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ORIGINAL PAPER

Electric hybridization kit for modification of a manual transmission motorcycle

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Abstract

Design and implementation processes of a functional model of an electric hybridization kit for modification of a manual transmission motorcycle are presented in this paper. Considering the complexity of the development and the need to integrate different disciplines of engineering and design, the design process follows the VDI Guideline 2206 and proposes the use of the V-model. Requirements stated by a multidisciplinary group of engineers and potential users are presented as the starting point of the design methodology, followed by a conceptual design phase, and a detail design process according to three specific domains: mechanical engineering, electronic engineering and information technology. In order to achieve fuel economy and fewer emissions, a control with three different driving modes [Internal Combustion Engine (ICE) mode, Hybrid Mode and Regenerative Mode] is proposed including an intelligent switch between a 125 c.c ICE system and a 1000 W BLDC electric motor. Finally, a functional model of the modification kit is assembled on the motorcycle and its functionality is verified. The results show a considerable decrease in the use of the ICE, identifying the electric modification kit as a viable solution for the environmental problem generated by the motorcycles segment.

Keywords Hybrid electric motorcycle (HEM) · Electric hybridization Kit · VDI guideline 2206 · Mechatronic product development · Design methodology · Manual transmission motorcycle

1 Introduction

Environmental pollution is a current problem that affects most of the countries of the world and is caused mainly by the burning of fossil fuels by mobile sources. Nowadays, technological advances and emerging environmental awareness have allowed leading automotive companies to present solutions, mainly hybrid and electric, to protect population health through the reduction of dependence on fossil fuels [1].

In Colombia, as in some Asian countries (e.g., Thailand, Vietnam, Indonesia, Malaysia, China, India, and Pakistan), the automotive fleet is composed mainly of motorcycles. This type of vehicle, due to its economy and versatility, represents 57% of the total number of vehicles registered in the country, making it an accessible solution for the majority of the population and a country development mainstay [2].

However, with 8 million units on average, motorcycles have become one of the main causes of pollution. High combustion inefficiency added to urban stop and go conditions have made them a focus of attention, being considered more polluting than passenger vehicles [3].

In the search for solutions, researchers and companies in the motorcycle industry, have developed hybrid [4,5], and electric motorcycles [6,7]. Unfortunately, these solutions propose replacing or greatly modifying the existing fleet, making them unattractive to users, that considering technological factors, such as limited range and long charging period; social factors, such as the acceptance of emerging technologies and insufficient charging stations; and economic factors related to the high price of the technology; have decided to keep with traditional highly polluting vehicles.

The current environmental problem generated by motorcycles opens a new research area focused on realistic,

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economic, and integrated solutions able to adapt to contexts without an adequate charging infrastructure, and to allow the use of the current motorcycle fleet, through electrical components integration. For these reasons, and to positively impact air quality, the development of an electric modification kit for currently circulating motorcycles is proposed.

The VDI 2206 methodology, used for the design of mechatronic products, is proposed for the prototype development [8]. This approach provides efficient solutions through the use and integration of different advanced methods and tools that support the interactive decision-making process in design and manufacturing [9,10]. This development is related to reverse engineering [11], conventional design approaches [12–14], the interaction of multiple disciplines (mechanical engineering, electronic engineering, and information technology), and inclusion of CAD/ CAM tools, to obtain an adequate solution regarding the design problem. Therefore, with an interactive approach, it is sought to be systematic in the process of introducing innovations in motorcycles to massify on an industrial scale these types of changes. The starting point is the main requirements established by a multidisciplinary group of engineers (physical, mechanical, and design engineers) and potential users, followed by the V-model development, according to macro-level and micro-level situations.

The next chapter presents a literature review of Hybrid Electric Motorcycles developed according to the systems that integrate the Electrical System (ES): Power Train System (PTS), Energy Storage System (ESS) and Control System (CS). Chapter 3 presents the VDI2206 methodology according to three different phases: System Design Phase (SDP), Domain-specific Design Phase (DDP) and System Integration Phase (SIP). Finally, conclusions are stated in Chapter 4.

