Optimization of the energy consumption of the electric drive for a postal delivery bicycle

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***Abstract*- The optimization of the energy consumption of a power-on-demand system, used for the electric drive for a postal delivery bicycle, is discussed. Postmen tend to minimize their own contribution to the total traction power in case of a power-on-demand system. The optimization principle links the maximal allowable armature current of the d.c. motor to the armature voltage. This optimization principle was implemented on prototype controller and validated on the road. An important reduction of energy consumption of about 30% was obtained. This solution allows encouraging the cyclist to deliver more biomechanical power as the contribution of the motor to the total traction power is reduced with increasing vehicle speed. However, at start the maximal traction force of the motor is still available and thus still allows lowering the physical stress on the postmen.**

I. Introduction

Light electric vehicles (LEV) are a promising new kind of device to extend the range of personal mobility vehicles [1-3]. But LEVs are also a promising alternative for vehicles goods delivery (e.g. postal service). Personal electric vehicles can offer several potential benefits to consumers and to society including lower running costs [4, 5], reduced trip times, and a lower environmental impact. As they are potentially suitable for mail delivery, a clear interest for LEVs exists among the European postal operators. In particular electrically assisted bicycles for postal delivery seem to have a very high potential. This is also confirmed by the fact that several European postal operators have launched calls for tenders to purchase electrically assisted bicycles, tricycles, caddies and trolleys to implement in their postal vehicle fleet. However, at the start of this research most products (electric bicycles) available on the market did not satisfy the high requirements of the (European) postal organizations. From this observation, a European consortium was created, resulting in the NEPH project, with the goal of developing a range of power systems for use in light electric vehicles for postal delivery.

As the postmen, delivering mails (and parcels) by bike, need to carry along a large payload, additional traction force coming from the electrical power system helps to perform his daily duty. Further, in the search of lowering the total cost of ownership of their delivery vehicle fleet, many postal operators are looking for alternative solutions for standard cars and mopeds. Further, congested cities make it increasingly expensive to organize timely postal deliveries with standard cars or delivery vans [6]. In addition postal companies are looking for more sustainable or greener ways of performing the delivery. Hybrid and electric vehicles are in this context a possible solution to lower the environmental impact and to give a ‘green’ image to the postal operators.

II. NEPH Power System

NEPH stands for New Electric Postmen Helper and is the acronym of the European industrial project that was officially launched in 2005 and formally closed in 2009. This project was granted the internationally recognized Eureka label (E!3364), that acknowledges it’s innovation and sustainability. The goal of Eureka is to stimulate research efforts of enterprises and to develop their innovation capacity [7].

The NEPH project was related to the study and development of a range of innovative electric power train systems designed for integration in a range of personal mobility devices, for helping postmen with their mail deliveries[8, 9]. This project had two clear main objectives:

- developing of a range of mobility devices to deliver mail in urban and suburban areas
- contributing to the 'European Sustainable Development Policy'.

The range of NEPH power trains developed are designated for integration into the following devices: electric assisted trolleys, electric assisted bicycles and related types (three-wheelers, four-wheelers). The main focus of the project was however on electric two-wheelers for postal distribution.

A schematic representation of the NEPH power system is shown in figure 1. From this figure we see that the power system is composed of the battery packs that function as the on-board energy storage system. Multiple battery packs can be involved. Further, the electric power unit is composed of a

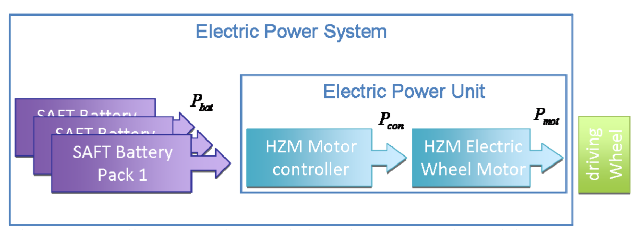

Fig. 1. Controller output characteristics when turning the pedals.

