]

2.2.2 Hall Elements

Hall elements in the BLDC motor is a flux conversion which can convert the magnetic flux density directly into the voltage which is known as Hall voltage, it is functioning as a magnetic sensor. The application of a magnetic field in a direction to the current \( I_C \) flow direction in the Hall elements cases the force to act on the electron in a direction to both the current \( I_C \) and magnetic field. Then, the potential difference which is called the Hall voltage to occurs on both of the hall elements end. [5]

Figure 2.3: Hall Element [5]

By the way, the Hall elements is also known as hall sensors which is define that it is necessary to known the position by the controller, hence, the hall sensors
likely tell the controller about the angular information of the rotor to the controller. This is because the voltage cannot be applied in order to create torque. All angular position of the rotors is providing by this sensors [6].

When the magnetic field is applied to a system of the rotors with an electric current, a hall voltage is perpendicular to the field and generates the current. The hall sensors act by sending three signal that consist of six states. Each state is corresponding to certain position that shows by the rotors, the state can be determined by using 60° accuracy [6]. This accuracy is illustrated in figure 4.

![Figure 2.4: six hall sensors stated of the rotors [6]](image)

Even though, some said that brushless dc motors are similar with the conventional dc motors in theirs static characteristic, actually both of motor have obvious differences in several aspect. If both motors were compared in terms of nowadays technology, it more clearly information when the differences is used rather than using similarities, this because, it is helpful in understanding application each of the motors in certain ways. If the function of electrical motor was put in discussion, it is must not ignore the significance of windings and commutation of both motors. Firstly, commutation is refers to the process which convert the input of direct current to alternating current, then properly distribute the current to each of the winding in the armature. The conventional dc motor commutation, it is undertaken
by brushes and commutator, while in BLDC motor, it is done by using semiconductor such as transistor. In Table 1 below is comparison of convectional and BLDC motor. [3]

<table>
<thead>
<tr>
<th></th>
<th>Conventional motor</th>
<th>Brushless motor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical structure</strong></td>
<td>Field magnet on the stator</td>
<td>Field magnets on the stator Similar to AC synchronous motor</td>
</tr>
<tr>
<td><strong>Distinctive features</strong></td>
<td>Quick response and excellence controllability</td>
<td>Long-lasting Easy maintenance (usually no maintenance required)</td>
</tr>
<tr>
<td><strong>Winding connection</strong></td>
<td>Ring connection The simplest: Δ connection</td>
<td>The highest grade: Δ or Y-connected three phase connection Normal: Y-connected three-phase winding with grounded neutral point, or four-phase connection The simplest: two-phase connection</td>
</tr>
<tr>
<td><strong>Commutation method</strong></td>
<td>Mechanical contact between brushes and commutator</td>
<td>Electronic switching using transistors</td>
</tr>
<tr>
<td><strong>Detecting method of rotor’s position</strong></td>
<td>Automatically detected by brushes</td>
<td>Hall elements, optical encoder, etc.</td>
</tr>
<tr>
<td><strong>Reversing method</strong></td>
<td>By a reverse of terminal voltage</td>
<td>Rearranging logic sequencer</td>
</tr>
</tbody>
</table>

*Table 2.1: Comparison between conventional and BLDC motors. [3]*

In addition, the stator creates the magnetic field which is the rotor rotate at the constant frequency. This BLDC motor did not experience the “slip” that is
commonly occurs in induction motors. Corresponding to its type the stator have the equivalence number of winding, the BLDC motor can came in single-phase, 2-phase and 3-phase. Amongst this kind of motors, 3-phase motors are widely used. [6]

2.2.3 Stator

The stator of a BLDC motor consists of stacked steel laminations with windings located in the slot that are axially cut along the inner periphery just like in figure 5 shows. The BLDC motor stator maybe resembles to induction motor, but it is for the certain way, but not in all aspect. The BLDC motors have star connection of three stator winding which is each of the windings are consist of numerous coils interconnected to form a winding. The windings then were dividing over the stator in order to form even number of poles. [4]

For the stator windings, there are two types of stator which is trapezoidal and sinusoidal motors. The differentiation of the basis interconnected coil in the stator windings gives different types of back Electromotive Force (EMF). [4]

Back EMF is voltages that generated by rotation of the BLDC motors. The back EMF is opposing the main voltage which is supplied to the windings based on the Lenz’s Law. The back EMF is in opposite direction of the energized voltage in context of polarity. There are few factors that mainly influences back EMF:

- Rotors angular velocity
- Rotor magnets magnetic field that generated
- Number of turns in the stator windings.

Equation of the Back EMF is:

\[
\text{Back EMF} = (E) \propto NlrB\omega
\]

Where:

- \(N\) - The number of windings turns per phase,
- \(l\) - The length of rotor,
- \(r\) - The internal radius of the rotor,
B. The rotors magnetic field density
ω. Motor’s angular velocity.

After the motors are designed, the magnetic field of the rotor and the number of turns in the stator winding remain unchanged. The potential difference that crosses the windings can be calculated by subtracting the back EMF value from the voltage supply. [4]

When the signal is triggered, the trapezoidal motor gives a back EMF in trapezoidal form and the sinusoidal motor’s back EMF produce sinusoidal pattern. This pattern can be seen in Figure 5 and figure 6. By the way, the phase current for the back EMF also have trapezoidal and sinusoidal variations in the respective types of motors, which from this condition, it cause the torque output produce by sinusoidal motor was smoother than that of trapezoidal motor. Even so, there is increasing of the copper intake by the stator windings because of sinusoidal motors take the extra windings interconnection that cause by the stator peripheral.

