Comparative Study for electric vehicle performance with or without a boost converter

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***Abstract*— Electric transportation has become a topic increasingly treated by both academic and industry. In electric vehicles, electric engines represent a crucial element that make differences in term of efficiency, weight and other various parameters varying from one type to another. Brushless motors are ones of these different types that have become widely used for their various benefits. However these performances depend on the vehicle internal parameters (the power supply, implemented controlling mode etc ...) and external parameters (weight, resistive forces etc ...). In this paper, a comparison of electric vehicle performance depending on the supply voltage is processed in two cases: the use of a battery connected directly to a Brushless DC motor controller, and the use of a boost converter to maintain a constant voltage (the max value of the used battery) while the battery supplies a decreasing voltage during operations. The results are compared in term of the impact of each parameter and its variation on other ones.**

Keywords— Electric transportation, Brushless DC motor, Boost converter, Voltage regulation, Battery autonomy, Vehicle range.

I. INTRODUCTION

The growth in emissions of greenhouse gases, lack of natural resources, such as oil and its bad consequences on the environment, are some indicators that have supported and will promote the use of electric transportation instead of the fuel-based one.

In the light of this vision, searches are now numerous to improve the performance of electric vehicles, and in various fields such as chemistry for batteries, electronics for the implemented driving modes, the power electronics for managing and controlling the needed energy etc…

This development in power electronics and also in magnetic materials, in addition to other benefits like the high efficiency, easy control, low inertia, low weight and low cost of maintenance, have allowed Brushless DC motors (BLDCM) to become widely implemented and used in electric vehicles. They present more gains compared to other electric engines types on board of electric vehicle.

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However, good performance of the BLDCM is related to certain parameters among which we mention in the first place the supply voltage, i.e. the variation of the supply voltage, which is related to the consumption of energy when driving, has an impact on the one of the remaining parameters such as the vehicle speed. In the other hand, and in the second mention, we cite the resistive forces to the advancement of the vehicle which are also related to the speed of this latter. In other words, the supply voltage, the speed of the electric vehicle, the resistive forces are interrelated variables and are responsible of the vehicle performance and its autonomy.

In this paper, two power modes are processed to compare the results of each. The first mode is to connect the BLDCM controller directly to the battery, while the second mode is to use a BOOST converter placed between the battery and the BLDCM controller to keep the value of the terminal controller voltage equal to the max battery charge voltage. The results of these two methods will be compared in terms of speed, range, covered distance and battery voltage.

The paper is divided into sex sections. Section II presents the schematics of the two power modes with the shapes of the supply voltage of each mode. Details on the brushless DC motor functioning are presented in section III with the modeling equation of this motor. Section IV clears the resistive forces equations related to the speed and other parameters and their impact on the vehicle performance. Simulation results are presented after in section V with comparing between the two modes of power impacts on the vehicle autonomy, the vehicle speed, the travelled distance and the battery voltage. This will be followed with a conclusion in section VI.

II. CONTROL MODES

Fig.1 and fig.2 show the wiring topology between the different used devices for the two controlling modes:

i) Directly connecting the battery to the motor controller,

ii) Using a BOOST converter between the battery and the motor controller.

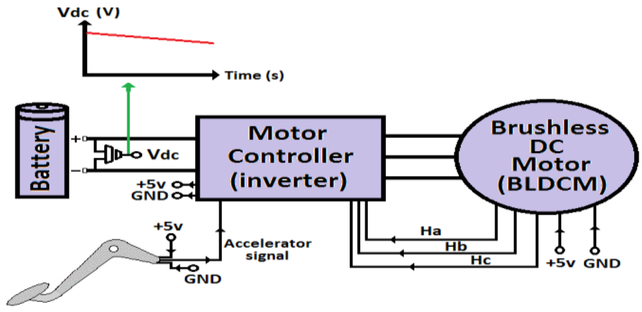

Fig. 1, the used topology connecting directly the battery to the motor controller

