Four Wheel Electric Vehicle Behavior Using Fuel Cell Supply Moving on Mountain Region Condition

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Abstract: Autonomy is one of a most problems for commercialized electric vehicles. Especially that uses four wheels for motions. The weakest point for this kind is the battery energy management system, to solve this problem a Proton Exchange Membrane Fuel Cell is used. The PEMFC autonomy depends on storage state of fuel, in this work we focuses the relationship between mountain slope road effect and PEMFC power consumption behavior. In this study, the variation of the slope angle during trajectory is made and the behavior of PEMCF energy is presented in each steps. Simulations are carried on Matlab software. The proposed energy system develops the autonomy and gives more positive signs on stability for this vehicle moving on slope road condition with different road angles, the fuel cell response is quickest compared with lithium battery moving in the same condition.

Keywords: PEMFC, slope angle, four wheel, autonomy, electric vehicle.

1. Introduction

The fuel cells are fuel-flexible, scalable, and modular, they remain excellent candidates for a wide range of electric vehicle applications from small electric scooter to an electric bus. Fuel cells are currently being demonstrated on land, in the sea, and in the air[1,2].The objective of uses Proton Exchange Membrane Fuel Cells (PEMFC) powered by hydrogen is to build a zero emission electric vehicle, suitable for use in widely populated areas [1,2,3] . PEM fuel cell is very important for power system, because it facilitates the understanding of the involved phenomena.PEM fuel cells were invented in the 1960s for military applications, after that it have been used since the 1970s in submarines. The first model was used for vehicular applications. Engelhard developed a fuel-cell-powered forklift about 1969. Many models have been proposed to simulate fuel cells in the literature, which have generally each the own specificities and utilities, following the studied phenomena [3,4]. The Direct Torque Control strategy (DTC) is one of the main technologies control for power propulsion system such as four wheel electric vehicle which need robust control. This kind of control have many more performances due to its simple structure and ability to achieve fast response of flux and torque. Those performances attracted growing interest in the recent years. DTC-SVM can improve effectively the torque ripple, and system's robustness. DTC-SVM method give high performance in modern driving vehicular technologies for AC motors and improve the system robustness, evidently reduce the torque and flux ripple, and effectively improve the dynamical performance [6,7]. The Buck-Boost converter is used to enssure the energy required for the EV and the propulsion system. The aim object of this paper is to understand the behavior of PEM fuel cell controlled by DC-DC converter for 4WDEV slope road regions.

For this reason the paper plan work is organized as follows:

Section I present an overview on fuel cell.

Section II shows the modeling of electric vehicle load and principle components of PEMFC.

Section III shows direct torque control based space vector modulation with schema.

Section IV gives simulation results and their discussions.

Finally, the conclusion is drawn in the end of paper.

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2. Electric vehicle as mechanical Load

The most forces act on vehicle as mechanical load are resistant forces as it shown in Figure 1. The forces opposite to the vehicle motion are: the tire force, aerodynamic force and the slope force that depends on the road slope angle [1,2 3].The total resistive force is the sum of all resistance forces given by :

$$F_r = F_{tire} + F_{aero} + F_{slope} \tag{1}$$

$$F_r = mgf_r + \frac{1}{2}\rho_{air}A_f C_d v^2 + Mg\sin\beta$$

The vehicle mechanical load parameters are listed in appendix.

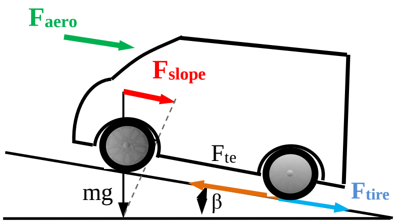

Figure 1. The vehicle resistant forces moving on slope

The vehicle studied in this work consist of four wheels induction motor vehicle, this kind of car use technology of in-wheel motors by means each wheel is integrated on induction motor of lorey somer product [4] , this method permit to reduce motion losses , the four wheel drive is used for urban traffic. The speed reference of each motor is computed using an electronic differential [1,4,6]. The motor are supplied using Fuel cells controller by Buck boost DC-DC converter. The detailed control schema of the EV is shown in Figure 8. The control strategy this propulsion system use DTC-SVM method for torque and current estimation [6,9].