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motor controller unit and a wheel motor, installed in the front wheel. The electric (postal) bicycle equipped with this power system, can be described as a double drive parallel hybrid with two driving wheels [10]. The front wheel is driven by the electric power unit while the rear wheel is driven by the pedals through the chain. A gear system is involved because the hub motor used has an internal gear system.

The motor has a nominal voltage level of 36 Volts. The continuous rated power of the motor has been set to 250 Watt. The motor can however, for short instances deliver more power. The maximal torque and current of the motor are limited by the maximal admissible torque of the gear system used. The motor used for the NEPH project has a maximal output torque of 60Nm and a maximal armature current of 33 Amperes. The wheel motor can be built in a spoked wheel of different sizes [11, 12]. The electric motor is controlled by a step down converter. A buck-boost converter was not used to keep the cost and complexity of the motor system as low as possible. Therefore regenerative braking, as described in literature[13, 14], is not possible. The controller unit uses a detector to sense the forward turning of the pedals. This detector has two built-in sensors (inductive) that sense the sequence of the holes in a perforated disc connected to the pedal axis. If the pedals are not turning, the motor speed is limited, corresponding to a vehicle speed of about 6km/h (walking speed). The full range of the twist grip position is allocated to the reduced speed range (0-6km/h), in case the pedals are not turning. This functionality is also denoted as ‘start-up assistance mode’. This allows activating the electric assistance when walking aside the bicycle. As soon as the pedals are turning, the maximal motor speed is available again. A twist grip is used to regulate the desired speed of the motor. The NEPH power unit is thus a power-on-demand system [10].

Besides the electric power unit, the electric power system for the NEPH vehicles includes a rechargeable battery pack. Two different nickel-metal-hydride battery packs of 36 Volts are available and where used to offer a modular range of energy storage systems to power the range of NEPH vehicles. The 36 Volts battery pack is available with two different cell sizes. The number of battery packs that are required to perform a specific postal delivery round can vary from 1 small pack to up to 3 larger packs.

III. Optimization of the Energy Consumption of the Electric Drive System

This manuscript discusses the optimization of the energy consumption of a battery-electric drive system for use in an electric bicycle for postal distribution. An optimization algorithm was developed to reduce the required energy capacity from the battery packs. This optimization has been developed to avoid the need for more than one battery pack to complete a postal delivery trip.

The control principle that is described below corresponds to the control software for a battery electric drive system used on the electric bicycles for postal distribution was developed in the framework of the Eureka NEPH project [8, 9].

The purpose of the proposed control software change is to limit the energy consumption of a postal bicycle equipped with the drive system mentioned above.

It was reported by some European Postal operators [10] that, according to the experience acquired during their internal tests, the postmen use the full twist grip position to move from one postal delivery point to the next one, with minimal muscular effort. The purpose of this software change is to encourage the postmen to perform more muscular effort during delivery with the postal electric bicycle hence needing less energy from the battery.

It is considered that a drive system using a control based on the measurement of the cyclists' effort (using a force detecting device) allows implementing a proportional share of efforts. Using this measurement of effort, the power from the electric drive can be made proportional to the driver’s biomechanical input power. However, the proposed solution without measurement of effort allows improving the energy consumption in the short term based on software change only. In addition, the use of an expensive force or torque sensing device, often patented, can be avoided in this way. A solution with a control strategy based on effort measurement (i.e. a pedal power control system) would require more development time and leads to an increased initial vehicle cost and an increased components count. The latter can lead to a decreased availability and maintainability in postal service.

IV. Description of the Standard Control Principle

An overview of control principle of electric bicycle can be found in the literature [15-18]. The NEPH drive system uses a motor control unit including an electronic buck chopper to control the energy transfer from the battery to the permanent magnet DC motor. The twist grip position (*Tgr*) is converted directly into a duty cycle control leading to output characteristics as shown in figure 2.

