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Decision Based Control Approach for BLDC Motor Drive in Pedal Assisted Electric Bicycle

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Abstract— **The electric bicycle is powered by a battery to provide "assist". The assist control is provided by a pedal assist sensor or a throttle sensor. This article presents a simple decision-based control approach for the brushless DC (BLDC) motor of pedal assisted electric bicycle. The duty cycle of the motor is controlled via user input through throttle sensor, feedback information of the pedal via the pedal assist sensor (PAS), and speed feedback using speed sensor. A sensorless field-oriented control (FOC) algorithm is used for the control of BLDC motor to realize an efficient system. The overall system is designed, and hardware implementation is carried out. The steady-state performance, dynamic performance and the thermal performance of the overall system is validated on the developed hardware prototype.**

Keywords—Brushless DC Motor (BLDC), Electric Bicycle, Field-Oriented Control (FOC), Pedal Assist Sensor, Throttle Sensor.

I. INTRODUCTION

An electric bicycle is a conventional bicycle added with a battery powered motor, which provides a power assist while riding the bicycle. Motor provides assistance when rider starts pedaling, and some electric bicycles are equipped with throttle function where there is no need to pedaling. Electric bicycles are gaining popularity as there are lot of benefits like making the ride more comfortable, enjoyable, safer, riding electric bicycle helps to climb uphill terrains with assist, environmentally friendly, low-cost transport option for short distance, fashionable, making recreational activities a good clean fun-keeping healthy and fit, pedal assist increases the traveling range. Even if the battery gets discharged, it can still be used as a conventional bicycle to reach the destination.

The electric bicycle available in the two categories; (1) assist control is provided by throttle sensor placed on the handlebar which controls speed from the zero to maximum and (2) pedal assist or pedelec where the assist provided is based on pedalling velocity of the rider [1]-[2]. It describes the different types of electric bicycle, different energy sources for storing and supplying the power to the motor, control strategies, and different electric motors and arrangement for the electric bicycle [3]. A model-based control study of power assisted bicycle presented where the electric motor is connected in-line with the pedal shaft to provide the power assist [4]. A reinforcement learning based power management (RLAPM) method proposed to improve the quality of riding for pedal assist as per the environmental condition [5]. A performance evaluation of the electric bicycle with front wheel motor arrangement shown with considering the different conditions such as rider weight, road slope [6]. The conventional bicycle converted to the electric bicycle by installing the power kits and traveling range can also be increase by using different material of batteries [7]. Equation based modelling of the brushless DC motor with different speed control techniques of the brushless DC motor is derived [8].

In this paper, an electronic controller is proposed for BLDC hub motor using AMT49406 sensorless FOC based BLDC motor driver. The speed of BLDC hub motor is controlled by applying a PWM input to the motor driver. A code free sensorless FOC algorithm if fully integrated to achieve the best efficiency. Code free architecture offers robust algorithm. Closed loop speed control is implemented using AMT49406 motor driver. Microcontroller unit (MCU) used for generating the PWM as per the input received from the throttle, pedal, and speed sensors. The duty cycle of the PWM output depends on the either throttle sensor input or pedal assist sensor input. Throttle and PAS are the two important control inputs that decide the level of motor assistance available to the rider, they both support to manage amount of assist that is desired. To provide the ride of comfort to the rider, closed loop speed control is implemented. PAS and throttle inputs are compared and analysed in reference to bicycle speed. If the speed of the electric bicycle increases above 25 kmph then assist from the motor is reduced until the speed drops below 25 kmph.

II. PROPOSED SYSTEM ARCHITECTURE

A. Proposed system architecture diagram of electric bicycle

Fig. 1, represents the proposed system architecture diagram of the electronic controller for the electric bicycle.