2 Related work

In this field of sustainable, clean, and high-efficiency transportation, the main characteristics of motorcycle design and manufacturing have changed and are becoming more complex. The competition with current non-renewable technologies has forced researchers to investigate around principal systems [Power Train System (PTS), Energy Storage System (ESS) and Control System (CS)], in order to identify viable architectures and components solutions for the competitiveness of hybrid motorcycles in the global market.

Some studies have focused on the development of Hybrid Electric Motorcycle (HEM), integrating all the systems in functional prototypes. For instance, Asei et. al [15,16] developed a 125 c.c. hybrid scooter, implementing a 500 W Brushless-DC (BLDC) motor in the front wheel, a basic CS using actuators and motorcycle internal signals, and a lithium chemistry battery as the ESS. Tong and Jwo [17] presented a Continuous Variable Transmission (CVT) scooter prototype with a combustion engine of 50 c.c. The prototype included a servo motor connected to a gearbox in the rear wheel, a CS with functions such us a PID speed tracking, low battery protection, and current-limiter, and a lithium chemistry battery as the ESS. Finally, Morandin et.al [18,19] proposed a hybrid interconnected power train architecture for a 125 c.c Aprilia motorcycle including a CSwith two operating modes (driving mode and generating mode), and a NiMH chemistry battery as the ESS.

On the other hand, it is possible to evidence the approach of some researchers in a specific system. In the field of the CS, that represents the interaction between both Power Sources (PS). Ping and Peicheng [20] presented an algorithm of fuzzy PI and hardware with a simple structure. Hsu and Lu [21] presented a motorcycle management system including an Electronic Control Unit (ECU) and a principal system controller with three driving modes: Electric mode, Engine/charging mode, and Hybrid power mode. Xiao et al. [22] proposed a parallel control system with three driving modes: engine independent driving, motor independent driving, and engine-motor coordinated driving, through a hardware-in-the-loop simulation applying a PID control algorithm. Finally, Liu et al. [23] proposed a self-tuning Radial-Basis Function (RBF) PID speed controller with Fuzzy current-limiter and the adaptive capability for uncertain load and road networks conditions.

In the field of the ESS, Khalig et al. [24] developed a state of the art of different battery chemistries for electric and hybrid applications. Cao et al. [25] and Weigl [26] proposed Hybrid Energy Storage Systems (HESS) based on Ultra Capacitors (UC) technology for HEM applications. Ferrari et al. [27] identified UC technology as the most appropriate for charge/discharge applications through the comparison between three different technologies: UC, LiPo, and NiMH.

Finally, in the field of the PTS, there are four different power-train interactions for HEV: series hybrid, parallel hybrid, series-parallel hybrid, and complex hybrid [1]. Morandin et al. [18] developed a parallel hybrid architecture integrating an electric motor with a ICE system through a power split e-CVT. Sheu and Hsu [28] developed a model of a parallel hybrid architecture using some mechanical transmission components, however, the size and the mechanical losses made difficult to implement it in HEM.

Different researchers have successfully developed functional prototypes and component solutions for HEM applications. It is possible to identify a preference for Continuous Variable Transmissions (CVT) since they can operate in automatic handling mode, having high efficiency and easy interaction between propulsion sources. Additionally, the presented prototypes involve radical modifications that do not allow an easy modification as the proposed hybridization kit, and, that is the reason why the information obtained will be used to develop an electric kit for modification of a man-