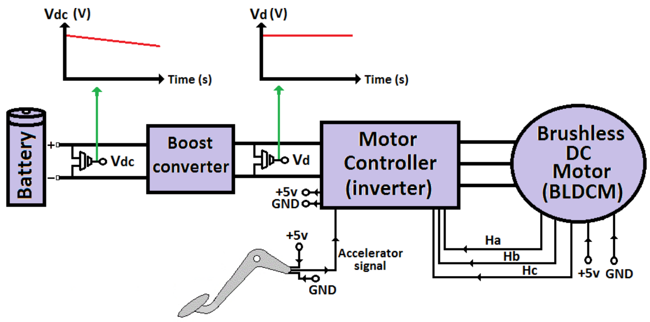

Fig. 2, the used topology connecting the BOOST converter between the battery and the motor controller

On the other hand, by regulating the supply voltage to a constant value the speed remains constant. However, the resistive torque increases compared to the configuration of fig.1, and it is this difference that will be treated with the details of important part of the schematics presented (the brushless motor and the different parameters influenced and more precisely the resistive forces).

The functioning of the BLDCM will be discussed in the next section with different equations linking between voltage, current and speed and between the remaining parameters of the engine.

III. The Brushless Dc Motor

Brushless DC motor is a three phase synchronous motor [1] constituted by a fix part (the stator) and a rotating part (the rotor). Unlike the DC motor, where the commutation is done by brushes, the brushless DC motor is controlled by an inverter which give him more advantages such as: i) more efficiency, ii) low weight, iii) low noise and most of all low cost of maintenance. Fig. 3 presents an inverter schematic composed by a 3 phase bridge of MOSFETs and the BLDCM equivalent model [2].

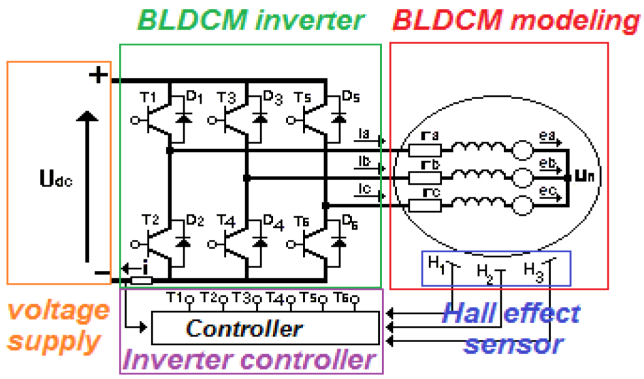

Fig. 3: Inverter schematic and BLDCM equivalent model

BLDCM have generally trapezoidal back-emf [3], which refers to a square current waveform. This controlling mode, and also because it require only low resolution position sensor and only one current sensor, makes this BLDCM type more desirable instead of motors with sinusoidal back-emf that require a high and more expensive position sensor, such as an absolutely encoder and resolver.

The motor equivalent model is presented as a series resistance connected with the inductor and the back-EMF. The speed is monitored by a throttle which delivers an analog signal proportional to the throttle position. This analog signal is converted to a PWM (pulse with modulation) signal with a specified duty-ratio which will control the MOSFET's gate.

Equations linking between the BLDCM parameters are presented as follow:

$$\begin{aligned} V_a &= r_a i_a + L\frac{di_a}{dt} + e_a + V_n \\ V_b &= r_b i_b + L\frac{di_b}{dx} + e_b + V_n \\ V_c &= r_c i_c + L\frac{di_c}{dx} + e_c + V_n \end{aligned} \tag{1}$$

Where r_a, r_b, r_c are the resistance of each phase, i_a, i_b, i_c are the phase current of the stator windings, L is the inductance of each phase winding, e_a, e_b, e_c are the back-emf, V_n is the neutral point voltage, V_a, V_b, V_c are the phase voltage of the stator winding.

The electromagnetic torque and the mechanical equations are:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{W} \tag{2}$$

$$\frac{dW}{dt} = \frac{1}{J}(T_e - T_L - BW) \tag{3}$$

Where W is the mechanical velocity of the motor (rad/s), J is the moment of inertia, B is the friction coefficient and T_L is the load torque.

To vary the BLDCM speed, which means controlling the stator phases current, the rotor/stator position is important to know. This is achieved by using generally three Hall Effect sensors placed on the fixed part of the motor (the stator). These three sensors deliver a combination of signals referring to the rotor position. From these combinations the right command to the inverter's MOSFETs is given. Fig.4

shows the current and back-emf waveforms of BLDC motor and table I presents the combination of the three Hall Effect sensors with the right command to give to the MOSFETs to monitor the motor in the clockwise direction.

