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CONTROLLING OF BRUSHLESS DC MOTORS IN ELECTRIC BICYCLES USING ELECTRONIC BASED CIRCUIT WITH 8-BIT MICROCONTROLLER

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ABSTRACT

Since the cost of fossil fuels is gradually increasing day by day as well as government policy is also towards the minimization of atmospheric pollution, it is mandatory for the human being to concentrate more on designing a hybrid bicycle powered by re-chargeable lead acid batteries. The aim of this paper is to design an electronic control unit for brushless DC (BLDC) motors in an electric cum human powered bicycle, characterized by new solutions for the control method and the 8-bit microcontroller system. A dynamic model of the vehicle has been realized, and the characteristics of the ECU have been individuated [01]. A basic electric bicycle runs on a BLDC motor, is powered by batteries and controlled from an ECU. The BLDC motor for the electric bicycle is of the standard three phase trapezoidal type, typically rated at a few hundred watts and the battery voltage is usually 36V or 48V depending on the circuit current. Almost all the electronics in the electric bicycle are found in the ECU, it contains the inverter circuit for the motor; temperature sensor; fault detection; SMPS; analog and digital IOs; and finally the controller itself. Some ECUs have advanced features such as Remote Key Entry (RKE) and electric horn as well. All of these as well as the wiring packed into a metal box of typical dimensions 10x7x3 cm3. Most electric bicycle manufacturers prefer an inverter circuit designed with discrete components for cost consideration, this circuit takes up about half of the PCB leaving even less space for the rest of the circuit [02]. This gives you an idea of the challenge facing the designers. From the MCU point of view, not only must it be functionally acceptable, it must be able to withstand the harsh environment within the box. The XC866 microcontroller has been used in this. An effective PWM control strategy has been studied, adjusting the motor torque and the current in order to increase the availability range. Finally, a feasibility study of a regenerative braking system based on the super capacitor technology has been carried out. All the components of the drive have been selected among the models available on the market. In this paper the results of the simulations are presented and other technical-economical aspects such as energy consumption and costs are also briefly discussed [03].

KEYWORDS: *Power-assisted bicycle, permanent magnet DC motor [PMDC], super capacitors, regenerative power control, Electronic Control Unit [ECU], Microcontroller*

I. INTRODUCTION

This Human-powered hybrid electric vehicle becomes, a solution to personal transportation in an environment where atmospheric pollution must be limited, where automotive traffic overcrowding is severe, and where parking space in urban centers is not available. Electrical bicycles offer extremely efficient, pollution-free transportation for urban and suburban areas, and the addition of electric drive extends their range. Motorized bicycles are an economic and ecological vehicle suitable for all ages; the use of a helmet is not compulsory; they will not normally require registration and taxes, licensing or operator qualification.

The motor action is progressively reduced and finally interrupted if a 25 km/h speed is reached (such speed limit is imposed for security reasons), if the cyclist stops pedaling or if the brake is used. Pedaling is the main form of propulsion, while the motor gives extra speed, especially uphill.
The electrical drive consists of four main components:

1) a motor
2) a power transmission system
3) a control system or electronic control unit [ECU]
4) a battery pack