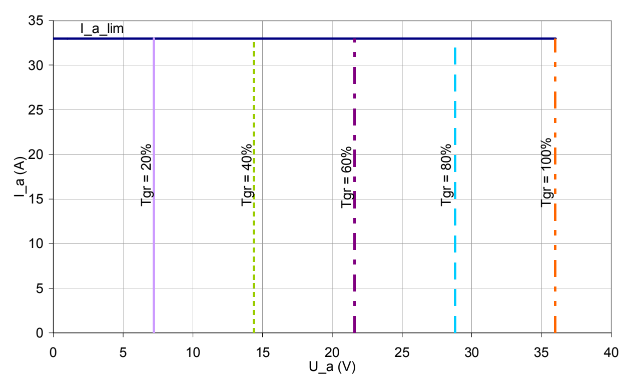

Fig. 2. Controller output characteristics when turning the pedals.

The twist grip position *Tgr*, or the mechanical position of rotation is described by a percentage of the twist grip's rotation compared to the maximal possible rotation. This results in a value between 0% and 100%, where 0% corresponds to no rotation of the twist grip and 100% corresponds to the maximal possible rotation.

The output characteristic shows the relation between the output current and the output voltage of the motor control unit for different positions of the twist grip (20%, 40%, 60%, 80% and 100%). From the characteristic it can be seen that the output voltage is proportional to the twist grip position but has no influence on the output current. However, the output current is limited by the controller to the limit value (i.e. 33 Amps). This can be seen as a pure voltage regulation of the motor.

Additionally, a current limiting algorithm is included based on a PI controller. As the motor controller imposes the d.c. motor voltage, and given that this motor has a permanent magnetic field, the bicycle speed is principally determined by the twist grip position. Pushing harder on the bicycle pedals only has a minor influence on the bicycle speed and hence the cyclist has no encouragement to deliver more muscular power at cruising speed. This leads to high energy consumption and leads to a fast battery energy depletion hampering the postal application.

These characteristics lead to a use for postal delivery during which the bicycle accelerates at motor current limit (I_{a_lim}) when moving from one postal box to the next one. In Belgium for example, this acceleration occurs very often during the mission, as it is mandatory that the postal boxes are reachable from the pedestrians' sidewalk. Hence, the postman moves on the sidewalk from one mailbox to the next one without getting off the bicycle and with only very limited need to park the bicycle for short time. The motor system develops a high acceleration force so the postman feels no need to deliver more muscular power than to comfortably turn the pedals. The current limit (I_{a_lim}) is only influenced by the motor temperature measurement. $I_{a\_lim\_th}$ equals I_{a_max} when the motor temperature is normal. When the motor temperature approaches its maximum allowable value, the motor temperature limit $I_{a\_lim\_th}$, is gradually lowered.

V. Relating the Armature Current Limit to the Output Voltage

The proposed solution for lowering the battery energy consumption is to relate the current limit I_{a_lim} to the controller's output voltage, and hence connecting the available traction force to the bicycle speed. The output characteristic in the case of turning the pedals is shown in figure 3.

A proposed mathematical expression for the current limit is given by equation 1.

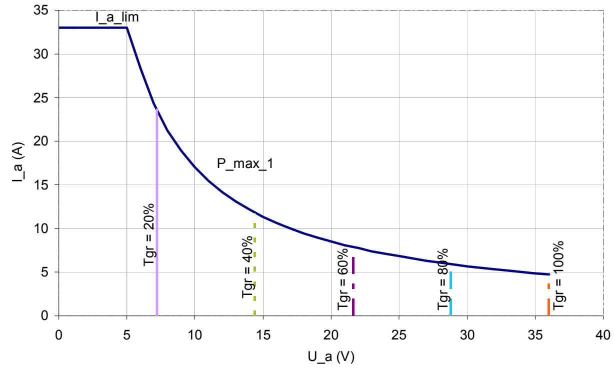

Fig. 3. Controller output characteristics when turning the pedals.

$$I_{a\_\mathrm{lim}} = \min(I_{a\_\mathrm{lim}\_th}, P_{\max\_1} / U_a) \tag{1}$$

With this expression the current limit I_{a_lim} is lowered inversely proportional with the output voltage U_a. As the available motor traction force lowers with the speed of the bicycle, pushing harder on the pedals leads to higher speed and hence encourages the cyclist to deliver a significant part of the moving effort. Maximal starting force will remain available for the postmen to accelerate the bicycle from standstill to a minimal speed. An adequate value of P_{max_1} was found experimentally, starting from a value of 170 W.