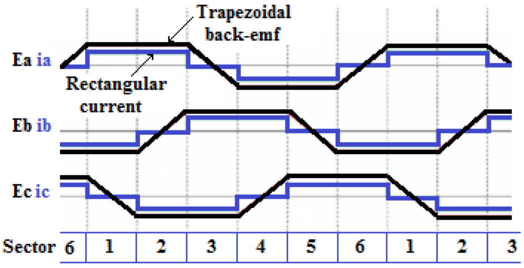

Fig. 4: Back-emf and current waveforms for BLDC motor for the controlling sector when motoring

TABLE I. HALL EFFECT SENSORS AND ACTIVE MOSFETS FOR MOTORING MODE

Sector	1	2	3	4	5	6
Active Mosfets	T1-T4	T1-T6	T3-T6	T3-T2	T5-T2	T5-T4
Hall effect sensors combination	$H_1 = 0$ $H_2 = 1$ $H_3 = 1$	$H_1 = 0$ $H_2 = 0$ $H_3 = 1$	$H_1 = 1$ $H_2 = 0$ $H_3 = 1$	$H_1 = 1$ $H_2 = 0$ $H_3 = 0$	$H_1 = 1$ $H_2 = 1$ $H_3 = 0$	$H_1 = 0$ $H_2 = 1$ $H_3 = 0$

Despite all advantages of BLDCM, torque ripple represents the main drawback of this type of electric motors. Its source can be a wrong or non-optimal design, or from the part of the inverter where we encounter such ripples because of the switching.

For the BLDCM, different control modes [4] can be chosen depending on the imposed performance criteria. Pulse with modulation (PWM) is the most used control technique implemented for electric drive. In [5] [6], a comparison of PWM controlling mode for BLDCM motor is presented. The results are showing that the ON-PWM has the lowest current ripple for both commutation and conduction period.

In [7] [8], a new PWM mode is detailed for minimizing the current ripple due to the freewheeling diode. This control method is named PWM-ON-PWM mode.

The ideal motor control is to have two conducting phases in each section presented in table I. Taking as example the section 1 state we have:

$$i_a = I,\ i_b = -I,\ i_c = 0,\ e_a = E,\ e_b = -E$$

Changing those parameters in equation (2), we get the electromagnetic torque for the ideal conditions:

$$T_e = \frac{2EI}{W} \tag{3}$$

For the next formulas, some assumptions are considered: the motor runs at a constant speed; the current and torque ripples are neglected. This allows writing the equation as follows:

$$T_e - T_L - BW = 0 \tag{4}$$

$$\Rightarrow \quad W = \frac{2EI - T_L}{B} \tag{5}$$

Equation (1) becomes:

$$\begin{aligned} V_{DC} &= r_a i_a + L\frac{di_a}{dt} + e_a + V_n \\ 0 &= r_b i_b + L\frac{di_b}{dx} + e_b + V_n \\ V_c &= e_c + V_n \end{aligned} \tag{6}$$

$$\Rightarrow \quad V_N = \frac{V_{DC}}{2} \tag{7}$$

Replacing (7) in (1) we get the equation linking between current and voltage.

$$I = \frac{V_{DC} - 2E}{2R} \tag{8}$$

From equation (5) we get:

$$W = \frac{EV_{DC} - E^2 - RT_L}{RB} \tag{9}$$

From equation (9), it can be understood that the speed is related to the supply voltage, i.e. an increase in voltage supply gives more speed to the vehicle but with a constant load torque. However, changing the speed of the vehicle implies a load torque change. Resistive forces on the vehicle when rolling are presented in the next section.