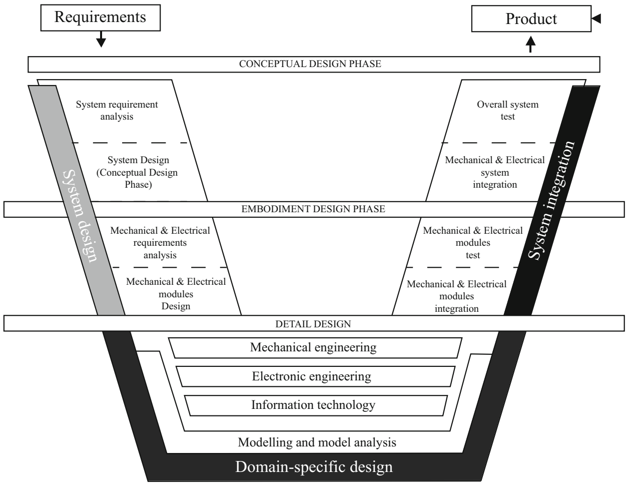


Fig. 1 V-shaped model on the macro-level [8]

ual transmission motorcycle with an engine size lower than 135 c.c for the Colombian context.

3 Design methodology

An electric kit for motorcycle hybridization is an innovative product that integrates different engineering domains. The VDI2206 methodology for mechatronic systems divides the design process into three phases, as it is presented in Fig. 1. “System design” that establishes a cross-domain solution concept with the main physical and logical characteristics of the design matter, “Domain-specific design” that establishes a detailed interpretations and calculations in a separate way for each technical system, and, finally, “System integration” for assessing the performance of the overall system when the individual domains are integrated, taking into account different computer modeling and simulations systems [29].

3.1 System design phase (SDP)

The SDP is developed according to the conceptual design process proposed by Pahl and Beitz [30].

3.1.1 Requirements definition

Table 1 presents the main requirements of the hybridization kit stated by a multidisciplinary group of engineers (physical, mechanical and product design engineers) and potential users [31].

3.1.2 Functional analysis

The main function of the kit was established as “transform” electric energy into mechanical energy. The hybridization kit has information inputs related to the ICE motorcycle and environmental factors and outputs related to the energy/force flow that the kit generates. A total of nine inputs flows (three energy/force flows and six information flows) and 4 output flows, all of them energy/force flows, were identified, as it is shown in Fig. 2.

Table 1 Main requirements

#	Requirements
1	The kit should make the motorcycle more ecological
2	The kit should make the motorcycle more efficient
3	The kit must reduce motorcycle operation cost
4	The kit must be minimally invasive
5	The kit must be affordable
6	The kit must be small
7	The kit must be safe
8	The kit must keep motorcycle driving ease
9	The kit must keep the motorcycle loading capacity
10	The kit must keep the motorcycle autonomy

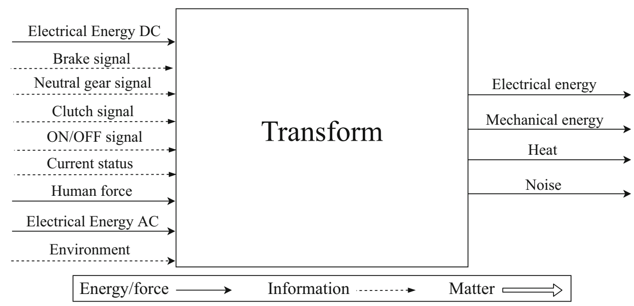


Fig. 2 Black box of the hybridization kit

Furthermore, considering the main function and the inputs/outputs flows, a functional structure is proposed in order to break down a complicated design into manageable blocks, and be able to analyze the interaction between the motorcycle system functions and the hybridization kit functions.

The result of this design phase is a solution concept illustrated in the functional structure and divided into subfunctions to which working principles or solution elements are assigned in order to help in the following phases of the product development process, as it is shown in Fig. 3.