VI. Comparative On-Road Tests

A comparative test was performed to investigate the influence of the new control algorithm that was implemented into two different prototype controllers of the electric drive system for electric bicycles. In particular the influence of the new control algorithm on the energy consumption is of interest.

For this purpose on road tests were organized with a prototype electric postal bicycle (see a picture of the prototype manufactured by Ludo nv. in figure 4)

Fig. 4. Prototype used for the on-road comparative tests.

Three different controllers were installed side by side on this electric postal bicycle (see Figure 4) and were connected one after the other:

- Controller nr. 1: the controller with unchanged control algorithm.
- Controller nr. 2: the first new controller with new control algorithm (Parameter value 1 for P_{max_1})
- Controller nr. 3: the second new controller with new control algorithm (Parameter value 2 for P_{max_1})

A test route in Neder-Over-Heembeek (Brussels Capital Region), as described in [8], was chosen to perform this comparative on road test.

Postal distribution was simulated by performing a full stop, with 3 seconds waiting, at every mail box encountered along the test route. The test route is situated in an urban area with a high horizontal density of distribution points. In addition, the area has some important slopes (up to 12%).

The test route is characterized by the following figures:

- Total distance: 2,4 km
- Number of mail boxes: 150 boxes
- Total Mass: 196,4 kg
  - Bicycle: 41,4 kg (inclusive the motor system)
  - Batteries: 26,4 kg (2 packs of 522Wh - Ni-MH)
  - Cyclist: 85 kg
  - Payload: 43,6kg
- Cumulative height difference: 37m

It is to be noted that it concerns a heavy-duty bicycle with a steel frame to withstand the high payloads, inclusive the required luggage carriers for receiving the useful charge (mail items). This results in a relative high bicycle mass. The use of Li-ion batteries could lower the battery mass from 26,4kg (prototype) to 11kg (industrial version) for the same amount of energy. These are the battery pack masses for a configuration with two separate packs with a removable and rugged case suitable for postal application.

The same test route was completed, using the three different controllers.

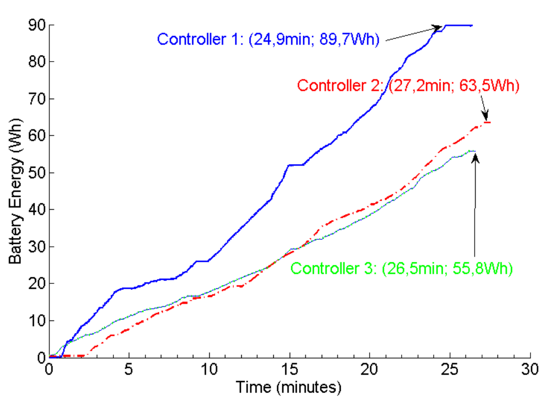

Fig. 5. Prototype used for the on-road comparative tests.

The battery current, I_b, and the battery voltage, U_b, were recorded, using a Fluke Scopemeter (type196B). The battery current is measured, using a LEM current transducer (type LEM-100S). A sampling frequency of 12,5Hz was used, allowing a maximal recording time of 50 minutes.

From this measurement data, the instant power taken from the battery, $P_{battery}$, is calculated:

$$P_{battery}(t) = I_b(t).U_b(t) \tag{2}$$

Then, the energy consumption can be derived for the three different test rounds:

$$E_{Battery}(t) = \int_{\text{begin of trip}}^{t} P_{Battery}(t)dt \tag{3}$$

VII. Test Results

The same test route was completed three times, using respectively controller number 1, 2 and 3. The battery voltage and the battery current were recorded during these tests.

