Design and evaluation of a Self-charging Battery electric two wheeler

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Abstract. With the world shifting to EVs from conventional fossil fuel run automobiles, there should exist a mediator to effectively make this switch effortless and smooth, at least to overcome range anxiety and the resistance to use new technology. Therefore, we propose a self-charging HEV and not a complete PHEV. Since the Indian automobile market comprises mostly two-wheelers that make up 50% of the total sales, it is a good platform to introduce a hybrid powertrain. Key factors are that it should be cheap, easy to run and maintain, highly fuel efficient and should give good performance than its traditional ICE only counterparts. The main idea for this paper is from old diesel-electric locomotives that used a rudimentary hybrid layout to put power to the wheels via an electric motor. Our concept uses the same principle but optimised for a two-wheeler. The bike is powered by a single cylinder petrol or a single cylinder diesel engine that acts as a generator to power a battery which in turn powers a motor to drive the rear wheel. The older locomotives used traction motors to pull heavy loads, whereas our motorcycle can be set to a speed of high torque and low fuel consumption to increase its range which ultimately matters to the Indian consumer. The battery itself can be smaller to reduce the weight that is attributed to EVs. This kind of self-charging EV is especially useful in emerging EV markets like India who is planning a shift to EVs in the near future.

1. Introduction
Our focus is on a series hybrid vehicle as it is more feasible on a small platform like a motorcycle. A series hybrid uses its internal combustion engine to charge a battery which in turn powers a motor which drives the wheel [1].

2. Engine
As far as the engine is concerned, it is set a single speed, usually at a speed at which it produces the
most torque. Petrol engines produce peak torque at very high RPM and at this engine speed, fuel consumption will be very high. On the other hand, diesel engines produce peak torque at very low RPMs and also consume very less fuel at these low engine speeds. Therefore, we have decided to use a single cylinder CI engine, fueled by bio-diesel and set at a speed which gives max. torque and max. fuel efficiency by referring the power vs. torque curves and fuel consumption vs. engine speed curves. The addition of running the CI engine on bio-diesel, raises the eco-friendly quotient of the motorcycle. A bio-diesel grade of B5[2] requires no change in usage in a CI engine and can meet emission norms. Power outputs will be nearly identical and has a much lesser ignition delay.

![Figure 1. Single cylinder CI engine.](image)

3. Biodiesel Conversion
The engine used for this study is powered by a vegetable oil derived biodiesel. Biodiesel is usually prepared by a process called transesterification. Prolonged use of biofuels leads to the decrease in engine life due to deposits in combustion chamber. Also biofuel in its native form is unsuitable for use at low temperatures as it freezes at 14°C. Bio-fuel is also prone to corrosion. Also biodiesel has lower calorific value than diesel which causes an increase in brake specific fuel consumption thereby decreasing the fuel efficiency of the vehicle. The increased viscosity of the biodiesel prevents the formation of a suitable air fuel mixture leading to improper burning of fuel in the combustion chamber thereby causing a decrease in the brake thermal efficiency of the engine. Additionally, choking of fuel injectors and sometimes the cylinder is also observed due to this. Due to incomplete combustion, an increase in HC emissions was observed when biodiesel was used to fuel the engine. An increase in oxygen content led to a reduction of CO emissions while an increase in CO₂ emissions was observed. Also an increase in smoke percentage was observed. This can be attributed to the incomplete combustion of fuel in the combustion chamber. A reduction in combustion chamber temperature led to a reduction in NOₓ emissions. Though vegetable oils, in the beginning, might seem like a cheaper alternative, the transesterification process used to produce biodiesel is an expensive affair and it raises the costs considerably. Hence an alternative process of production needs to be devised before mass adaption can take place.

3.1. Charging circuit
The internal combustion engine charges a battery using a device to convert mechanical energy to electrical energy like an alternator or dynamo.
A dynamo is more suited to a medium range speed and does not charge the battery while idling or at low or high speeds and does not have overcharge protection or voltage regulation. But, it produces a supply of direct current. An alternator on the other hand, charges a battery at all speeds and has an inbuilt voltage regulator and bridge rectifier to convert direct current to alternating current. Therefore, it’s the better pick of the two. Next, the alternator can be a moto-alternator as the motor part can act as the motor in the regenerative braking circuit[9] which further charges up the battery during braking and deceleration of the motorcycle.

3.2. Battery
This device charges a battery, which can either be a lead acid having lower charge density with lower voltage delivery or a lithium ion/polymer having a higher charge density with higher voltage delivery capable of quick charge than a traditional lead acid accumulator but is rather expensive. The battery is a Lithium ion battery pack which can be placed on the lowest point of the motorcycle providing least center of gravity [7].