B. Approach

The sensorless field-oriented control algorithm provides smooth speed/torque control which helps to improve the ride of comfort to the rider. Sensorless FOC algorithm will not require any feedback from the hall effect sensor which will save the cost and complexity of the hub motor design. It also provides overcurrent and gate driver protection which will help to protect the Mosfet from damage. The speed sensor is implemented on the front wheel to get the feedback of the speed and it always compares with the maximum speed to control the assist provided from the hub motor. If the speed increases >25 kmph then assist provided from the motor controlled proportionally. Stop taillight implemented using the A6261 LED driver. In the normal condition LEDs glows with a lower brightness and when the brake is applied then LEDs glows with higher brightness. It will be helpful when riding the bicycle and when you apply for the brakes it will provide an indication.

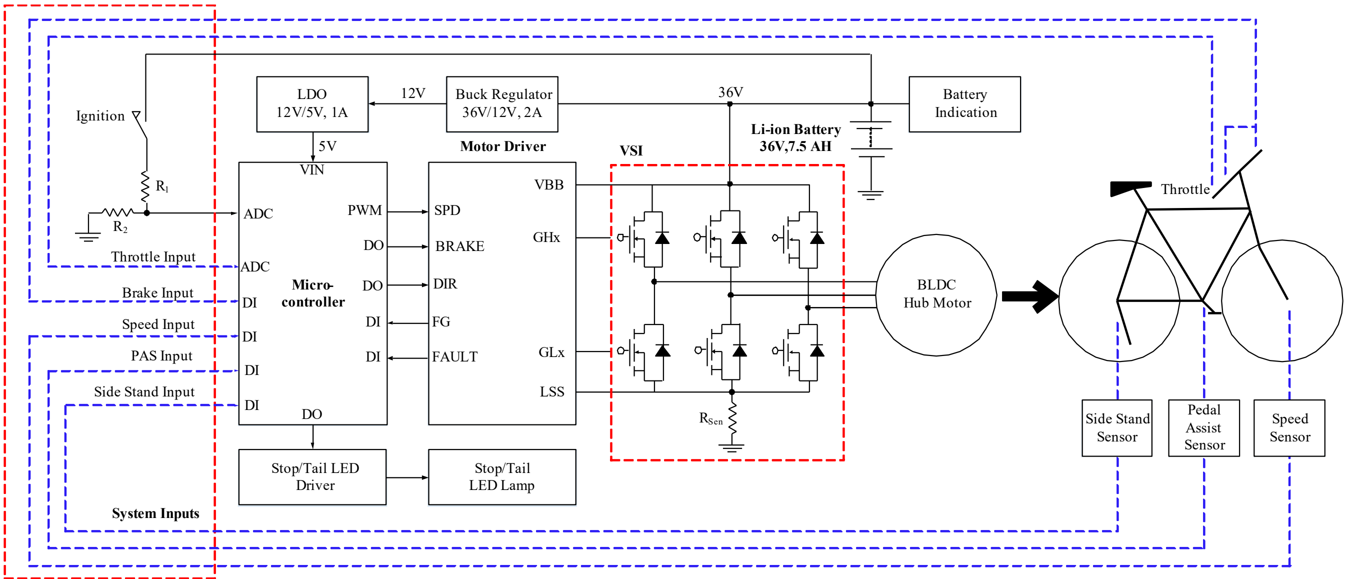

Fig. 1. System block diagram of the pedal assisted electric bicycle.

C. Operation

Lithium-ion battery of 36V, 7.5AH is used to provide the supply power to all the circuit. Ignition switch is used to turn on / off the battery supply, when ignition switch is off, it can run as a conventional bicycle. A 300W, 36V BLDC hub motor fitted on the rear wheel. Battery supply of 36V is stepped down to 12V using A4447 buck regulator and then 5V LDO used to provide supply to the MCU, PAS sensor, throttle sensor, speed sensor and 3.3V LDO used to provides supply to the interface.