IV. ELECTRIC VEHICLE PERFORMANCE

When rolling, a vehicle is subjected to different resistive forces. These forces are the acceleration force F_{acc} (10), the aerodynamic force F_{aero} (11), the rolling resistive F_{roll} (12) and the force of the hill climb F_{climb} (13) [9].

$$F_{acc} = m.a \tag{10}$$

Where:

- m: mass of the vehicle (kg).
- a: vehicle acceleration (m/s²).

$$F_{aero} = \frac{1}{2}.C_d.A.\rho.V_r^2 \tag{11}$$

Where:

- C_d: The drag coefficient
- A: Frontal area (m²)
- ρ: Density of the air (kg/m^3)
- V_r: Relative speed (m/s)

$$F_{roll} = C_r.m.g \tag{12}$$

Where:

- g: gravitational force (m/s²)
- C_r: The rolling coefficient

$$F_{climb} = m.g.\sin(\theta) \tag{13}$$

Where:

- θ: road gradient (rad).

The total resistive force F_{tot} and the needed power from the motor (14) are presented as follow [10]:

$$F_{tot}=F_{acc}+F_{aero}+F_{roll}+F_{climb}$$

$$P_{motor} = F_{tot}.V \qquad (14)$$

Where: V represents the vehicle velocity.

Equation (9) becomes:

$$W = \frac{EV_{DC}-E^2-R(\frac{1}{2}.C_d.A.\rho.V_r^2+C_r.m.g+m.g.\sin(\theta))}{RB} \qquad (15)$$

The implemented electric motor has to produce higher power than the resistive one to overcome this latter and moving forward. Since the vehicle speed is an image of the battery voltage, and the same speed is related to the resistive forces presented in previous, changing any parameter will make difference in the vehicle performance. For our study we will focus on the battery voltage as a varying parameter.

Simulation of an electric vehicle, with the battery connected directly to the motor controller in first case, is compared with the one where connecting the battery with a boost converter to the motor controller in the second case.

V. Simulation Results

To compare the two control modes, the simulation results are presented in terms of speed, traveled distance, the state of charge (SOC) of the battery and its voltage. Fig.6 to fig.9 shows the results of these parameters with and without using the BOOST converter.