BMS-Battery management system is a critical part of any EV-Electric vehicle architecture and thus we have incorporated the BMS into our motorcycle as well [3]. It can shut down individual cells when overcharging occurs and can also detect unusual spikes and falls in cell voltage. While choosing a battery for an EV, the charge density, lifecycle, price, weight and packaging size are the major factors that need to be taken into consideration. According to recent studies Li-S batteries, due to their low weight, increased energy storage capacity and low price can be projected as one of the best sources of power for an EV.

3.3. Electric motor
The battery then powers a motor which can be PM-Permanent magnet or BLDC- Brushless DC
electric motor which powers the rear wheel of the motorcycle via chain/belt/shaft drive or if it is a hub-motor, then it can be integrated into the wheel of the motorcycle[6]. The electric motor is a BLDC Hub-motor[4] which powers the rear wheel of the motorcycle. It is integrated into the wheel assembly and also accommodates the rear brakes. PMDC are the oldest types of motor available. They are easy to manufacture and can be controlled very easily. They have good starting torque characteristics. On the other hand, the PMDC type requires regular maintenance because the brushes wear out after a certain period of usage. Also, a considerable amount of energy is lost as heat making them less efficient. Hence to rectify these losses, the BLDC motors were devised. The BLDC as the name suggests are brushless motors that are powered by direct current. The major advantages of a BLDC motor are high efficiency, greater reliability, lesser maintenance, high speed to power ratio, higher acceleration rate etc. The heat in a BLDC motor, unlike a PMDC motor, is generated in the stator which is easy to remove. Another major type of motors that find a frequent application is the PMAC type that runs on AC. However, they lack speed control and hence cannot be used for EV applications. Though series wound DC motors might be a suitable replacement for the current drivetrain, they draw large amounts of current to run and hence can be seen only in applications as huge as the locomotives. Hence, considering the above scenario, BLDC motors are most suitable for drivetrain applications in an EV [8].

Figure 4. Layout of the motorcycle.

4. Design calculation

4.1. Energy consumption

Energy consumption can be found to calculate size of battery.[5]

Power to weight ratio = Rated power / Mass of vehicle

\[ PWR = \frac{PP}{m} \]

\[ PWR = \frac{6}{0.32} \]

\[ PWR \sim 19 \text{ kW/tonne} \]

Since the power to weight ratio is lesser than 22 kW/tonne, WLTC Class 1 test standards are to be followed.

Total force = Inertial force + Road slope force + Road load force + Aerodynamic drag force

\[ F_{tot} = F_i + F_s + F_r + F_a \]

Inertial force = Total vehicle mass * Vehicle acceleration

\[ F_i = m \cdot v \cdot a \]
Fi = 320 * 7
Fi ~ 2240 N

Vehicle acceleration = Speed difference * Time difference
av = Δv * Δt
av ~ 7 m/s^2

Road slope force = Total vehicle mass * gravitational acceleration * sin * road slope angle
Fs = mw * g * sin (αs)
Fs = 320 * 9.81 * sin (9)
Fs ~ 1292 N

Road load (friction) force = Total vehicle mass * gravitational acceleration * road rolling resistance coefficient * cos * road slope angle
Fr = mw * g * crr * cos (αs)
Fr = 320 * 9.81 * cos (9) * 0.009
Fr ~ 30.7 N

Aerodynamic drag force = 1/2 * air density at 20 °C * air drag coefficient * vehicle frontal area * vehicle speed
Fa = 1/2 * ρ * cd * A * v^2
Fa = 1/2 * 1.2 * 11.1 * 0.8 * 0.6 * 11.1
Fa ~ 35.4 N

Ftot ~ 3598 N

The total power Ptot = Total force * Vehicle speed
Ptot = Ftot * v_v
Ptot = 3598 * 11.1
Ptot ~ 39.9 kW

By integrating this over time, we will get our energy consumption which will be used to calculate battery size.

Energy (propulsion) consumption ~ 100 Wh/km

4.2 Battery
To estimate the average capacity of the battery, we use this formula,

Average energy consumption = Energy required for propulsion + Energy for auxiliary equipment * 2 – battery efficiency
E_avg = (Ep + Eaux) * (2 – ηp)
E_avg = (100 + 10) * (2 – 0.9)
E_avg ~ 121 Wh/km

The battery pack is to be designed for an average energy consumption of 121 Wh/km.

4.3 Motor
A few parameters are to be determined before deciding the size of the electric motor.

Weight of motorcycle with payload ~ 300 kg
Average city speed ~ 40 kmph
Slope ~ 15%
Motor speed = Speed * 60 / \(\pi\) * Diameter of wheel
\[NT = VN \times 60 / \pi \times DW\]
\[NT = 11.1 \text{ m/s} \times 60 / 3.14 \times 0.381 \text{ m}\]
\[NT \approx 550 \text{ RPM}\]

Ttractive force = Acceleration due to gravity * slope * (mass of motorcycle + mass of payload)
\[FT = g \times k \times (m_m + m_p)\]
\[FT = 9.81 \times 0.15 \times 300\]
\[FT \approx 470 \text{ N}\]

Motor power = Ttractive force * speed
\[PM = FT \times VN\]
\[PM = 470 \times 11.1\]
\[PM \approx 5170 \text{ W}\]

Torque = Diameter of wheel * Ttractive force / 4
\[TT = DW \times FT / 4\]
\[TT = 0.381 \times 470 / 4\]
\[TT \approx 45 \text{ Nm}\]

Therefore, our motorcycle requires an electric motor of the above given specifications.