Throttle and PAS are the two important control inputs applied from the rider decides the level of the motor assistance, they both support to manage amount of assistance that is desired. The throttle input provides motor assist without rider pedaling. In the PAS sensor condition motor assist is provided when the rider starts pedaling. AMT49406 sensorless FOC based motor driver is used to drive the hub motor with duty input from MCU. The algorithm first checks if ignition key is on, or side stand is retracted or if no brake is applied if any of the condition does not match then motor will not provide the assist. The controller checks if throttle input, throttle provides the analog input from 0.8V to 3.3V to the controller when the rider accelerates the throttle. Controller provides the input to the motor driver as per the throttle accelerates and motor driver provides the input to the inverter section to supply input to the three phases of the motor to provide the assist.

In the PAS input is applied in the pedelec condition when rider starts the pedalling, and assist applied depends on the how fast the pedal is applied. The frequency of the PAS sensor changes from 2 Hz to 25 Hz as per the pedal input applied by the rider. In the condition where throttle input and PAS input applied that time controller compares both the input and provides the assist depending on whichever input is higher. A speed sensor is implemented on the front wheel of the bicycle to provide the speed feedback of the electric bicycle to the controller. Controllers check the speed input and decide to increase or decrease duty if it is lower or higher than 25kmph.

III. DESIGN AND SELECTION OF COMPONENTS

System Specifications: BLDC Motor of 300W, 36V, Line-Line resistance 173 mΩ, inductance 197.5 µH, and maximum speed 233RPM. Li-ion battery of 36V, 7.5 AH is used to provide the supply to the system. The design and selection of components are described below.

A. Motor Driver Selection

To drive the 36V, 300W hub motor the motor driver should suffice the torque requirement and have the smooth startup to improve the ride of comfort. AMT49406 3-phase sensorless brushless DC motor driver is used which can operate from 5.5 to 50V supply voltage [9]. A field-oriented control (FOC) algorithm is fully integrated to achieve the best efficiency performance. Motor speed is controlled through analog, PWM or clock input. The PWM input provided to the motor driver through the MCU depends on the throttle and PAS input. To tune the parameters as per the motor characteristics, a simple I2C interface is provided for setting motor-rated voltage, rated current, rated speed, resistance, and startup profiles.

The motor rated current at rated speed and normal load must be programmed to the EEPROM for proper operation. The AMT49406 will limit the motor current to 1.3 times the programmed rated current during acceleration or increasing the load, which protects the IC and the motor. The VDS voltage across each power MOSFET is monitored by the motor driver. If the VDS across any enabled MOSFET is higher than the threshold, an OCP fault is triggered, and the IC will stop driving immediately. The application circuit of AMT49406 driver is as shown in Fig. 2.

B. Mosfet Selection

The MOSFET selection for the inverter section is depends on the gate drive source current and switching frequency of the motor driver. The gate drive source current is 55 mA and switching frequency is 25 kHz, it will decide the gate charge value of the MOSFET. The drain to source voltage (V_{DS}) and drain current (I_D) of the Mosfet should be twice the battery