The battery pack and thus the vehicle autonomy is the main aspect to be focused on. In this sense, a closed loop control circuit for the output power control has been studied to be implemented in the electrical drive, avoiding undesired accelerations and increasing the battery range. Such a solution is not commercially available [04]. The recovering of the braking energy by means of the super capacitor technology can determine a reduction of the electromagnetic stresses on the battery pack, so that a longer battery life is achieved.
The XC866 microcontroller has an enhanced 8051 core with a minimum of 2 clocks per machine cycle rather than the standard 12 clocks per machine cycle. The memory size is 4/8/16K bytes, enough for all types of electric bicycles [05]. It has a powerful capture compare unit (CCU6) designed specifically for motor drive application. To complement the CCU6 is a feature-rich 10-bit, 8-channel ADC module that is designed to work closely with the CCU6 and can be programmed to perform some tasks automatically. This is an important characteristic for sensor less BLDC control, as this not only reduces the code size, more importantly it reduces the CPU load. The trend now for electric bicycles is towards sensor less BLDC control. The weakness of the sensor BLDC control is vulnerability of the Hall sensors, which can be spoiled by extreme temperature, humidity, wetness, vibration etc. The electric bicycle, being an outdoor vehicle, will be subjected to these things regularly. Even bad wiring can incapacitate the electric bicycle. Most electric bicycle failures are related to the Hall sensors of the motor. Apart from the Hall sensors, the rest of the motor is very rugged, the magnet, coil and the metal casing do not spoil easily. Another advantage of the sensor less BLDC control is the higher efficiency as compared to the sensor control [06]. Badly placed hall sensors in a motor can cause lower than expected efficiency.
In this particular section of this technical paper, the feasibility, merits, demerits, controls and overall view are discussed in brief.

II. ELECTRICAL DRIVE DESIGN

The power propelling a bicycle and rider goes mostly into overcoming wind resistance and lifting mass up hills at normal bicycle speeds. Bearing and tire friction are small but can equal wind resistance at very low speeds. The electric motor torque curve is a function of road slope p, rolling friction coefficient C_{roll} (whose value depends on the road conditions), and wind speed V_w, cyclist resistance coefficient C_r, and total mass m of the bicycle-cyclist system. Equation (1) represents the equilibrium and equation (2) keeps the pretend body pressure drag and skin friction drag into account [07].

$$T_{tot} = T_{air} + T_{slope} + T_{friction} \qquad (1)$$

$$C_{air} = ((C_r . A. \rho)/2) (V_c + V_w)^{2}. b \qquad (2)$$

Experimental elaborations have been performed to estimate the total torque variation in function of speed with three standard slope grades: 1%, 10% and 12%. Figure 1 shows that, moving from a flat road to a climb, the total requested torque passes from 2.17 Nm to 19.43 Nm, for a 7.2 km/h speed. Figure 2 shows the influence of the total mass of the system on the required power. Provided that the cyclist is pedaling, the above mentioned law does not fix any constraint on the level of the assistance. However it strongly affects the battery autonomy.