3.2 Domain-specific design phase

Starting from different sets of subfunctions with assigned solutions, a prototype design phase is developed from three different domains: mechanics, electronics, and informatics. The research has been carried out on a motorcycle reference *NKD 125*, from the Colombian *AKT Motos* company, since they correspond to a specific segment (Street/sport)

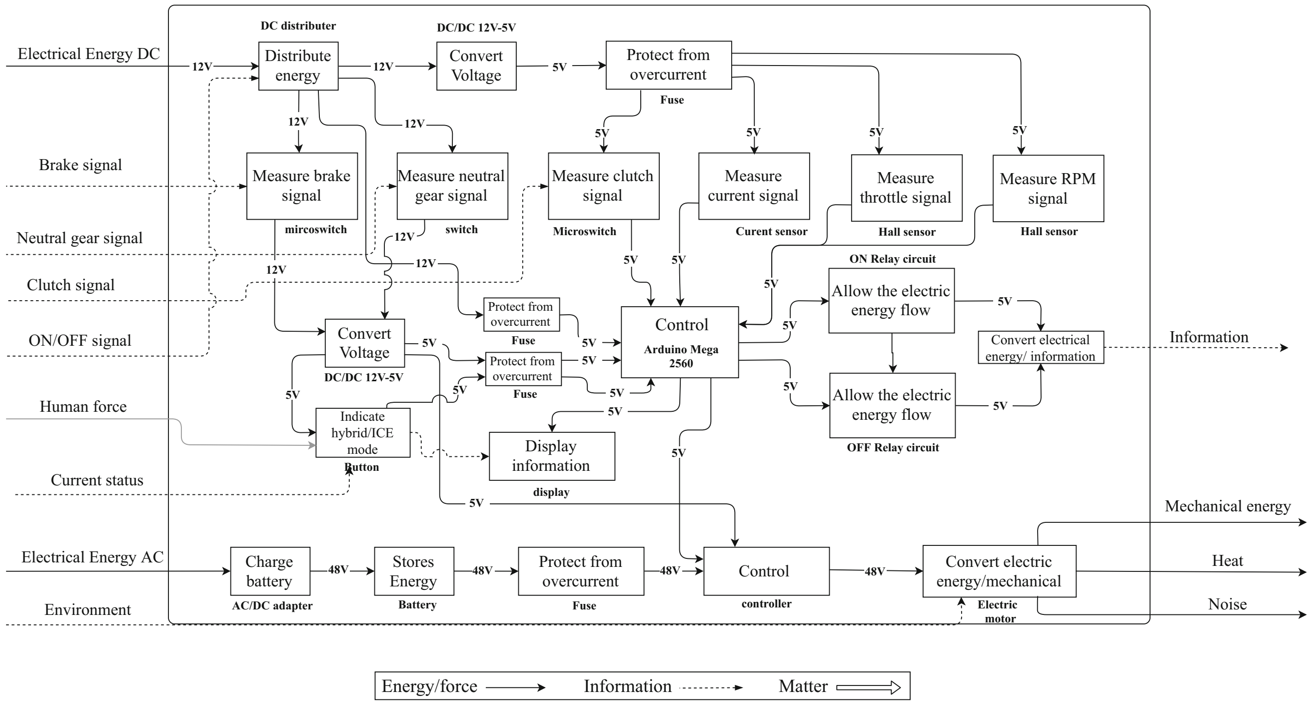


Fig. 3 Functional structure and Morphological chart final solution

and engine size (lower than 135c.c) that represents more than 50% of the motorcycle in the country [2].

A parallel architecture is defined in order to simplify the motorcycle intervention degree and satisfying main requirements. In the mechanical engineering domain, the principal components of the kit (motor, controller, and battery) were sized, acquired commercially, and 3D modelled for a Design for Assembly (DFA) process. In electronic engineering, the schematics and PCB design, HEM signals identification, and the installation process were carried out. Finally, in the informatics domain, a control system, based on a Finite-State Machine (FSM), is proposed taking into account the battery State Of Charge (SOC) and environment conditions.