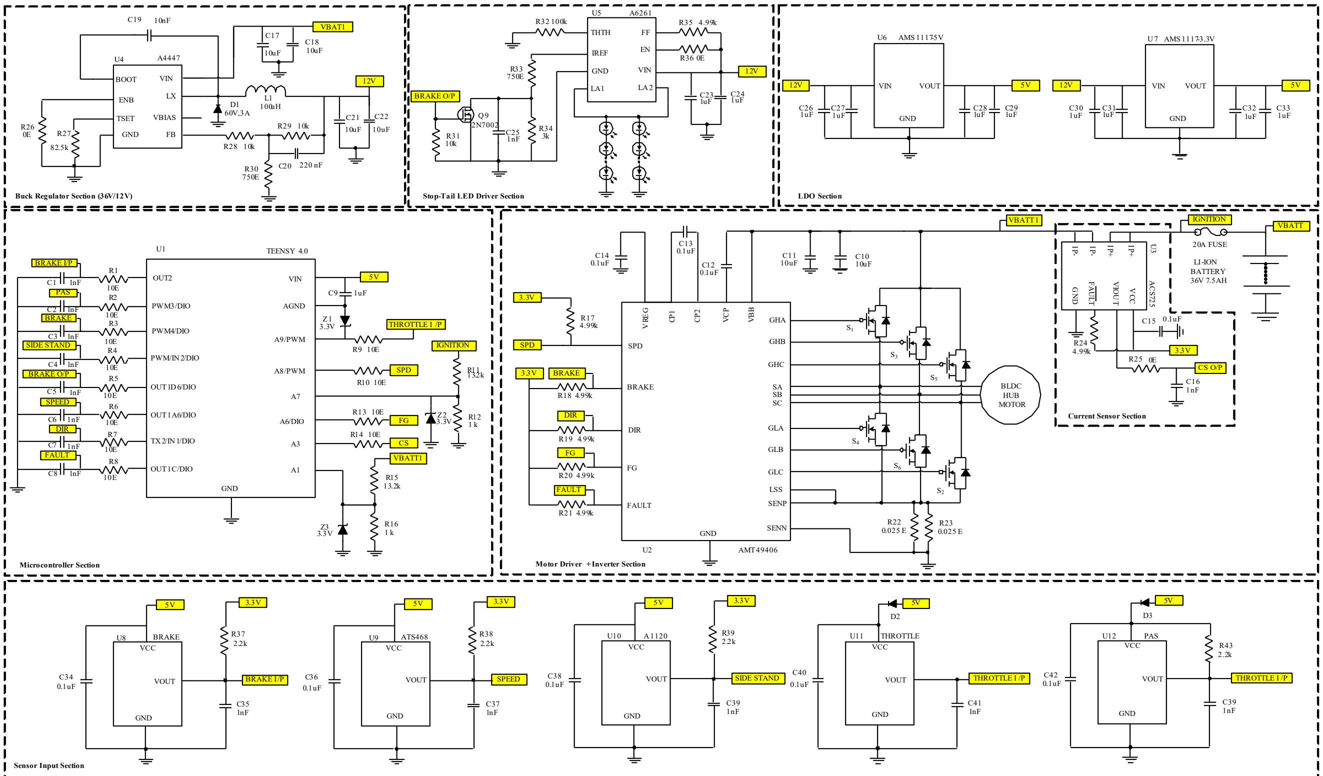

Fig. 2. Schematic diagram of implemented system.

voltage and load current requirement. The 75V, 20A with 10 - 15 mΩ Rds_on resistance and Qg <30 nC Mosfet suffice the application requirements.

C. Speed Sensor

To measure the speed of the bicycle a 44 teeth ferrous target mounted front wheel. To measure the ferrous target required sensor which can provide pulses to the MCU for speed calculation. ATS468 is a three-wire true zero speed differential peak detecting speed sensor IC with inbuilt magnet [10]. ATS468 works on differential magnetic field, thus it is immune to the effects of the external magnetic field. The interface circuit of the ATS468 speed sensor is as shown in Fig. 2. The arrangement of speed sensor and ferrous target assembly on the front wheel is as shown in Fig. 3. The bicycle speed correlation from Hz to kmph is as below: maximum speed is 25 kmph.

- The tire diameter of bicycle is 26”.
- With this diameter bicycle travel about 2.07 meter.
- 1 km travel distance = 500 revolutions of the tire.
- 1 kmph speed = 500 revolutions per 3600 second.
- Speed sensor provides 44 pulses per revolution.
- 1 kmph speed = (400 *500) / 3600 = 6.11 Hz
- Speed sensor frequency = 25 * 6.11 = ~155 Hz

D. Current Sensor

Hub motor used for electric bicycle is of 300W, 36V. So, the 8.5A current flows from the battery in maximum load condition. ACS725 unidirectional hall effect current sensor is used to measure the battery current [11]. It works on 3.3V supply with 20A current range and sensitivity of 132 mV/A.

Fig. 3. Speed Sensor Assembly.