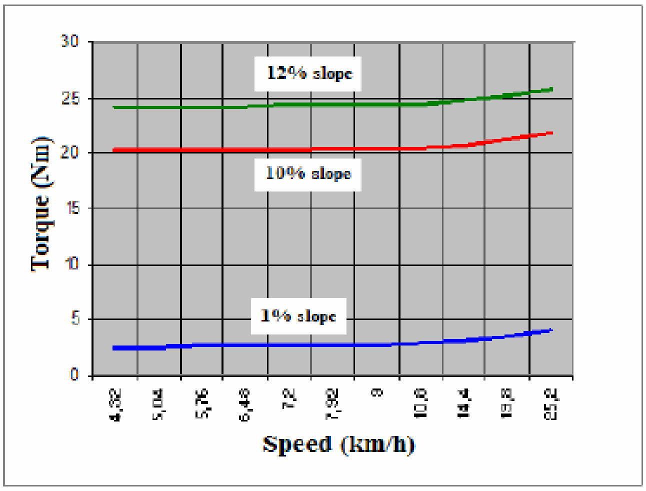

Figure 1. Slope influence on the total torque for an 80kg cyclist

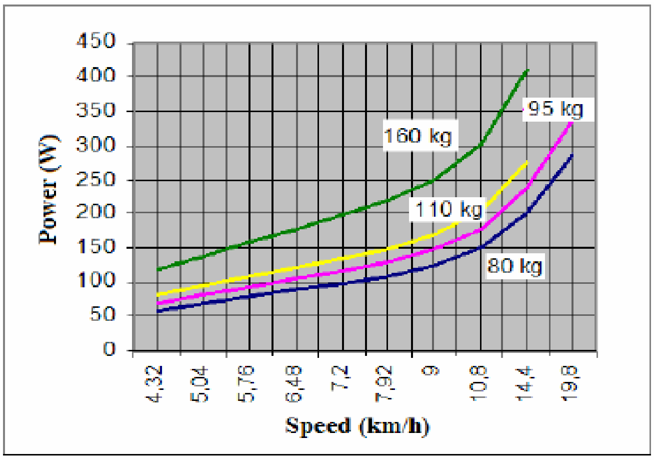

Figure 2. Mass influence on the total required power

III. CHOICE OF THE ELECTRIC MOTOR

Two different types of motors are commonly chosen for the auxiliary drive of such vehicles: DC Brushed motors and radial flux DC Brushless motors with permanent magnets (RFPM). Mostly for its reduced size and higher efficiency a DC Brushless motor with a particular shape a so-called hub motor – can also be selected (external rotor and internal stator). For this work a 250W DC brushed motor has been selected. The electric motor is positioned on the rear wheel for a simpler installation [08]. The power transmission system is of the direct drive type, so that gears and coupling joints are avoided.

A closed loop commutation system makes it possible to regulate the DC motor voltage and then to control the absorbed current. The load torque depends on the road journey; according to the mechanical assistance level, the control system will regulate the voltage so to obtain the proper current and torque value. Such a closed loop control system is not available on the present market. This kind of regulations also allows estimating the battery state of charge and operating to improve the battery independence. It is possible to estimate the electrical power required by the motor. For the present case a limit P_n = 250 W is fixed, corresponding to speed n_n. Therefore, the operation is limited by a curve in which electromagnetic torque and speed change in a way that the power absorbed by the motor is constant (see Figure 3).

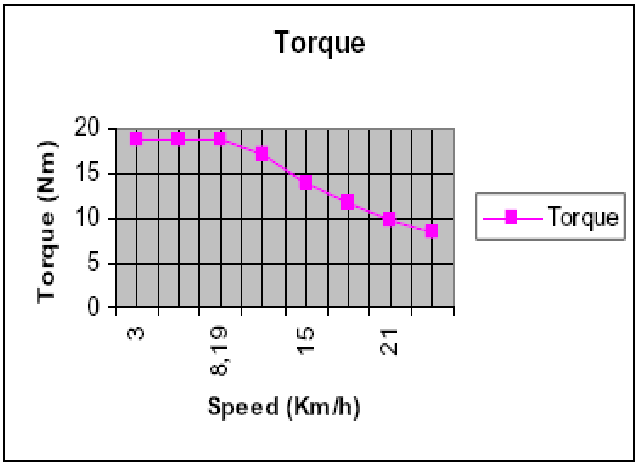

Figure 3. Operating limit for the DC brushless motor

IV. CONTROL SYSTEM

The combination between the cyclist muscular power and the power of the motor are optimized by means of a specific control system that can manage the power inputs in the different load conditions [09]. The basic configuration for a pedaled cum electric cycle can be represented by the following scheme (Figure 4) in which the power flows are shown.