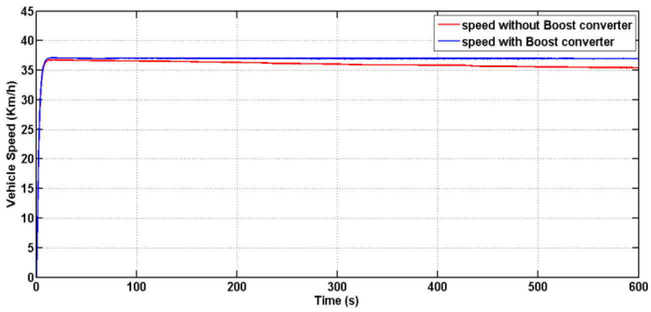

Fig.6. Vehicle speed with and without Boost converter

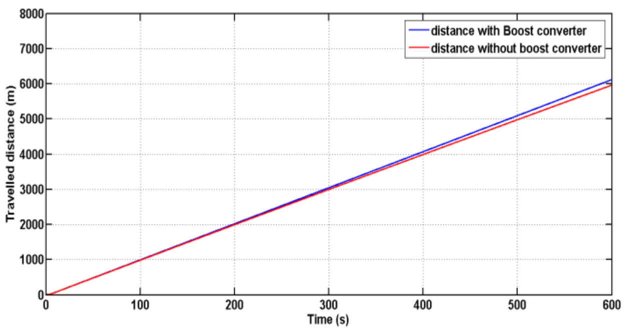

Fig.7. Travelled distance with and without Boost converter

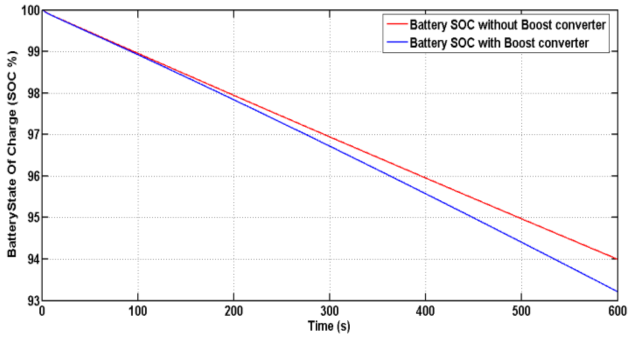

Fig.8. Battery state of charge (SOC) with and without Boost converter

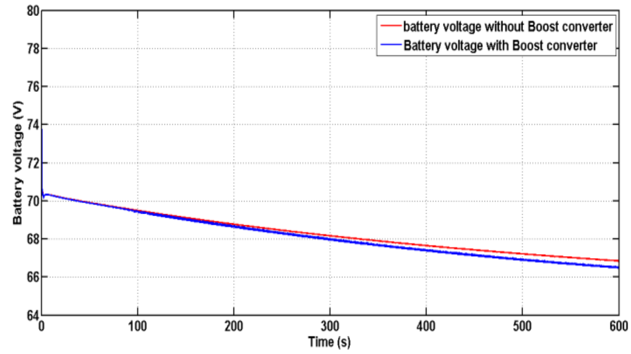

Fig.9. Battery voltage with and without Boost converter

From the simulation results and when using the BOOST converter, the speed remains constant comparing to that without using the converter (figure 6); this is due to the difference of the input voltage of the motor controller.

However, this constant speed has an impact on the battery autonomy and so the vehicle range: the battery state of charge is lower using the BOOST converter. This can be explained by the fact that the resistive force on the electric vehicles is more important, and more precisely, the aerodynamic force because it is related to the square of the speed. This difference of autonomy is also noticed in the battery voltage at the end of the simulation (figure 9).

An advantage of using the BOOST converter is the gain of the distance traveled on the same time of rolling.

Having advantages and disadvantages of using the BOOST converter let us distinguish certain cases where using the BOOST converter is better than rolling with the battery connected directly to the engine controller, and where this direct wiring is more efficient and suitable for the driving range and the for the driver expectations. Fig.10, fig.11, fig.12 and fig.13 present respectively the simulation results of the vehicle in term of travelled distance, vehicle speed, battery state of charge and the battery voltage with and without boost converter for a programmed case of same traveled distance.

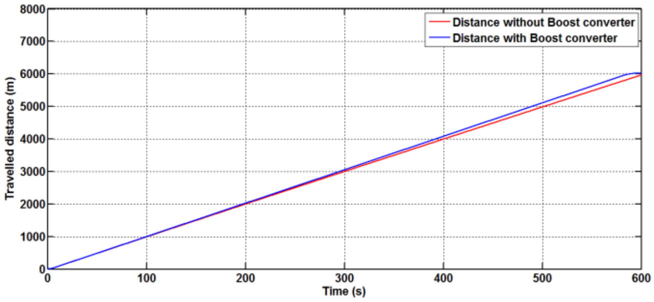

Fig.10. travelled distance with and without Boost converter stopping at the same value

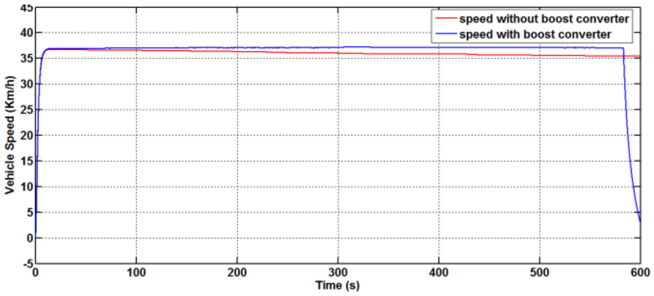

Fig.11. Vehicle speed with and without Boost converter for a same travelled distance

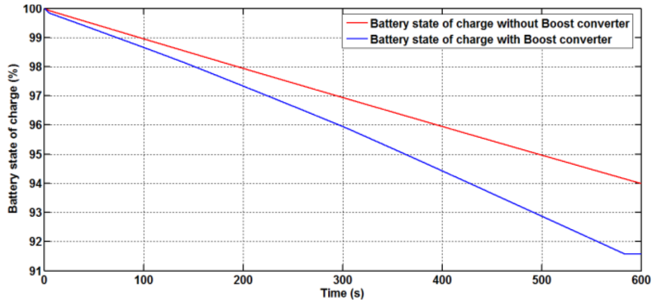

Fig.12. Battery state of charge with and without Boost converter for a same travelled distance

