Electrically Propelled Bike: a comparison between Two Control Strategies

Arnaud Sivert, IEEE Reviewer E-mail : arnaud.sivert@u-picardie.fr
Franck Betin, E-mail : franck.betin@u-picardie.fr IEEE Member,
Sebastien Carrière, E-mail : sebastien.carriere@u-picardie.fr
Laboratoire des Technologies innovantes (L.T.I)
Institut Universitaire de Technologie de l'Aisne, I.U.T, 13 av. F.Mitterrand, 02880 Cuffies, **France**

Abstract: *This paper outlines the benefits of the constant power control compared to the constant force control. The constant power control allows to cancel the intensity peaks supplied by the battery and have better dynamic speed. Indeed, for the same energy consumption during acceleration, displacement is larger with the constant power control. However, this control strategy causes a current peak motor. Therefore, there are trade off which exist between the constant power and constant driving force to control a motor. Many curves present in theory and practice the two control strategies. The power constant control is obviously applicable to any electric vehicle. We applied the two commands to 1500W brushless electric bikes from a test bench. These bikes reach 60 km/h with a difficult compromise between weight, power, autonomy and price. The constant power control is the most suitable because it increases the life of batteries which represent 35% of price. The constant power control is achieved through regulation of the battery current and not of regulation motor. However, a limitation of motor current priority must be made for low speed values. In addition, the battery current control makes it easy to limit the current to 1C during deceleration or downhill runs (regeneration).*

Keywords: control strategy, electrical bike, torque control, power control.

1. Introduction

The paper deals demonstrate the benefits of the constant power control compared to the constant force control. The constant power control is used to cancel the intensity peaks supplied by the battery and to have better dynamic speed [1]. The benefits of power control are obviously applicable to any electric vehicle. In the paper, the both strategies control will apply to a brushless motor of 1500W for bike. It is possible to use these bike engines 60 km/h by taking insurance for lower engine power inferior at 4000W. These e-bikes have a difficult compromise between weight, power, autonomy and price. These bikes were made possible thanks to new battery Li-po or Li-ion. But to increase the lifetime of batteries which represents 35% of the price cycle, we applied the constant power control which allows limiting the intensity peaks during acceleration.

2. E-bikes

Our bikes can go 60 km/h on flat road for the most powerful. The acceleration is 4 seconds to reach 36 km/h. The maximum intensities for battery and for motor, the maximum speed and acceleration time can be configured in the controller. In 2010, the cost of our bikes was € 1.400 with the instrumentation for a power of 1500 W. In 2011, the cost decreased to € 1.000. These bikes do not need pedal assistance but only a handful throttle accelerator [3].

Fig 1: Our electric mountains bikes from 500W to 1500W.

Bicycle DC Motors are brushless wheel motor that have very high specific power rate but it is possible to use classical motors outrunner of 4000W. The controller (1500W, 60V, 40A max, 2400W max) can brake and reload the battery on the road downhill. The charger of battery reloads until to 10A and can balance Li-po to 5A. We will now mathematically quantify the electric bike to know these features and understand its control. For the sake of simplicity, we will not go into details of the mechanical losses of the motor, or control (regulation speed and current), internal resistance of batteries. But, the reader can download the detailed study carried out by our students on the website: http://aisne02geii.e-kart.fr/.

Now, we will see the force and power required by e-bike in steady state.

3. Forces and power in steady state speed

In a steady state speed, the motor force is equal to the resistive force. This force depends on the bearings, the tires, the road slope, and the air resistance.

Their respective equations are:

$$F_{resistive}(N) = F_{Road} + F_P + F_A \qquad (1)$$

$$F_P(N) = M(kg) \cdot g \cdot slope(\%) \quad \text{with } g=9.81 \qquad (2)$$

$$F_A(N) = f_a \cdot [V(Km/h) + V_{wind}]^2 \qquad (3)$$

The F_{road} depends of the pavement, tires and driver weight. It is negligible compared to the air resistance F_A. The power needed can be observed in a steady state speed on figure 2 for a weight of M=100kg.