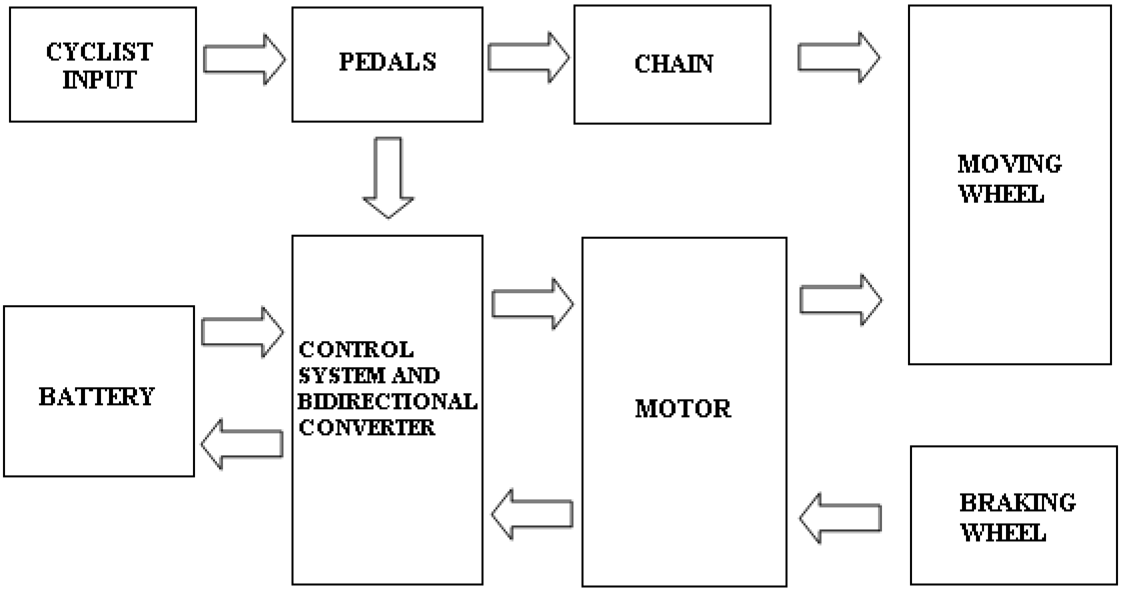

Figure4. Power flow – Schematic Diagram

V. BIDIRECTIONAL CONVERTER

Such converter allows the current flow in both directions: from the battery to the motor when the electrical motor is working as a motor; from motor to the battery, when it is working as a generator. In the motor mode, as mentioned above, the main condition to obtain the motor assistance is that the cyclist is pedaling in the forward direction. The converter, in the step-down mode, assures a constant link voltage value for sourcing the inverter. It has to keep the link voltage independent from the battery output voltage (V_d) which is connected with its state of charge [10]. Fig. 5 shows a scheme for the step-down converter.

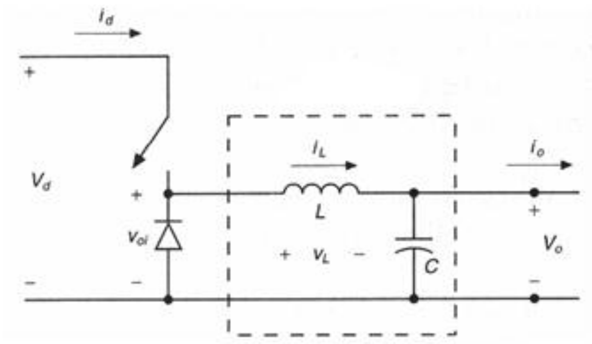

Figure 5. Step-down Converter

When the electrical motor is working in the generator mode, the current flows toward the battery pack for the regenerative braking. In this condition it is necessary to use a step-up converter (Figure 6)

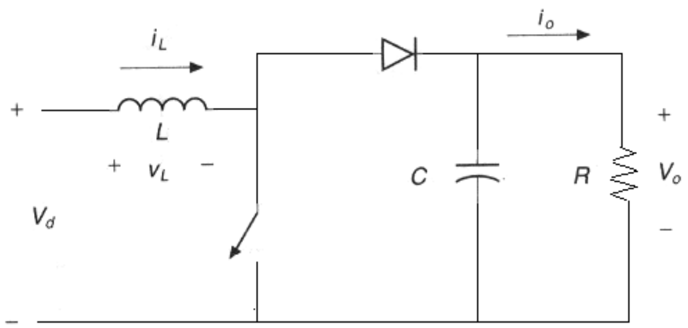

Figure6. Step-up converter

VI. REGENERATIVE BRAKING

The battery types chosen in this work are Lead acid with a nominal voltage of 12V and a 27h capacity. Since the level of assistance is strongly influenced by the battery range, the management of the battery charge and discharge phases is particularly important [11]. The possibility to recover the braking energy is of great interest in designing the electrical drive. The regenerative power control for electric bicycle method is a simple and low-cost solution. Under appropriate conditions, the batteries can be recharged. During a deceleration or braking, an amount of kinetic energy is usually lost as friction on the wheel. The regenerative braking system allows recovering part of such kinetic energy, to be used to feed either the battery or the electrical drive [12].