E. Throttle Sensor

Throttle sensor or also called an accelerator position sensor, basically provides manual acceleration control to the MCU to provide the power assist to the bicycle without any pedaling required from the rider just like motorcycle or scooter. The throttle allows the start of the bicycle from the zero speed to the rated speed by providing the analog input voltage to the MCU and it provides the duty cycle input to the motor driver to drive the motor. Fig. 5 shows the mapping of duty and motor speed with throttle input. If the speed of the bicycle increases >25 kmph then controller cuts the throttle assist. A low-cost non-contact type linear hall effect sensor is used for throttle positioning, which will provide the proportional output as per the throttle (magnet fitted over the throttle) movement.

F. Pedal Assist Sensor (PAS)

Pedal assist sensor activates the electric motor assistance by the pedaling action. The level of assistance of the electric in a pedal assist system is usually a function of the pedaling velocity. Electric bicycles with PAS are also called “pedelecs”. In this

Fig. 4. Pedal Assist Sensor (a) complete assembly (b) Internal construction

technology force applied by the rider is measured using the PAS sensor located in the pedal. The PAS sensor uses 12 magnets as shown in Fig. 4 and provides 12 pulses per revolution of the pedal shaft by using the hall effect switch in the forward direction only. With the 30 Hz of the pedaling rate motor speed reaches a maximum level of 155 Hz as shown in Fig. 6.

IV. ALGORITHM

A closed loop algorithm developed for motor control. Motor control algorithm takes bicycle speed, throttle and PAS input parameters and provides duty cycle to traction control. The MCU reads speed sensor, PAS sensor and throttle sensor inputs and generate the duty cycle output which is given to AMT49406 motor driver.

A. *Software Approach*

In the control algorithm closed loop strategy is used to provide the better ride of comfort to the rider. Control action taken by comparing the input from the speed, throttle, and PAS. If the speed of the motor >25 kmph then duty cycle reduces by 5% until speed reaches to <25 kmph. The duty cycle control strategy is shown in Table-I.

B. *Microcontroller Unit (MCU)*

The system requires a floating-point, high-speed MCU with sufficient I/O modules as shown in Table-II. The Teensy 4.0 features an ARM Cortex-M7 microcontroller is used to control all the operation.

TABLE-I
DUTY CYCLE CONTROL STRATEGY

Throttle	***Speed***	***PAS***	***Duty Cycle (%)***
X	X	X	No Change or Zero duty cycle output.
X	X	✓	Duty cycle increases as per PAS input.
X	✓	X	No Change or Zero duty cycle output.
X	✓	✓	Check speed and adjust the duty cycle
✓	X	X	Duty cycle increases as per Throttle input.
✓	X	✓	Compare Throttle and PAS input and adjust the duty cycle as per higher input.
✓	✓	X	Check speed and adjust duty cycle
✓	✓	✓	Check for maximum speed then compare and decide duty cycle as per higher input.

TABLE -II
PIN FUNCTIONS

Pin Structure	***Functions Required***	***Nos.***
Analog Input	Throttle, DC Current, Battery Voltage, Ignition	4
Digital Input	Brake In, Speed, PAS, Side Stand, FG, Fault	5
Digital Output	PWM, LED Out, Direction	3