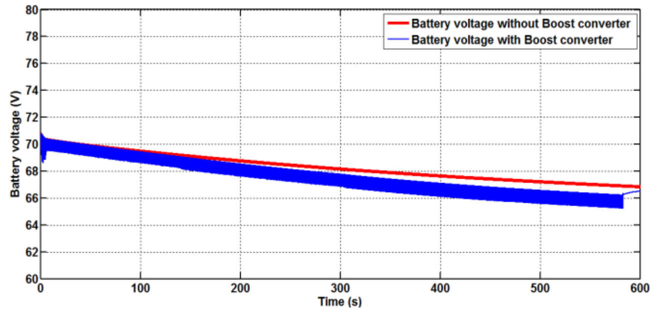

Fig.13. Battery voltage with and without Boost converter for a same travelled distance

Using the boost converter for the case of a same desired distance (the distance without boost converter) has given results of more gain of time. This can be seen in the travelled distance (fig.10) and the vehicle speed (fig.11), where the distance is saturated and the speed reaches zero before reaching the final time of simulation. However, this gain of time has a disadvantage of more energy consumption (fig.12 and fig.13).

Since the battery autonomy is a crucial parameter, the last case will treat the vehicle performance for the same energy consumption as without using Boost converter. Fig.14 to fig.17 presents the simulation results for this case.

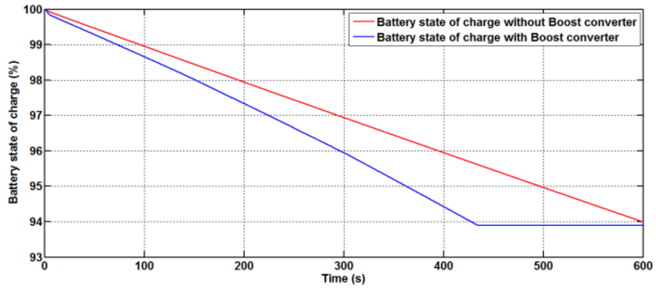

Fig.14. Battery state of charge with and without Boost converter for the same energy consumption

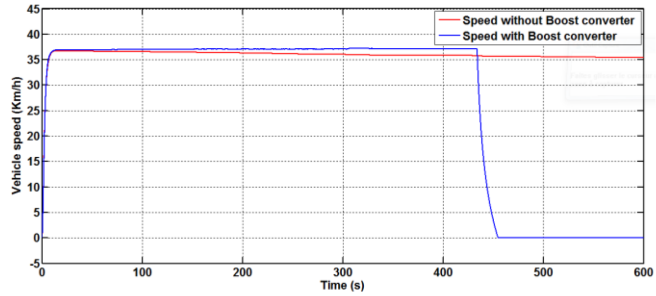

Fig.15. Vehicle speed with and without Boost converter for the same energy consumption

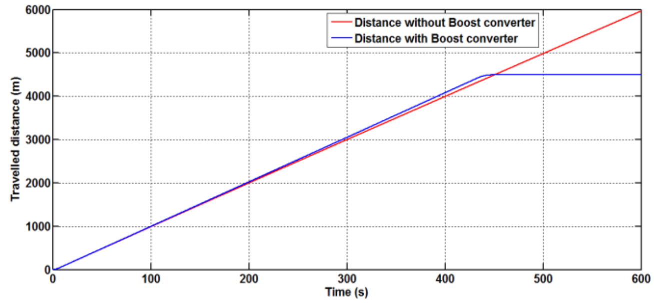

Fig.16. Travelled distance with and without Boost converter for the same energy consumption

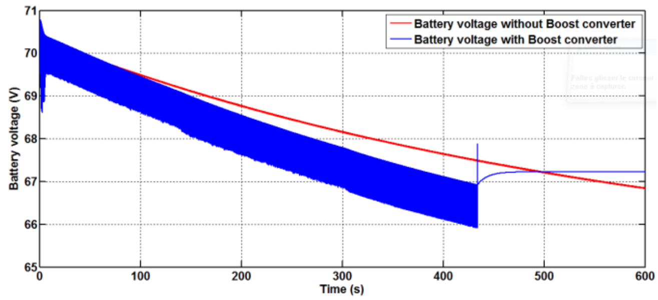

Fig.17. Battery voltage with and without Boost converter for the same energy consumption

For this case, and when rolling using the Boost converter, the vehicle is programmed to stop when the Battery state of charge reached the value of the one when rolling without using it (fig.14 and fig.15). The travelled distance in this case is less when rolling with the Boost converter.