The intermittent characteristic of the journey route lead by the rider can be smoothed by the introduction of a super capacitor bank. As it is known, a super capacitor can store amounts of energy and then distribute it depending on the required power, minimizing the energy losses. The super capacitor bank raises the total weight of the drive of approximately 3kg, but avoids the electromagnetic stresses on the main source of the cycle, improving the battery performance and increasing the autonomy and the life of the battery itself. Under specific conditions, imposed by a bidirectional converter, in a particular time interval a regenerative brake can be obtained [13]. The core of the system is represented by a Buck-Boost converter with IGBT power static switches. The Boost side is connected to the super capacitors bank; the Buck side to the battery packs (see Figure 7). The control system measures the following quantities: the battery and the super capacitors bank voltages, the state of charge of the battery, the bicycle speed, and the instantaneous currents on the load and on the super capacitors bank [14]. A microcontroller elaborates those quantities and generates a commutation sequence by means of the PWM technique to control the power static switch [15].

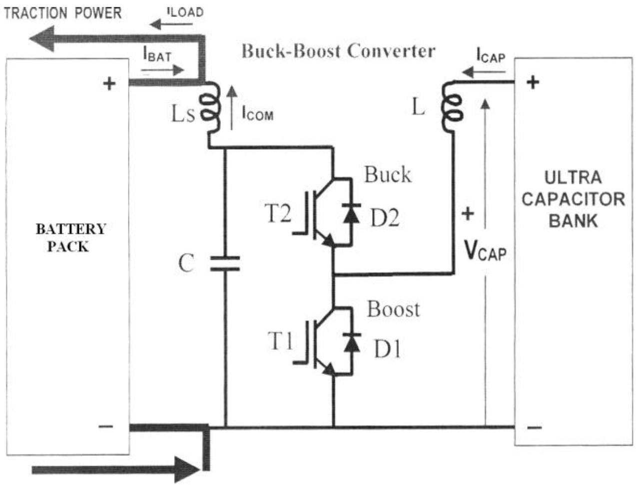

Figure7. Control system for the regenerative braking

When the bicycle exceeds a certain speed, the microcontroller lets the super capacitors discharge; if the vehicle is stopped, the super capacitors are charged, storing the accumulated energy [15].

The battery voltage level indicates how the vehicle is moving: acceleration leads to its reduction, in the opposite case, it leads to its increase, and the regenerative braking happens. In the later case the control system activates the Buck converter to store part of the kinetic energy in the super capacitors bank. During the acceleration phase T_1 is in switch mode allowing energy transfer from the super capacitors to the battery. In the regenerative phase (deceleration) T_2 is in switch mode allowing an opposite energy flow. This last operation is only possible when the cyclist stops pedaling. The brake lever allows two different modes: electromagnetic and mechanical [13].

The above mentioned operations are managed by the microcontroller and its function is the combination of two main control levels: primary and secondary. The first aims at generating a reference current I_{ref} to be feed to the super capacitors bank, in any load condition. Its inputs are: load current I_{load}, battery voltage V_{bat}, and super capacitors voltage V_{cap}. This first control maintains the right energy level inside the super capacitors bank by means of the bicycle speed V_c and of the state of charge of the battery. I_{ref} is sent to the second level control, where the current to compensate the super capacitors charge will be calculated. In this level the PWM signal is generated.