3.2.1 Mechanical engineering

Employing a dynamometer (Dynomite), an Air-Fuel Ratio (AFR) characterization (see Fig. 4) is developed in order to identify which ranges of RPMs produce more pollutants, and to modify them involving clean technologies.

Results showed that the areas with worst stoichiometric air–fuel mixture are those at the lowest motorcycle RPMs, indicating that the electric motor could replace the ICE at low angular speeds (first gear).

With this assumption, a driving cycle (see Fig. 5) is developed in order to determine the total time and the range of speeds where the motorcycle works in first gear.

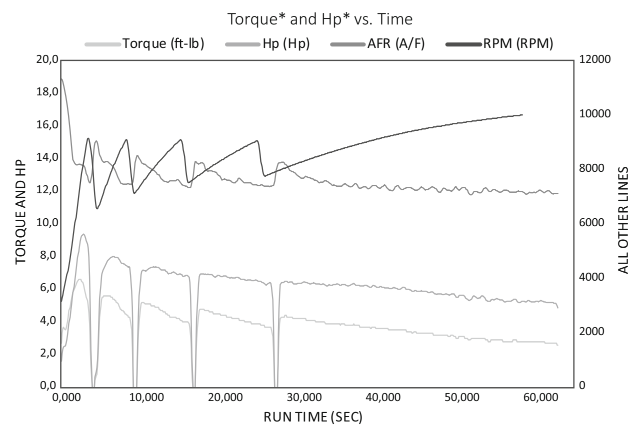


Fig. 4 Air-fuel ratio (AFR)

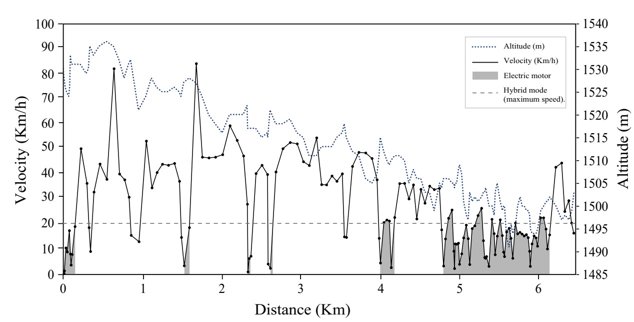


Fig. 5 Colombian driving cycle

Table 2 Information to calculate the power and the energy consumption

Motor efficiency (n)	75 %
Mass factor (m)	220 kg
Gravity acceleration (g)	9.81 m/s^2
Rolling resistance coefficient (Crr)	0.03
Air density (ρ)	1.2 kg/m^3
Drag coefficient (Cd)	0.7
Frontal area (A)	0.6 m^2

The analysis of this driving cycle shows that the motorcycle works under this condition, with a speed range of 0–20 Km/h, around a third of the total cycle (about 464 s). In this way, it is possible to consider that, in a manual transmission motorcycle, a parallel hybrid configuration, that replaces the ICE in this range, is a non-invasive solution that would reduce pollutants.

Therefore, the next step is to dimension the electric motor and the battery through the power and energy calculations (Eq. 1).

$$P_{out} = \frac{\mathbf{V}}{n}\left[m \cdot a + m \cdot g \cdot sen(atan(G)) + m \cdot g \cdot cos(atan(G)) \cdot Crr + \frac{1}{2} \cdot \rho \cdot Cd \cdot A \cdot (Vf - Vi)^2\right] \quad (1)$$