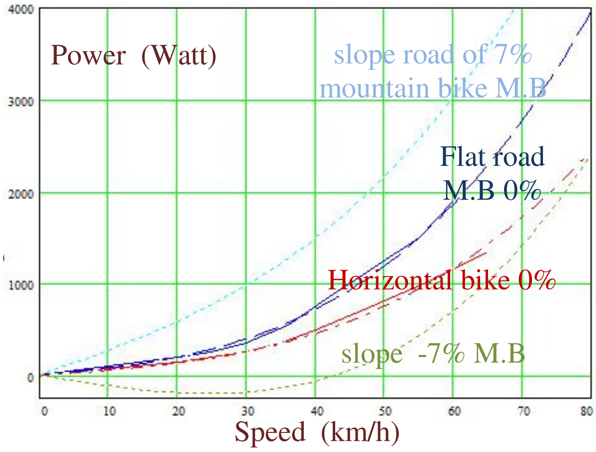


Fig 2 : Power motor vs speed and slope of road M.B=[f_a=0,0066 W/(km.h^{-1})^3, F_{road} =2N], Horizontal bike without fairing = [f_a=0,004 W/(km.h^{-1})^3, F_{road} =1.39 N]

The figure 2 shown that the recumbent bikes are more aerodynamic than the mountain bike M.B and requires less power.

Fig 2 : Our electric recumbent bicycle.

The power corresponds in steady state speed to the following equation (4):

$$P_{resistive}(W) = F_{resistive}(N) \cdot \frac{V(km/h)}{3,6} = P_{humane} + P_{elec}$$

The average human power is setting from 150W to 300W for a pedaling rate from 10 to 100 rpm. The cyclist is always adjusting the gear ratio to the relief in order to obtain the same power and a constant pedaling rate due to the resistance power. Now that the power of resistance is known, the accelerating force to start the vehicle must be studied. The motor are often controlled using force or constant torque strategy. We will see the dynamics of these types of speed control.

4. Motor force control

We will use the constant force to accelerate and decelerate the vehicle. These forces are limited by the values of motor intensity which is configured in the controller.

The cyclist fixes the motor reference with the throttle handle. The electro mechanicals relations of the engine are:

$$v(m.s^{-1}) = U_m/k = \alpha .\ U_{Batt}/k \qquad (5)$$

$$F_m(N) = I_m \cdot k \cdot \eta_{motor} \qquad (6)$$

Where U_m and I_m are the motor voltage and current. The α coefficient varies from 0% to 100%. It's the PWM duty cycle delivered by the controller.

The mechanical and electrical power is determined by the following equation:

$$P(W) = F_{resitive} \cdot v(t) = \alpha \cdot U_{Batt} \cdot I_{Batt} \cdot \eta_{motor} \qquad (7)$$

With U_{batt} and I_{batt} the batteries voltage and current, η the efficiency.

For simplicity in steady state speed, the resisting force will be considered constant at 30 N, the mass of bike and rider is 100 kg. It can be seen in Figure 3 that the intensity limit is set to start at 56 A. So the driving force of 280N will start because k is equal to 5.

The dynamics of the speed is imposed by the fundamental mechanical equation following:

$$F_m = M\frac{dv}{dt} + F_{Resistive} \qquad (8)$$

We can observe on the fig 3 that during the motor force is to 280 N and during the deceleration, it decreases to -220N.

The speed dynamic is determined by the differential equation (8):

$$v(m/s) = \frac{(F_m - F_{resistive})}{M} \cdot t + v(t=0) \qquad (9)$$

The acceleration and deceleration time will be 4 seconds to reach 10 m/s.