VII. PULSE WIDTH MODULATION METHODS

The XC866 is capable of handling BLDC motor control with Hall sensors or sensor less. For the hall sensor, there is a special mode in the CCU6 that handles the commutation logic with minimal software. Motors with Hall sensors that are placed 60 or 120 electrical degrees apart can be handled. Whether it is sensor or sensor less, various pulse width modulation (PWM) methods can be implemented with minimum software see figure1. The trapezoidal control of a BLDC means that at any time, only two of the three phases are energized, the other phase is left floating. In (a), the de-energized phase and half bridge are shown in dots. (b) shows the current flow during PWM on period. The ‘slow decay’ method is the usual modulation method where during the off period of the PWM, the load current is allowed to circulate in the bottom switches as illustrated in (c). The ‘fast decay’ method where all the switches are off during the off period of the PWM shown in (d), has the drawback of high load current spikes [14]. To improve the efficiency of the system, the synchronous rectification method can be used during high load. Instead of letting the load current circulate in the body diode during the off PWM period; it is more efficient to let the current circulate in the switch itself. This means that both the top and bottom switches of the same bridge need to be modulated instead of just the top switch. To implement this, some care must be taken to avoid a current shoot-through during the transition period where one switch is turned on while the other is turned off. The current shoot-through is avoided with the introduction of dead time. During the period of the dead time, the current circulation is through the body diode as in (c) but after the dead time, the current circulation is through the bottom switch, as in (e). The synchronous rectification can be used for the 'fast decay' as shown in (f) (see figure8). There is also the fault detection capability of the CCU6 where the output to the three-phase drivers can be immediately turned off when a fault is detected. As mentioned earlier, most manufacturers design the inverter drive circuit with discrete components, not the specialized motor drive ICs that have built in protection circuits, so this is an important feature as it complements the discrete inverter drive design with a protection capability. The ADC conversions can be automatically triggered by the CCU6 timers. It can be set to perform conversions at the ends of the on or off periods of the PWM. If the conversion needs to be performed at another point of the PWM, another timer can be configured in the single shot mode to start counting at the beginning of every PWM.

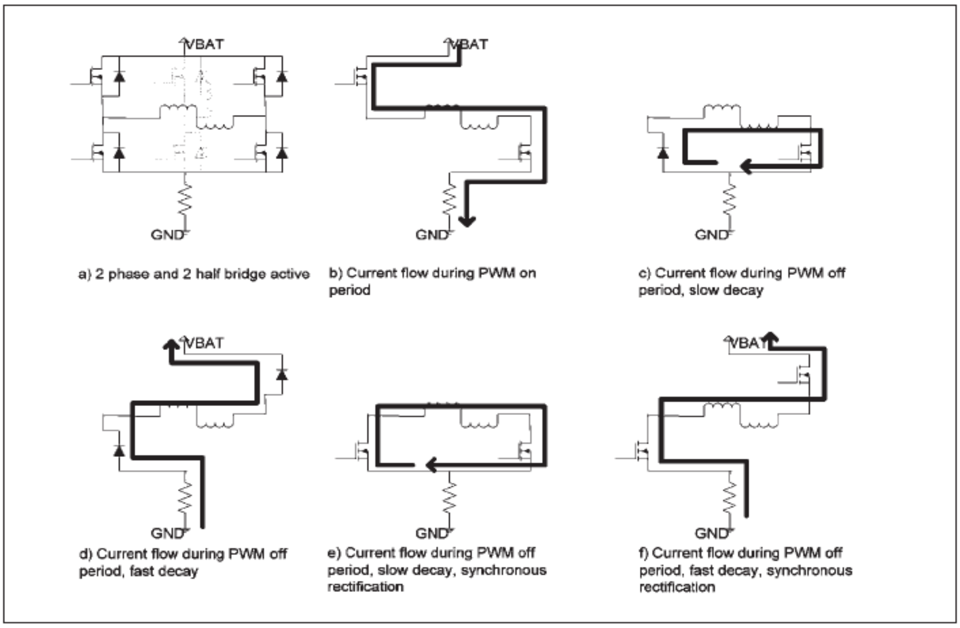

Figure8. - Operating limit for the DC brushless motor

Once configured and started, the whole process can be automated to a point where the program is only read in the conversion results. The completion of the ADC conversions can also be programmed to trigger an interrupt for the more timing critical algorithm [15]. An example of the usage is the sensor less BLDC control where the ADC is used for zero crossing detection. The interrupt can also be programmed to happen only if the result is within a certain range. For the classical method where the zero crossing detection is done at the on period of the PWM, and for the case where the BEMF signal is an increasing one, the interrupt can be programmed to happen only after the voltage is above the zero crossing point. For the zero crossing detection during the off period of the slow decay type of modulation, the range can be changed to near ground voltage. Apart from the 3 ADC pins needed for the zero crossing detection of the three phases, another 5 more ADC pins can be used to read the load current, battery voltage, temperature sensor, handlebar etc.