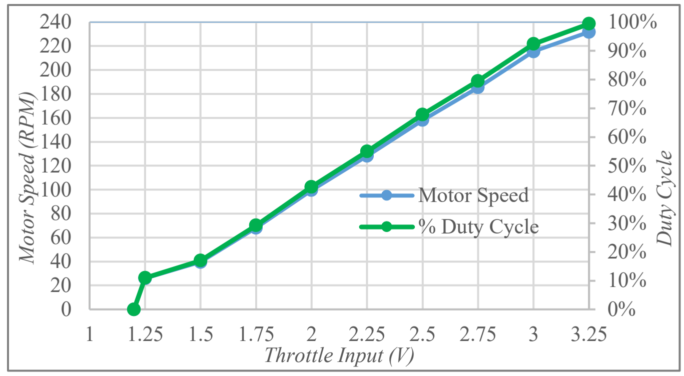

Fig. 5. Throttle Input Vs Motor Speed

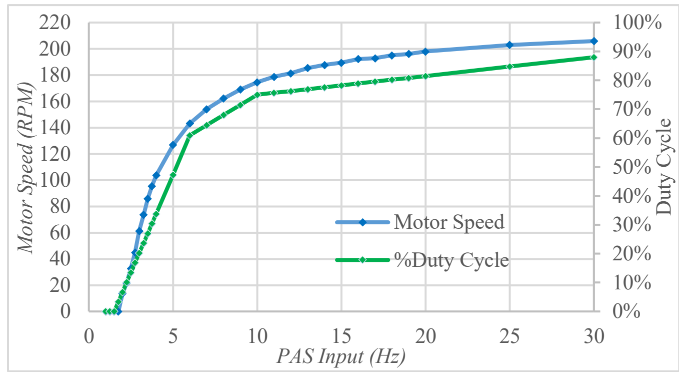

Fig. 6. PAS Input Vs Motor Speed

C. *Flowchart*

The software code is written in the Arduino IDE platform and in the first stage input and output parameters are set : brake input interrupt, ignition, battery voltage, duty cycle output, brake output, throttle, PAS as per the voltage and frequency requirement. Then it will check ignition switch is on or off and battery voltage within the range then it proceeds further. Algorithm continuously check the brake input. If the brake is applied, then it will not provide any assistance to the throttle or PAS input . If the brake is not applied, then it provides the power assist as per the throttle input and pedal assist as per the PAS input. Algorithm also reads the speed input from the speed sensor and if the speed increase > 25 kmph then it reduces the duty cycle input to the motor driver until the speed drops below 25 kmph. A flowchart of the processing algorithm is depicted in Fig. 7.

V. EXPERIMENTAL RESULTS AND VERIFICATION

A closed loop algorithm developed for motor control. The developed electronic controller tested with 300W BLDC hub motor and performance of the electric bicycle is shown below.

A. *Steady State Performance with Throttle Input*

In the steady state condition, the motor runs at constant speed when the throttle input is applied with fixed input as shown in Fig. 8.

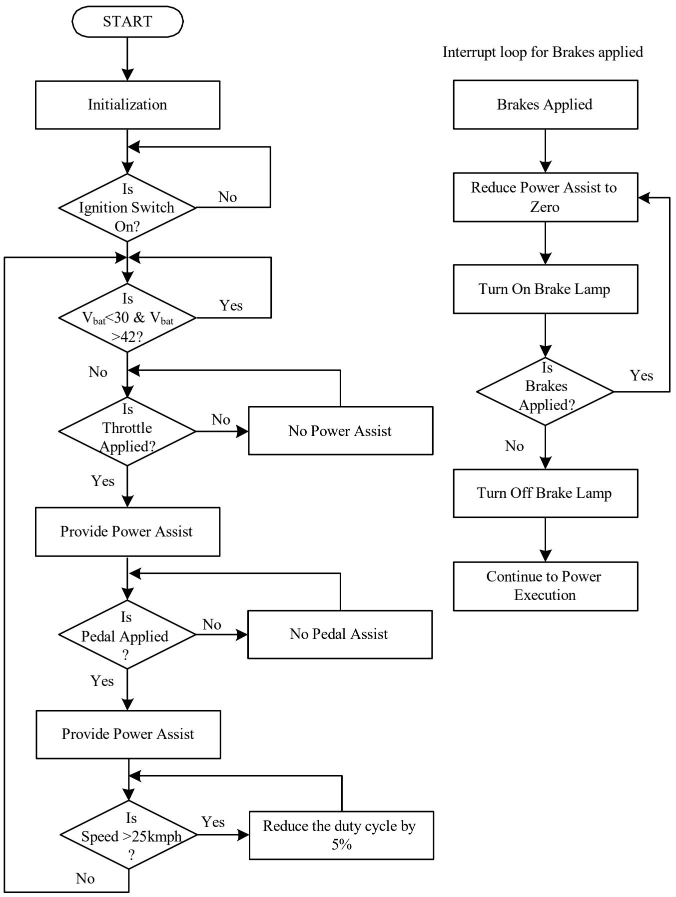

Fig. 7. Developed Software Flowchart.