On Figure 3, motor power and energy consumption can be seen. This energy is composed of course of the kinetic energy and of the energy required by the resisting force. The energy corresponds to the following equation (10):

$$E(W.H) = E_{kinetic} + E_{force\ resistive} = \int F_m(t) \cdot v(t) \cdot dt$$

For example, during acceleration, the energy required is equal to:

$$E\ (W.H) = \frac{1}{2} M \cdot V^2 + F_{resistive} \cdot \frac{V}{t_{acc}} \cdot \frac{t^2}{2} \qquad (11)$$

We can see that the energy recovered during braking is almost equal to the energy of acceleration recess near the resisting force. Note also the peak intensity to be provided by the batteries during acceleration and advanced regeneration during deceleration. However, all batteries are limited in rate of discharge and charge currents in such a way to do not destroy them. So there are trade off between the desired dynamics and the maximum currents allowed by the battery.

The following table shows that price depends on the rate of discharge for an accumulator 48V 10A.H.

It can also be observed with this table that the weight and volume increases when a current peak battery is required [4]. In addition, it can be seen that the current deceleration must be set by the rate of battery charge.

To cancel the current peak of the outgoing and incoming batteries, we will see that the constant power control is suitable.

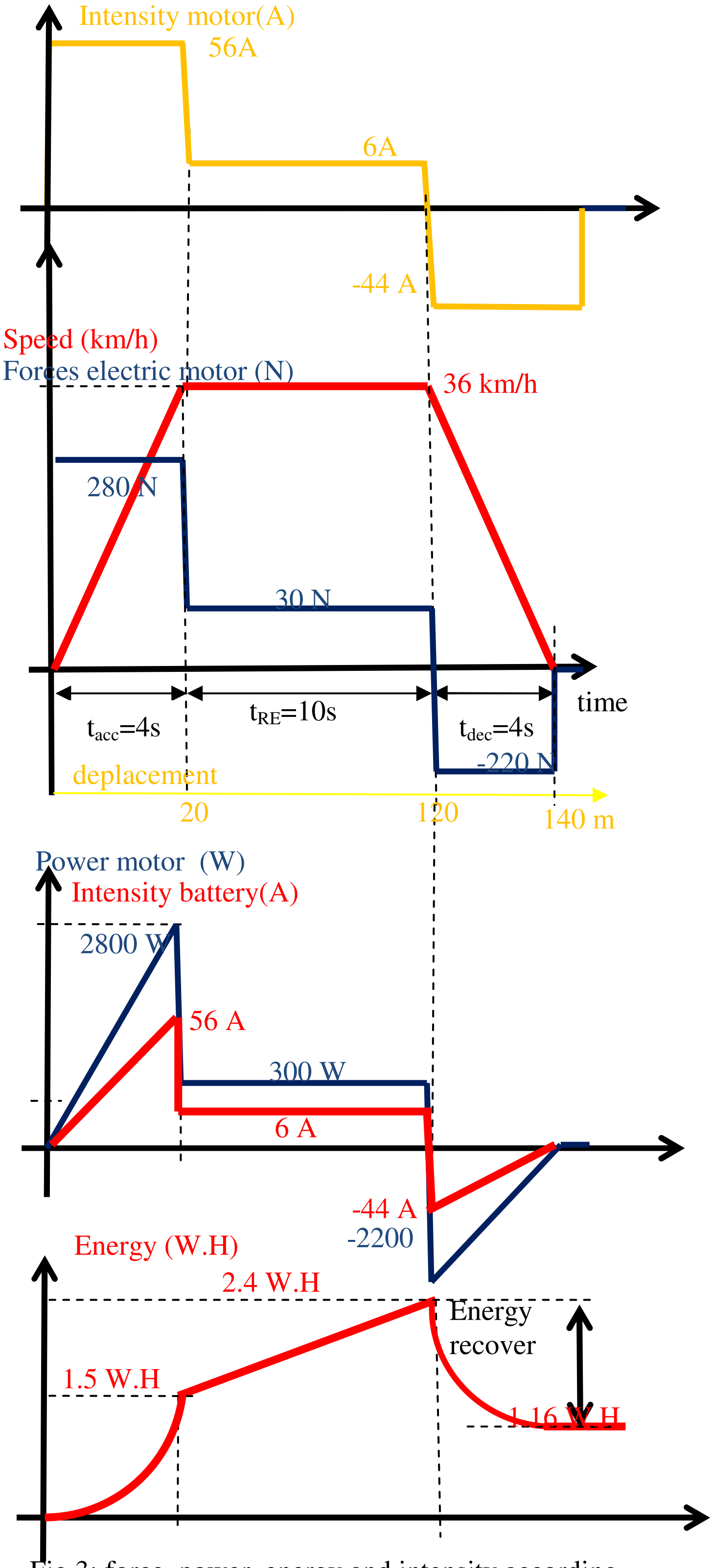


Fig 3: force, power, energy and intensity according to trapezoidal speed profile for a battery of 50V.