VIII. RESULTS AND DISCUSSIONS

Based on the experimental observations on the human cum electric powered bicycle, the performance analysis between Acceleration phase, current and voltage was carried out as it is shown in figure 9.

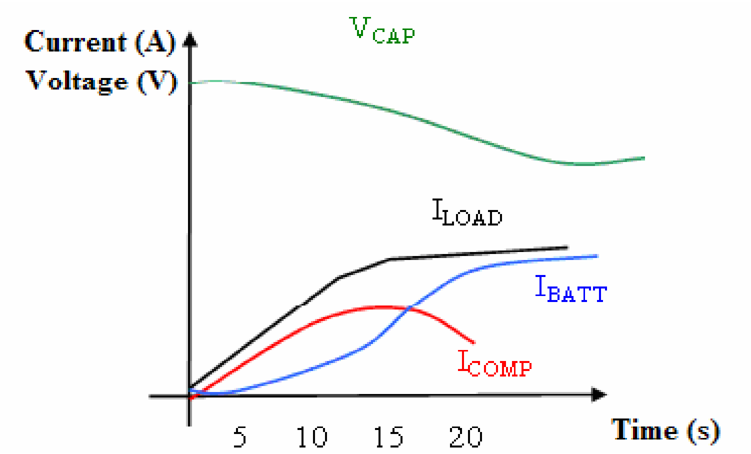

Figure 9. Acceleration phase

In the first case it has been considered acceleration from 4km/h to 8km/h. In the second case the cyclist stops pedaling. Similarly , the relation between Re-generative breaking phase, current and voltage for the acceleration and deceleration of breaking is also presented in figure 10

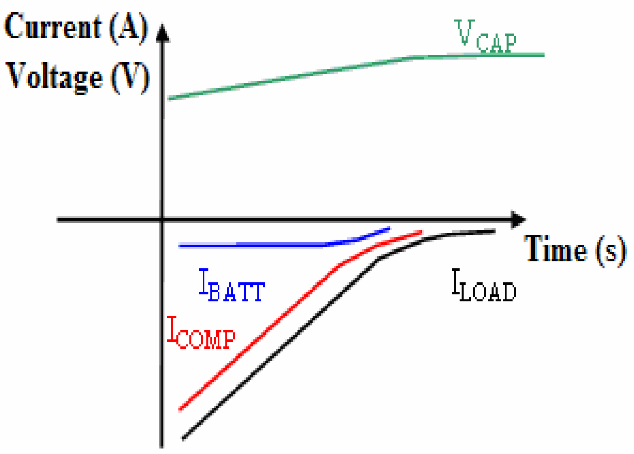

Figure 10. Regenerative braking phase

With the above technical solutions, a performance improvement up to 15-20% can be obtained.

IX. CONCLUSIONS

A number of different aspects thrust the use of electric bicycles in different situations. These include lower energy cost per distance travelled for a single rider, savings in other costs such as insurances, licenses, registration, and parking, improvement of the traffic flow, environmental friendliness, and the health benefit for the rider. In this paper, the design of an electrical drive for a motorized bicycle is described, using commercial components available on the market. On the basis of technical-economical consideration, the feasibility of such a system for industrial production has been analyzed. A dynamic model has been used to simulate the system behavior in a number of different situations. A closed-loop control circuit allows the optimization of the component operation, determining in particular a proper value of the motor torque with respect to the load and of the absorbed current. In this way, undesired accelerations can be avoided and the battery range can be increased. Also a suitable regenerative braking system, based on the super capacitor technology, has been studied. Such a system can reduce the electromagnetic stresses of the battery pack increasing the battery life and reducing the maintenance costs (periodic substitutions).

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