B. *Performance with PAS Input*

When the rider starts pedalling the motor assist will be provided after a certain pedalling rate and after the pedalling stops the motor assist also stops as shown in Fig. 9.

C. *Transient Performance*

Input supply of 36V from battery applied to the controller board and throttle input from 0.8V to 3V applied and the motor starts smoothly at the as shown in Fig. 10. The input supply of 36V from the battery applied to the controller board and throttle input reduced from 3V to 0.8V then motor stops smoothly as shown in Fig. 11.

D. *Brake Operation*

The brake input is not applied, then the motor provides the assist as per the throttle input and when brake input applied then motor stops assist and starts again after releasing the brake input as shown in Fig. 12.

E. *Stop-tail Operation*

A 6261 placed on the controller board and LED array is mounted on the bicycle, behind the seat. When the brake is not applied then it works in tail mode and draws about 25 mA current and LED glows with lower brightness. When the brake is applied, then it draws about 90 mA current and LED glows with the higher brightness as shown in Fig. 13, to provide the indication of brake is applied by the rider.

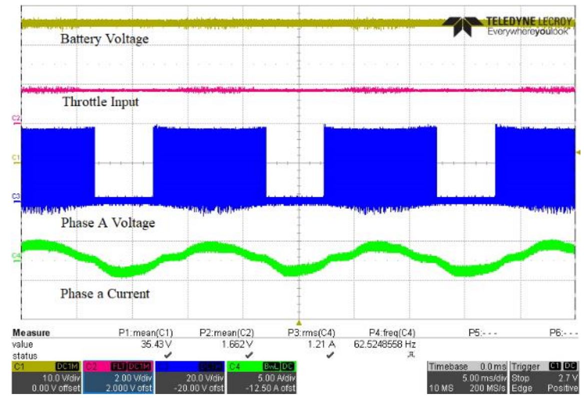

Fig. 8. Steady state performance with throttle input

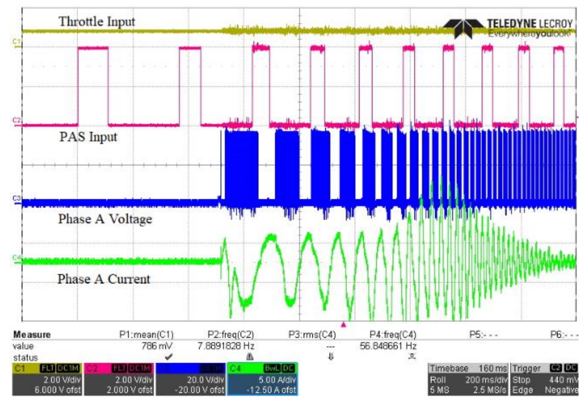

Fig. 9. Performance with PAS input

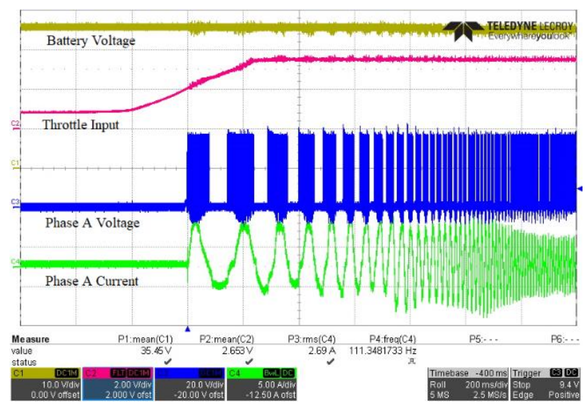

Fig. 10. Motor startup with throttle input.