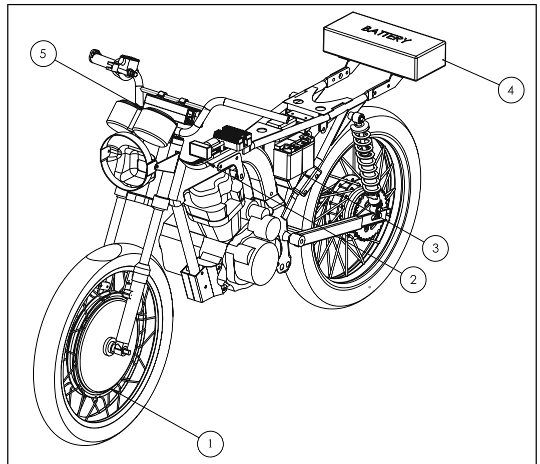
where $\mathbf{V}$ is the speed (m/s), n is the motor efficiency (%), m is the mass of the motorcycle (kg), a is the motorcycle acceleration (m/s^2), g is the gravity acceleration (m/s^2), G is the inclination factor (%), Crr is the rolling resistance coefficient, ρ is the air density (kg/m^3), Cd is the air drag coefficient, A is the frontal area (m^2), Vf is the final velocity (m/s) and Vi is the initial velocity (m/s).

Table 2 shows the information used to determine the power (W) and the energy (Wh) necessary to fulfill the driving cycle.

Motor calculations show that 1000 W satisfies power conditions. For this reason, a BLDC Hub motor with 1000 W, 48 V and 35 A with an internal controller is used.

The motor is mounted on the front wheel with minor modifications in the suspension forks and brake system. Furthermore, the energy necessary to satisfy the replacement of the first gear in the driving cycle is 84 Wh. However, in order to have an autonomy around 40 Km, a commercial 48 V 10 Ah LiFePO4 battery pack is selected and located in the motorcycle back.

Finally, a 3D model in a Computer-Aided Design (CAD) software (SolidWorks®) is developed, as it is shown in Fig. 6, in order to size and adjust the components and new parts construction or acquisition required for the final assembly.



#	Item
1	Brushless-DC HUB motor driver included
2	Engine Control Unit (ECU)
3	12v 6,5Ah motorcycle battery
4	48V 10Ah LiFePO4 battery pack
5	Electric kit control unit

Fig. 6 CAD model hybrid electric motorcycle

3.2.2 Electronic engineering

A schematic design (see Fig. 7) and a Printed Circuit Board (PCB) are proposed. An Arduino Mega 2560 microcontroller, overvoltage protection, overcurrent protection, and voltage converter are some of the principal components of the system. In addition, a LCD display 1602 A and a hybrid/ICE select mode button were included as the user interface.

The kit electrical system is developed as independent wiring, for the purpose of intervening as little as possible the original motorcycle wiring. All the electronic system is mounted into an IP-51 plastic box installed on the handlebar, and vehicular connectors were used in order to keep the modularity. All the electrical components, excluding the BLDC electric motor, are connected to the 12 V 6.5 Ah gel-cell motorcycle battery, and, therefore, to the ICE alternator.

Finally, a dual throttle design (electronic-mechanic), including the steel wire rope and a magnetic hall sensor, is proposed to maintain the user experience and the functionality of the motorcycle.

3.2.3 Information technology

A control system based on a FSM is proposed, as it is shown in Fig. 8.

The control includes a battery SOC calculated with the equation (2), according to the methodology proposed by Asaei and Habibidoost [15].