Below, the calculated energy consumption of the drive system (here expressed in Watt-hour) at the level of the battery is plotted against time (expressed in minutes):

The following color code is used in the graphs of figure 5:

- Blue: results corresponding with the test using controller number 1
- Red: results corresponding with the test using controller number 2
- Green: results corresponding with the test using controller number 3

From this graph an important difference in energy consumption can be observed between the controller 1 on the one hand and the controllers 2 and 3 on the other hand. The numerical values, taken from this graph, can be read in the table I:

TABLE I
Energy Consumption Comparison

	Total Energy consumption at end of the test route (Wh)	Relative energy consumption compared with controller 1
Trip with controller 1 (blue)	89,7	100%
Trip with controller 2 (red)	63,5	71%
Trip with controller 3 (green)	55,8	62%

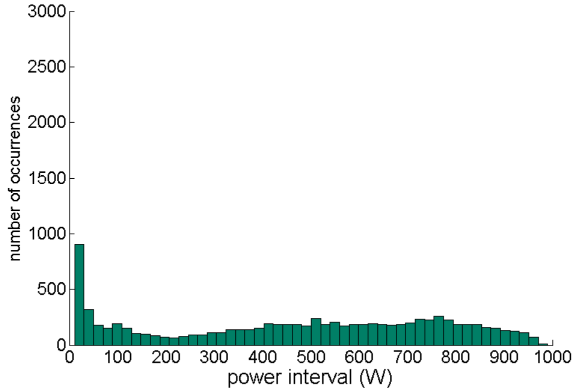

Fig. 6. Histogram of power spectrum of P_{bat}, when using controller number 1

The influence of the new control algorithm, with power limitation, on the power taken from the batteries can also be seen in the power spectrum of the power taken from the battery pack. In the three histograms below (figure 6 till figure 8) the influence of the power limitation can be observed. The power was calculated for every time step of 80ms. The occurrences of 0 Watt power use was removed from the data sets for reason of clarity of the plots. The difference in parameter setting between the controller number 2 and the controller number 3 can also be seen.

From the three histograms, it is clear that the new control algorithm causes a shift in the power delivered from the battery towards lower power levels and concentrates the power around a mean certain value. This mean value is different for controller number 2 and controller number 3, according to the parameter setting in the software. In particular, the parameter P_{max_1} is different for controller number 2 and controller number 3.

As no significant difference in mission duration ($T_{mission}$) could be observed the significant decrease in energy consumption could be explained in an increase of the driver's effort.

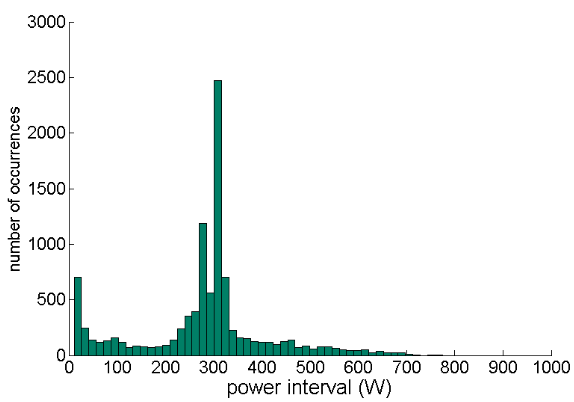

Fig. 7. Histogram of power spectrum of P_{bat}, when using controller number 2

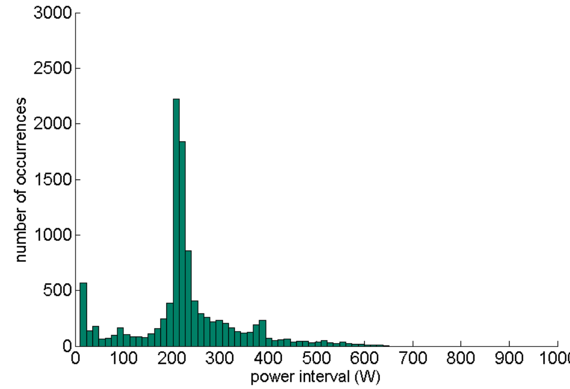

Fig. 8. Histogram of power spectrum of P_{bat}, when using controller number 3

VIII. Effort from the Cyclist

During the comparative on road tests, the cyclist was equipped with a heart rate sensor (Polar, type CS600) and the evolution of the heart rate, H (beats per minute) of the cyclist was recorded for the three test rounds with the different controllers.