Table 1 : Comparison of batteries different 48V

Kinds of battery li-po	Size & Volume cm^3	Mass kg	Price 2011	charge rate max	discharge rate max	R
10 A.H 12S	(1*10.6*10.2) 1300	2.5 kg	420 €	10 A= 1C	30 A = 3C	1 mΩ
13 A.H 12S	(0.6*20.8*13) 2000	3.9 kg	620 €	20 A= 1.5C	104 A = 8C	? mΩ
12 A.H 12S	(0.8*20.8*13) 2600	4.3 kg	800 €	24 A= 2 C	180 A = 15 C	? mΩ

5. Motor control with constant power.

When the battery power is limited, the bike runs at constant engine power P_{mlimit} [1] [5]. To know the speed dynamics, we have to solve the following differential equation:

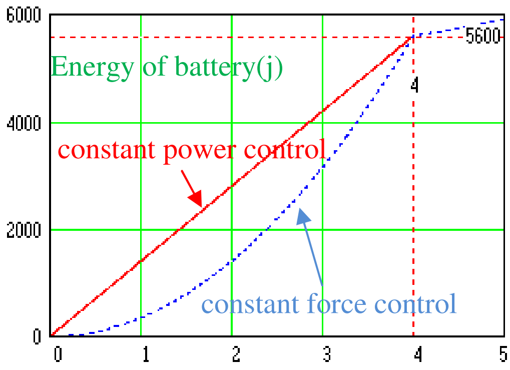
$$\frac{P_{m\,\mathrm{limit}}}{V} = M\frac{dV}{dt} + F_{\mathrm{resistive}} \qquad (12)$$

$$V(m/s) = \sqrt{\frac{2\cdot P_{m\,\mathrm{limit}}\cdot t}{M} + V(t=0)^2} \qquad (13)$$

$$D(m) = \sqrt{\frac{2\cdot P_{m\,\mathrm{limit}}}{M}}\cdot\frac{2}{3}\cdot t^{3/2} \qquad (14)$$

By neglecting the resistive force, the equation (12) can be solved and gives the dynamics of velocity and displacement corresponding to equations (13) and (14)

If the resisting force cannot be neglected, the differential equation is not resolvable then it will be simulated as shown in Figure 4 to compare the two control strategies.
If the power is limited to 1400W corresponding to the average power (Figure 3) during the acceleration, it will also take 4 seconds to reach the speed of 36 km/h (10 m/s). The energy will be the same for the two control strategies. But with the constant power control, the distance will be 27 m instead of 20m. Indeed, the dynamic speed at constant power is higher than that of the driving at force constant as it can be seen in Figure 4. In addition to the constant power, the battery intensity is constant equal to 28A during acceleration and does not reach 56A. Nevertheless, the motor intensity is very important for the low speeds. To not oversize the switches of controller, the motor intensity will be limited to 150A. The dynamics with this limitation can be seen on the figure 5.