![Figure 2.5: Trapezoidal Back EMF](image1.png)

![Figure 2.6: Sinusoidal Back EMF](image2.png)
2.2.4 Rotor

Rotor is a non-stationary part that rotates in an electric motor, electric generator or alternator. The rotor rotation is because by the wires and magnetic field of the motor that is arranged so that a torque is developed at around the rotor’s axis. [4]

The rotor is consist of permanent magnet and can be divide from two to eight pole pairs with alternate pattern of North (N) and South (S) poles. If refer to the requirement of field density for the rotor, proper magnetic field are chosen to make the rotor. In figure 8 is show the cross section of the rotor. [4]

In BLDC motor, iron losses phenomena not only occur in the stator but also in rotor. The rotor may experience iron losses that consist of three elements, the elements are the eddy current losses, the hysteresis losses and excess losses. To
detect the Iron loss, the information and knowledge about the Flux density are necessary. The Iron loss cannot be detected blindly and with lack of information about the flux. This is important for motor configuration, especially the motor with fractional number of teeth per poles and phase [7] [8].

2.2.5 Hall Sensors

The commutation of the BLDC motor is not the same with brushed DC motor which is the BLDC motor is controlled electronically. When the rotation of the rotor is about to start, the windings will be energized in a sequence. Before understanding about the winding that will be energized by sequenced, the rotor position of the motor must be known first. As said before, the position of the rotor is sensed by the three Hall Effect sensors which are embedded into the stator. [4]

The hall sensor gives either high or low signal when the rotor magnetic poles pass the sensor. The signals that are produced are used to indicate the poles near the rotor. The exact sequence of commutation of the rotor is determined by this way.

![Figure 2.9: Transverse Section of BLDC motor [4]](image)

2.2.6 Torque/Speed Characteristic

The BLDC motor have special torque-speed characteristic that is make it more optimal choice of the motor to be used on Electric Bicycle. The BLDC motor have the speed-torque characteristic that is can be controlled to be similar with permanent magnet DC motor. This kind of advantage is needed for designing electric bicycle so that it has optimal speed during moving. It is also needed to analyze the
consumption of torque and speed during going up the slope, go down the slope and pedaling on flat surface or road. This torque-speed characteristic of BLDC motor is one of the elements that are needed to be pay attention if performance of BLDC motors is mention [9] [10].

Before the torque or speed or any other value that produce by BLDC motor been determined, the analysis of motor commutation periods are necessary to be done, this purpose is to have a accurate result of the torque-speed characteristic [11]. This topic will be discussed in methodology of this project.

![Figure 2.10: Torque-speed characteristic [4]](image)

2.3 Conclusion

This chapter is about the literature review of the electric bicycle and electric bicycle which is BLDC motor. This chapter explains about the characteristic of the motor that should be used for the electric bicycle. Also, component of the motor also explained in this chapter. From this chapter, it is important that to know the characteristic of the motor should be used in order to achieve optimum design of electric bicycle.
CHAPTER 3

METHODOLOGY

3.1 Introduction

In choosing an motor for electric bicycle, which is Brushless DC motor (BLDC), there is few method will be used, the method is torque calculation, Losses, efficiency.

3.2 Torque Calculation

Before using any motor for Electric Bicycle, torque calculation is necessary to be considering, this is because each motor have its own torque limit for the motor to hold certain load. If a motor were used without calculating its torque or how much torque can the motor provide amount of torque to the electric bicycle. If the motor have low or insufficient amount of torque, this can lead to Electric Bicycle not even move or maybe can move but only without any load or rider. This is why Torque Calculation is important when choosing suitable motor for Electric Bicycle [4]. For this section, only formula will be stated.

3.2.1 Peak Torque ($T_p$) Requirement

The peak torque or also called maximum torque is required for the application, it can be calculated by summing the load torque ($T_L$), torque due to inertia ($T_J$) and the torque need to overcome the friction ($T_F$) [4].

$$\Diamond T_p = (T_L + T_J + T_F) \times 1.2 \quad [N/m] \quad (3.1)$$

The torque due to inertia($T_J$) is the torque that required accelerating the load from rest or from lower speed to higher speed. This can be calculated by using the product of load inertia, with the rotor inertia and load acceleration [4].
\[ T_j = J_L + M \alpha \]  
\[ [\text{N/m}] \]  

Where:

- \( J_L + M \) is the sum of the load and rotor inertia
- \( \alpha \) is the required acceleration

### 3.2.2 RMS Torque Requirement (\( T_{RMS} \))

The \( T_{RMS} \) or Root Mean Square (RMS) torque can be roughly translated to the average continuous torque required for the application. This value depends on several factors. The peak torque \( T_p \), load torque \( T_L \), torque due to inertia \( T_j \), frictional torque \( T_F \) and acceleration, deceleration and run times [4].

\[ T_{RMS} = \sqrt{\left(T_p^2 T_A + (T_L + T_F)^2 T_R + (T_j - T_L - T_F)^2 T_D\right)/(T_A + T_R + T_D)} \]  
\[ [\text{N/m}] \]  

### 3.2.3 Speed Range

Speed range is the limit or speed that needed to drive or run the application and is determined by the type of application. High operating speed can be accounted for the components of trapezoidal speed curve, it give an average speed equal to the movement speed [4]. The curve is shown in Figure 10.

![Figure 3.1: Trapezoidal Speed Curve [4]](image-url)