Further, the Polar CS600 also registers the altitude, A (meter above sea level) and covered distance, D (km) during the test rounds.

The relative altitude Ar is calculated as follow:

$$A_r = A - A_{\text{start}} \tag{4}$$

The measurement of the altitude is plotted against the trip distance in the figure 9 and helps to have an idea of the topology of the test route and to interpret the heart rate measurements.

Important slopes can be identified in the beginning of the test round, after about 1250 meter and after about 1900 meter.

The heart beat is compared to the average heart rate of that trip and gives the relative heart beat rate:

$$H_r = H / \widetilde{H} \text{ with } \widetilde{H} \text{ the avarage heart rate of the trip} \tag{5}$$

In the figure 10, the relative heart rates are plotted against the trip distance (in km)

In this figure an increased heart rate of the cyclist can be observed in case of the use of controller number 2 and number 3 compared with the case when using controller number 1. This can be explained by a higher effort from the cyclist. The latter is especially true when driving uphill (see the first 100 meter, after 1250 meter and at the last part of the trip after 1900 meter).

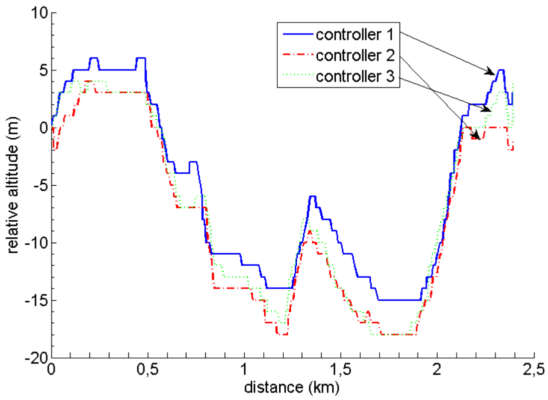

Fig. 9. Relative altitude versus trip distance

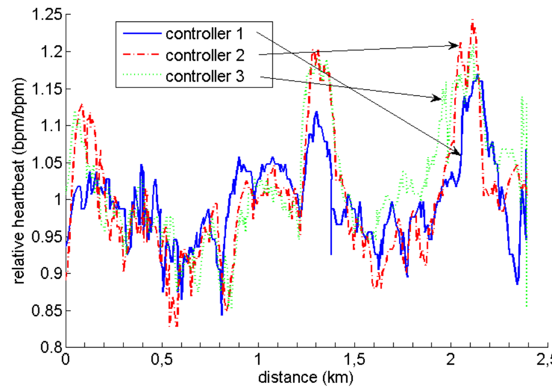

Fig. 10. Relative heartbeat in function of the trip distance

IX. CONCLUSIONS

The purpose of the software change was to optimize (to lower) the energy consumption from the battery packs and to encourage the postman to participate with more own muscular power to drive the vehicle. The first test results, described in the previous paragraph, show an important lowering of the energy consumption from the battery pack for a given mission. Now significant change in mission time was observed. On the hills, in case of the optimized controllers, the heartbeat from the cyclist is higher compared to the case of the standard controller. This is an indication that the cyclist had to deliver more effort and thus was encouraged to deliver a larger share of the total traction force. This adaptation in software is considered to be a good solution for lowering the energy consumption of the electrical power system used in the electric postal bicycle with the drive system.

ACKNOWLEDGMENT

The authors would like to thank all partners of the NEPH project for their valuable contributions.

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