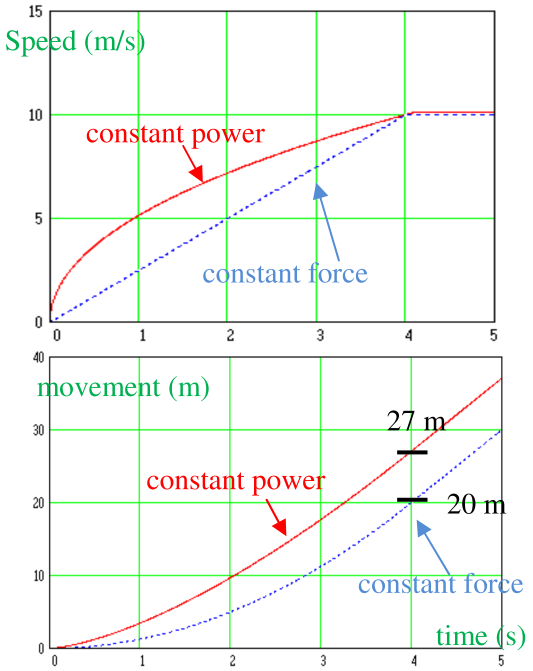


Fig 4 : Energy, speed, distance for control power and constant force with a load of 30 N.

When the motor current is limited, this causes a ramp on the current battery until it reaches 28A corresponding to the constant power. So the dynamics of speed will be slightly lower compared to Figure 4. But if the constant power to 1470 W is increase, the speed reached 10 m/s in 4 s.

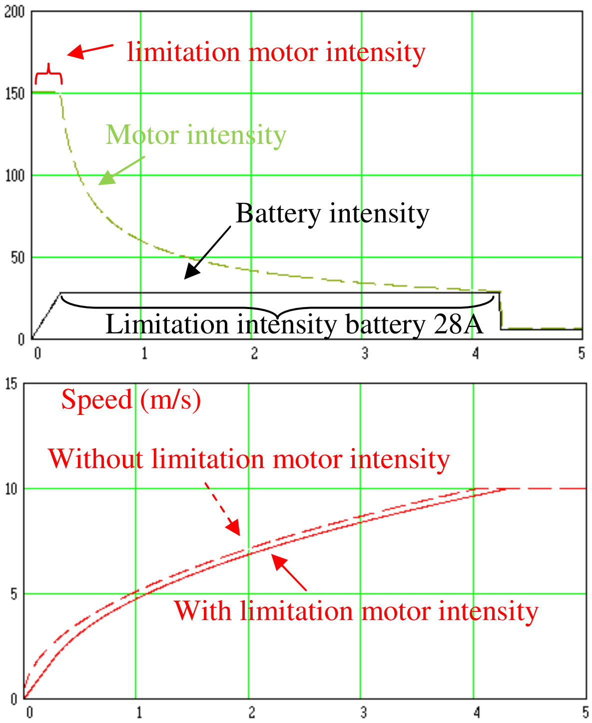


Fig 5 : Motor intensity and battery for constant power control with limitation intensity motor.

With a constant power control, there is never likely to exceed the maximum intensity of the batteries. But, there is a large motor current for

low speeds. Therefore, a thermal relay is required to protect the motor.
With the constant force control, the motor intensity limit is 3 to 4 times the rated current. So it is possible to exceed the maximum motor power when the slope of the road is important and destroy it and the batteries. A thermal relay is also necessary to protect the engine, but use more temperature sensors to monitor the batteries.

6. A test bench for e-bikes

The choice of rear motor is motivated by a way to reload the battery thanks to the human muscle strength. A pinch roller is installed on the device. A generator is connected on the pinch roller to test the motor wheel (see on figure 6). Some embedded instruments measure the voltage, the intensity, the wheel speed and calculate the power and the energy of the battery. A LCD monitor displays all parameters values:

45.5 V 50.9 kph
9.13 A 0.118 Ah

Figure 6: e-bike and test bed

An oscilloscope and a wattmeter recorder are used to measure the dynamic of the intensity, voltage and speed of the e-bike.

7. Control strategies for motor brushless of e-bike

To control the motor of an electric bike without sensor assistance, there are several strategies such as:
- Intensity limiting motor only (motor control with constant force during the start)
- controlling the speed and limiting the intensity motor,
- limiting the intensity from the battery (motor control with constant power during the start).