As a summary of the comparison, the use of a boost converter will depend on the battery autonomy and on the required performance by the driver: higher speed and long distance will require the boost converter if the battery can provide necessary power during working time and longer autonomy will require a direct power of the motor controller. However, to finalize the comparison, regulation of the speed for both mode of driving is done to compare the vehicle performance and the energy needed for those cases. Fig.18 to fig.21 presents the simulation results in term of speed, travelled distance, absorbed current by the motor and its average.

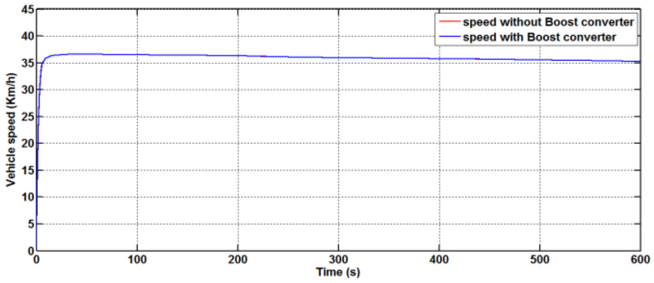

Fig.18. Vehicle speed with and without Boost converter with regulated speed

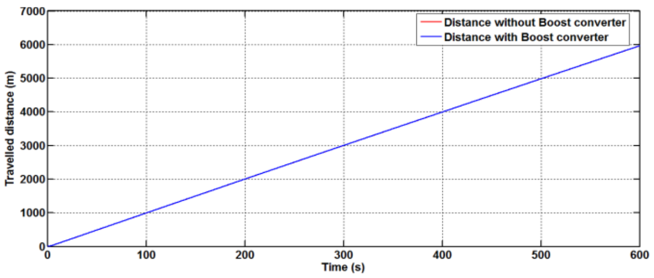

Fig.19. Travelled distance with and without Boost converter with regulated speed

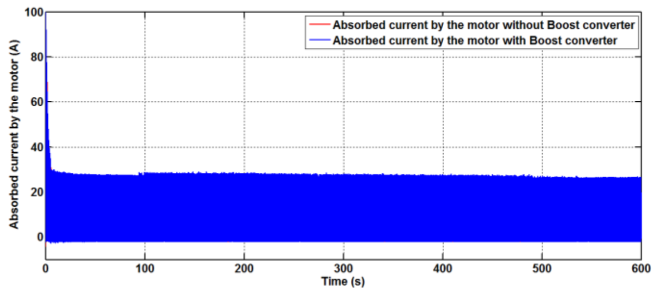

Fig.20. absorbed current by the motor with and without Boost converter with regulated speed

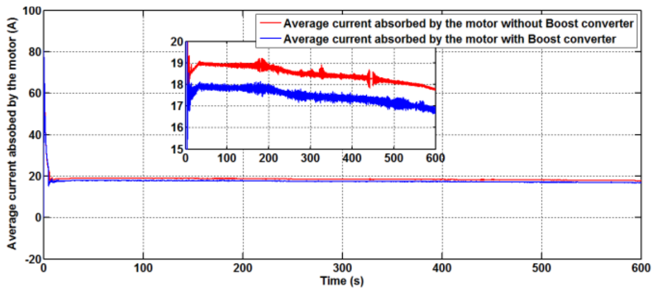

Fig.21. Average absorbed current by the motor with and without Boost converter with regulated speed.

From those results, rolling with the same speed, which refer to the same travelled distance and the same load torque using the boost converter, has more benefit in term of reducing the absorbed current by the motor from the battery. These results confirm those expected and understood from the equations presented in section IV.

VI. CONCLUSION

In this paper we proposed a comparison of two driving modes for electric vehicle: using Boost converter between the battery and the motor, or connecting the motor controller directly to the battery. Results have shown that using a boost converter has advantages in term of more speed and longer distance to travel, but with more consumption of energy. However more energy consumption is needed and reduces the vehicle range. The results are after distinguished between simulation of the same travelled distance and simulation of the same energy consumption and in summary the choice of using Boost converter or not will depend on the energy that the battery can support, the distance to be traveled and the performance required by the driver. However, when regulating the speed, energy consumption is less when using the boost converter.

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