5. Specifications
Three variants/designs have been made to assess which is most suitable.

| Variant | Engine power in hp | Battery capacity in kWh | Motor Power in hp |
|---------|--------------------|-------------------------|------------------|
| I       | 8                  | 4                       | 6.7              |
| II      | 8                  | 4                       | 5.3              |
| III     | 8                  | 4                       | 8                |

6. Range calculation

6.1. Fuel
Mass of fuel required to charge the battery once completely to 100%,
\[\mu = \text{Volume of fuel tank} \times \text{Density of fuel}\]
\[\mu = 13 \times 882\]
\[\mu \approx 11.6 \text{ kg}\]

Total Energy content of fuel, \(E = \mu \times C_V\)
\[= 11.6 \times 38476\]
\[\approx 122 \text{ kWh}\]

Power of an engine = \(P_e\) in kW
Variant I, \(P_e = 5.8 \text{ kW}\)

Duration engine can be run, \(t_1 = E / P_e\)
\[= 122 / 5.88\]
~ 20 hours

Fuel required for one hour = \( \frac{V}{t_1} \)
= \( \frac{13}{20} \)
~0.65 litres

Time required to charge the battery completely to 100% = \( t_2 \)
=\( \frac{\text{Battery capacity in kW} \times 3600}{\text{Engine power in kW} \times 60} \)
= \( \frac{4 \times 3600}{5.88 \times 60} \)
~ 40 min

Therefore, Fuel required for one full charge = \( \frac{V \times t_2}{t_1} \)
=\( \frac{13 \times 0.67}{20} \)
~0.42 litres

6.2. Motor
Time motor can run at peak power = \( \frac{\text{Battery capacity}}{\text{Motor power}} \times 60 \)
= \( \frac{4}{5} \times 60 \)
~ 48 min

6.3 Range
Range of the vehicle on 1 battery charge alone = \( \text{Avg city speed taken} \times \text{Duration motor can be run at peak power} \)
= \( 0.66 \times 48 \)
~ 31.6 km

Number of times battery can be charged = \( \frac{13}{0.4} \)
~31 times

Range in km = \( 30 \times 31.6 \)
~ 980 km

**Table 2.** Final vehicle specification.

| Variant | Charge time in min | Fuel required for one charge in litre | Range on one charge in km | Number of times battery can be charged | Total Range in km |
|---------|--------------------|--------------------------------------|---------------------------|--------------------------------------|------------------|
| I       | 40.8               | 0.42                                 | 31.6                      | 31                                   | 980              |
| II      | 40.8               | 0.42                                 | 39.6                      | 31                                   | 1220             |
| III     | 40.8               | 0.42                                 | 26.4                      | 31                                   | 820              |

Variant I has the ideal values as per calculations. Engines have been kept the same. They are the smallest direct power take off, dual-fuel diesel engines in the current market with least horsepower. Battery has also been limited to 5 kW for packaging reasons. Motor power has been varied and has been found that Variant II has the most range but is underpowered. Variant III is more powerful but has the least range. Therefore Variant I is the best pick out of the three designs for performance and range.

7. Key features
- The engine’s ECU is quite complicated and even more so owing to the new powertrain setup. The fuel supply will automatically be cut-off when the batteries are fully charged as
communicated by the BMS.

- Another feature is that the batteries can be plugged into a wall socket/outlet and the motorcycle can be used as a PHEV-Plug in hybrid electric vehicle.

8. Summary/Conclusions
Thus, this system enables us to use the conventional hybrid setup, albeit with a few changes, i.e. the ICE running in bio-diesel and also set at a speed where there is quite a high torque and low fuel consumption and the electric motor being a hub motor further reducing the frictional losses that will arise from a chain or belt drive. The estimated range is in around 980 km but will reduce by a margin when conducted on NEDC/WLTP/RDE conditions.

Definitions/Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| EV           | Electric Vehicle |
| ICE          | Internal Combustion Engine |
| PHEV         | Plug in Hybrid electric vehicle |
| RPM          | Revolutions per minute |
| CI           | Compression Ignition |
| B5           | 5% Bio diesel - 95% Petrodiesel blend |
| BMS          | Battery management system |
| PM           | Permanent magnet |
| BLDC         | Brushless Direct Current |
| HEV          | Hybrid electric vehicle |
| ECU          | Electronic Control Unit |

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