$$SOC = SOC_0 + \Delta Q / C_{battery}$$
$$\Delta Q = \int i.dt \quad (2)$$

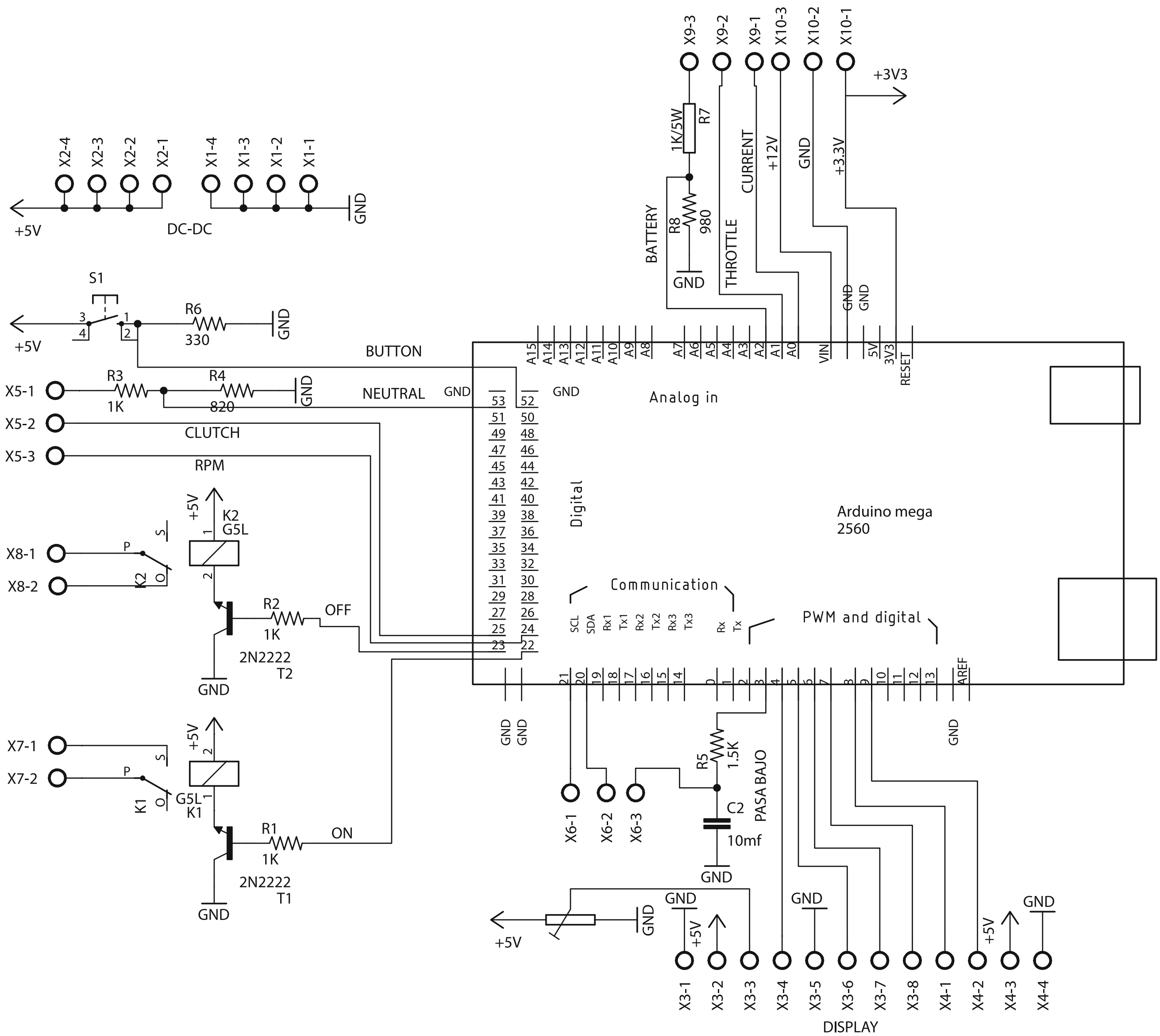


Fig. 7 Electronic schematic design

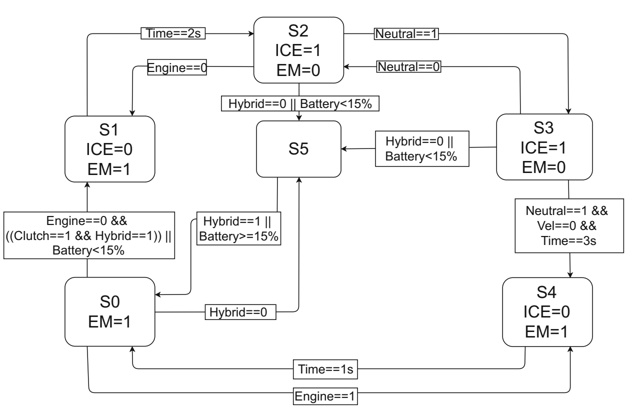


Fig. 8 Finite-state machine (FSM)

where SOC_0 is the initial SOC, ΔQ is the change in the battery pack charge, $C_{battery}$ is the capacity of the battery pack, and, i is the current of the batteries.