The second strategy is interesting because it can use a security sensor that has to be installed on the chain ring with the following features (fig 7) :
- If the pedaling frequency vanishes or is equal to 0.1 rd/s, the motor runs as a freewheel and the speed set-point is 0 km/h, whatever any action on the twist handle throttle
- If the pedaling frequency is lower than 0.15 rd/s, the speed set-point equals 13km/h even if the throttle is getting up to 100%,
- If the pedalling frequency is greater than 0.15 rd/s, the speed set-point matches with a ratio of the twist throttle,
- An electrical braking will occur when the throttle is at its start position when the bike is getting over 13 km/h. Below this speed the motor operates at a free wheel.

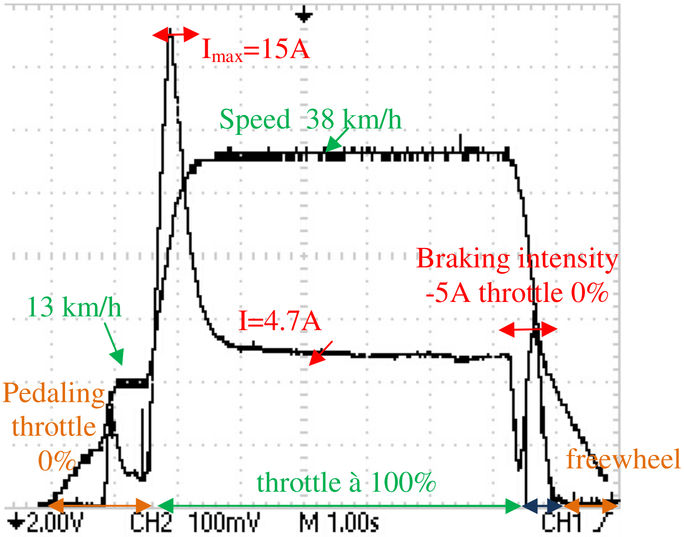


Fig 7 Second strategie : regulation speed and intensity battery (F_R 23N, wheel mass 7kg)

We have found again approximately the acceleration and deceleration times given by the equation (5) and (7) using the test bench.

$$F_{motor} = K \bullet I_{motor} = 5 \bullet (15A) = 75N$$

$$t_{accel} = \frac{(V_{final} - V_{init}) \cdot M}{3{,}6 \cdot (F_m + F_R)} = \frac{(38-13)\cdot 7kg}{3{,}6 \cdot (75-23)} = 0{,}9s$$

$$t_{decel} = \frac{(V_{final} - V_{init}) \cdot M}{3{,}6 \cdot (F_m + F_R)} = \frac{(13-38)\cdot 7kg}{3{,}6 \cdot (-25-23)} = 0{,}8s$$

With the test bench, the mass corresponds to the 7kg of motor and not the rider (100kg) as shown in Figure 3 & 4.

We can observe in Figure 8 that, using the third strategy without pedal sensor, the current battery is limited to 40A for 0.3s max at startup in such a way to have a good acceleration and after the current is limited to 20 A.

This application allows us to observe the regulation of current and the steady state current of 15A when the speed reached 64 km/h with a battery of 50V. Figure 8 allows us to observe the speed and the acceleration during the 2 phases to 40A (33m.s^{-2}) and 20A (5m.s^{-2}). After, it can observe the stop freewheel without regeneration.

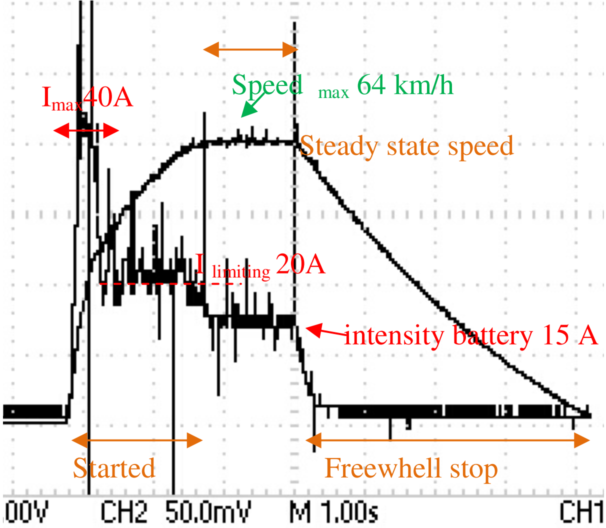


Fig 8 third strategie on the test bench : regulation intensity battery and speed

The figure 9 allows observed the dynamic of the speed and the intensity on the road.