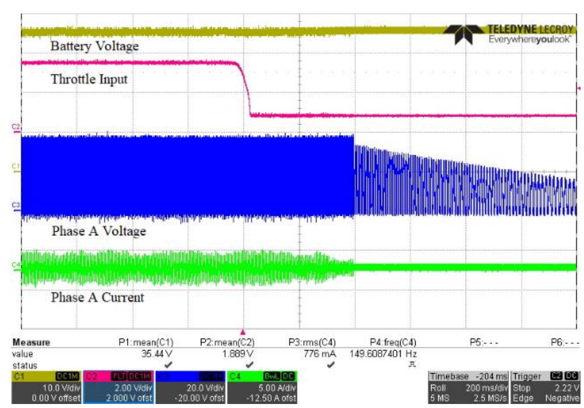

Fig. 11. Motor stopping with throttle input.

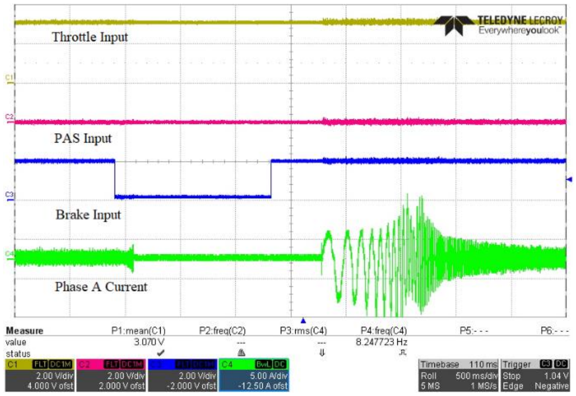

Fig. 12. Brake operation.

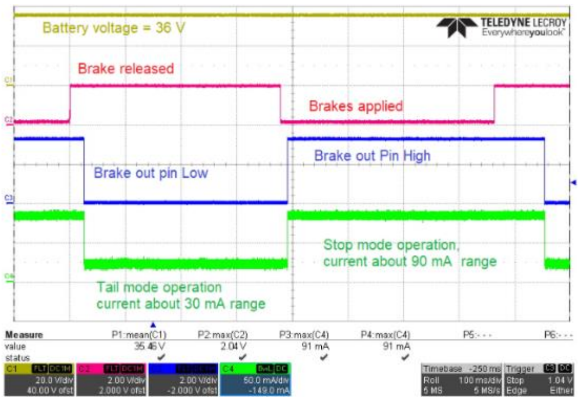

Fig. 13. Stop-tail operation w.r.t brake input.

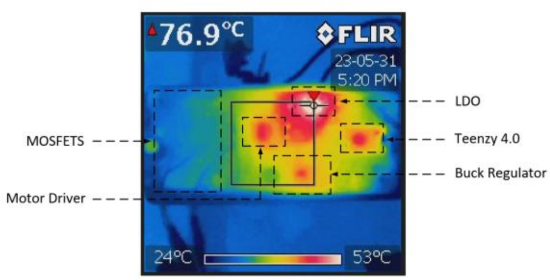

Fig. 14. Thermal performance at full load condition.

F. Thermal Performance

Fig.14 shows the thermal performance of the electronic controller board operating at the rated input voltage of 36V with throttle input at the load condition. As shown in the figure, the maximum temperature on the board is around 53°C at room temperature and LDO temperature goes up to 76.9°C.

VI. Conclusion

In this paper a closed loop algorithm has been implemented to provide the motor assist as per the inputs received from the throttle and PAS in conjunction with continuous monitoring the speed of the electric bicycle using speed sensor which enhances the rider's safety. A 3-phase, code free field-oriented controller AMT49406, has been used to drive the BLDC hub motor which provides a smooth startup and shutdown along with overcurrent protection to protect the MOSFETs in short circuit condition. Implementation of sensorless motor driver reduces the complexity of the motor by eliminating the need for 3 hall effect sensors used for motor commutation. A stop-tail LED function using A6261 LED driver and side stand sensor using A1120 hall-effect switch has been implemented as an additional safety feature.

Safety Protections

A. ACS725 Current sensor: Vin = 3.3V, I_{range} = 0-20 A, Gain = 132 mV/A.
B. A1120 Side Stand Sensor: Vin = 5V, Bop = 35G, Brp = 25G.

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