Finally, considering that the interaction between both power sources is the success of a HEM, three modes are proposed in the control system: Hybrid mode, ICE mode, and Regenerative braking mode.

– *Hybrid mode* Taking into account that the motorcycle has a manual transmission, user interaction is used as an actuator in a specific state of the logic control of the FSM in order to change the power source during the driving cycle. The hybridization kit identifies the neutral gear signal and enables the electric motor to be the

Fig. 9 Motorcycle integration

only propulsion source. When the user feels the necessity to change the gearbox relation, (s)he operates the clutch, and the microcontroller receives a signal which in turn starts the ICE system. During a driving cycle in urban areas, the vehicle makes frequent stops due to traffic and road signs, and as a result, the CS identifies the vehicle stop, and changes the propulsion source. Some extra functions, as low-battery, velocity, inclination, and engine ON/OFF signals, are being taken into account in order to change the power source, and identify the state of the engine, respectively.

- *ICE mode* The motorcycle works only in the ICE mode as a conventional motorcycle when the user selects ICE mode or when during the hybrid mode the battery level is low.
- *Regenerative braking mode* Brake sensors of the motorcycle (front and rear wheel) are connected directly to the electric motor controller, enabling the regenerative mode, independently of the two modes mentioned above.

3.3 System integration phase

Regarding the electric propulsion system, the BLDC HUB motor is mounted on the front wheel. The lower shaft diameter of the front fork is increased to assemble a machined bushing that allows fitting the geometry of the motor shaft. For safety, two High-Hold Cone-Point Set Screws per fork are implemented, and finally, a different brake disc is assembled to the motor frame and aligned with the front caliper.

The battery is installed on the motorcycle back simulating a top case. A sliding coupling bracket and a quick coupling power connector were installed, in order to remove the battery when charging. The kit wiring is connected to the specific motorcycle signals and to the 12 V 6.5 Ah battery, with minor modifications.

As the last modifications, the motorcycle throttle is replaced by the dual accelerator developed in the 3D printing process, and the hybridization kit ECU is installed in the middle of the handlebar through mechanized supports.

All systems installed on the motorcycle are verified and validated. The proposed control, the operating modes and the user interface work correctly, as well as the dual throttle and the exchange of propulsion sources through the user interaction. The final functional prototype is shown in Fig. 9.

4 Conclusions

A hybridization kit prototype for modification of a 125 c.c manual transmission motorcycle is designed and developed implementing the VDI2206 design methodology. A BLDC HUB electric motor with an integrated controller is mounted on the front wheel with minor fork tubes modifications, and a LiFePO4 48 V 10 Ah battery pack is installed in the back rack. The electronic system is installed on the handlebar with a simple assembly process and the throttle with two functions is designed and implemented in order to minimize the driving functions. Finally, a control system based on a FSM is proposed, including an Arduino microcontroller and some interfaces and protections.

The motorcycle in hybrid mode uses the electric motor at low speeds and for the regeneration process. It is possible to conclude that in a driving cycle of 1140 s, the electric motor can work around 35% of the total cycle, reducing considerably the emissions of Carbon Monoxide (CO) and Hydrocarbons (HC).

As future work, an emissions comparison between an Internal Combustion Engine Motorcycle (ICEM) with and without the electric kit is raised, for the purpose of concluding if there is a significant difference in the polluting and if this proposed kit could be a viable product for the Colombian context.

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