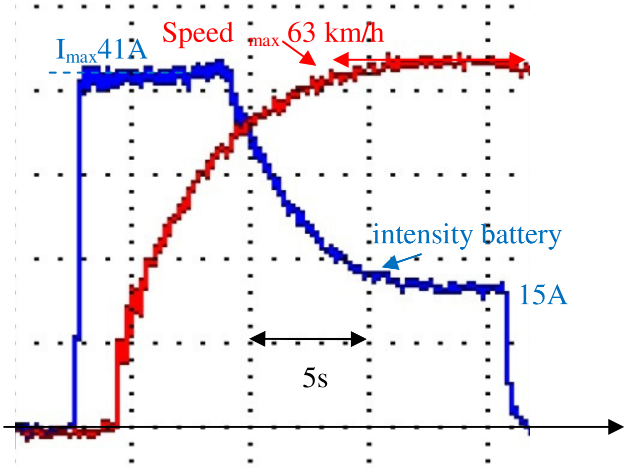


Fig. 9. third strategie on the road : intensity battery and dynamic speed

Conclusion

We have shown that using a constant power control can be eliminated the peak current of the battery but there are not protection from overload the motor. This control is achieved through regulation intensity of battery power and not on the motor. But a limitation of motor intensity priority has to be made for low speed values. In addition during deceleration or downhill, the battery intensity regulation allows to limit the current to load rate maximum. This constant power control allows having better control over acceleration constant force for the same power consumption. The profits of constant power control are obviously applicable to all electrical vehicles. Moreover, it has long been used for electric traction railway [5].

However, many manufacturers offer variable speed control with constant torque and never constant power control.

References

[1] Donoghue, John F.; Burghart, James H « Constant Power Acceleration Profiles for Electric Vehicles » *Industrial Electronics, IEEE Transactions on Digital*, 1987 , Page(s): 188–191 : 10.1109/TIE.1987.350953

[2] Benoit Rozel, Wilfried Frelin, Emmanuel Hoang, Gilles Feld, “ charge simulator for Home Trainer”, CETSIS'2005, Nancy, 25-27 octobre 2005

[3] A.Sivert, F.Betin, J.Becar “An Electrical Bike For Project Based Learning Platform”, *EVER ecologic vehicles & renewable energies de MONACO*, Avril 2011.

[4] Vandana, R.; Fernandes, B.G.; “Optimal sizing of motor Battery system for in wheel electric vehicles” *IECON 2010 36th Annual Conference on IEEE Industrial Electronics* , 2510-2515, 10.1109/IECON.2010.5675157.

[5] Popa, G “Determining the Optimal Operating Regime of the Traction Motors for Constant Power Operation of the Vehicle” *Automation, Quality and Testing, Robotics*, 2006 IEEE International Conference on , 205-208

[6] Chang-Hua Lin; Hom-Wei Liu; Chien-Ming Wang; “Design and implementation of a bi-directional power converter for electric bike with charging feature” *Industrial Electronics and Applications (ICIEA)*, 2010 the 5th IEEE Conference ,538–543, 10.1109/ICIEA.2010.5517092

Arnaud.sivert was born in France.
He received the Ph.D. degree from the University of Picardie Jules Verne, Soissons, France, in 2000.
In 1994, he joined an Institute University of Technology in the Department of Electrical Engineering, as an Assistant Professor. His major research interest is the control of electrical machines
I.U.T has produced many prototypes electric vehicles since 2008 and participates in the French national challenge of electric kart. In 2011, I.U.T participated in the first challenge of French National electric bike.

The e-bike as a teaching support is used in technical field activity as electrical engineering or mechanical engineering and also in theoretical field activity as physics and mathematics. The e-bike teaching tool turns all mechanical or human parameters such as forces and powers into their electrical analogy representation. The e-bike allows understanding some facts.