3. Fuel cell model

The first fuel cell presented by Allis Chalmers built consist of an alkaline fuel cell produced 20 horsepower for demonstrated a tractor o, ne year latter, Pratt & Whitney delivered the first of an estimated 200 fuel cell auxiliary power units for space applications. In 1967 latter Union Carbide delivered a fuel cell for scooter army application [4]. By principle hydrogen PEMFC produce energy via chemical reaction [1,2,3]

$$H_2 + \frac{1}{2}O_{t2} \rightarrow H_2O + heat + electrical\ energy \tag{2}$$

Based on this reaction and in order to get an electric current, hydrogen oxidation and oxygen reduction are separated by a membrane, this last one conduct protons from the anode to the cathode side. The semi reactions on both anode and cathode are:

$$H_2 \rightarrow 2H + +2e - anode$$

$$O_2 + 4e - \rightarrow 2O_2 - cathode \tag{3}$$

When protons are transported through the membrane, electrons are carried by an electric circuit and electrical energy is produced. Modelling of this system is getting more and more important as powerful fuel cell stacks and take into account all factors to be integrated into smart power systems. In [2,3,5,6] Jeferson M. Corrêa introduced a model for the PEMFC. The model is based on simulating the relationship between produced voltage and partial pressure of hydrogen, oxygen, and current. The output voltage of a one cell can be defined as the result of the following expression [1,2,3,5,6], figure 2 explain in easy way fuel cell scheme:

$$V_{FC} = E_{Nenst} \quad V_{act} \quad V_{ohm} \quad V_{conc} \tag{4}$$

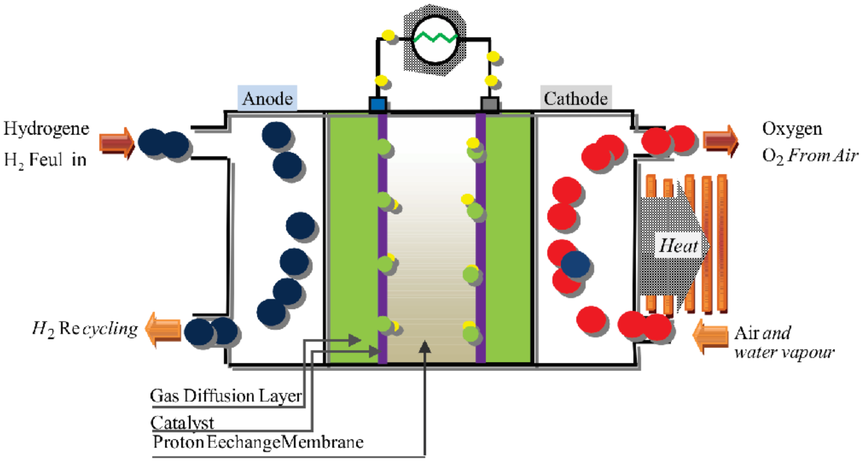

Figure 2. Basic PEM fuel cell shemas.

4. Direct torque control based on space vector modulation (SVM-DTC) of one wheel motor

Classical DTC has some disadvantages; the most important of them is the high ripple torque. In this method two controller are employed to regulate the flux amplitude and torque respectively as it depicted in Figure 3. This make the torque and the magnitude of flux under control, by generating the voltage pulse for inverter command. The SVM principle is based on the switching between two adjacent active vectors and two zero vectors during one period. It uses the space vector concept to compute the duty cycle of the switches[6,7,8,9].In this model no decoupling mechanism is required. Due to the structure of the inverter, the DC bus voltage is fixed, therefore the speed of voltage space vectors are not under control, but we can adjust the speed by means of inserting the zero voltage vectors to control the electromagnetic torque generated by the induction motor. The selection of vectors is also changed. It is not based on the region of the flux linkage, but on the error vector between the expected and the estimated flux linkage [6,7,8,9]

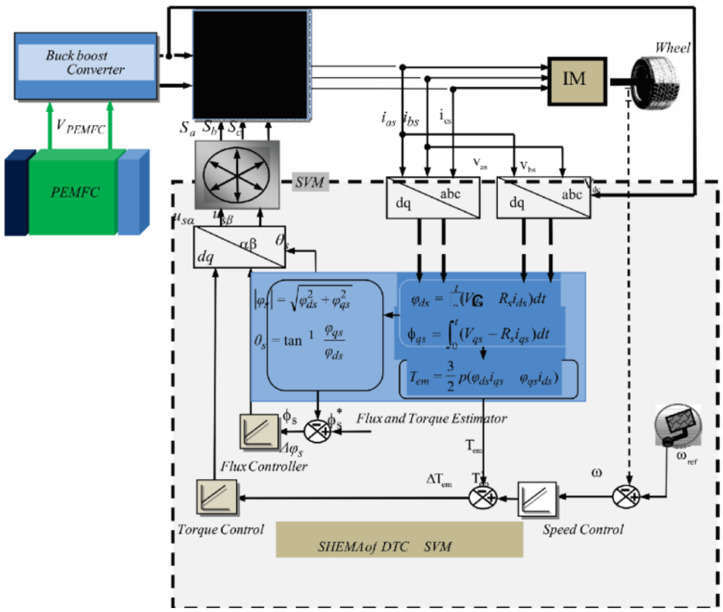

Figure 3. Control schema Bloc Fuel cell DTC-SVM of one wheel-motor

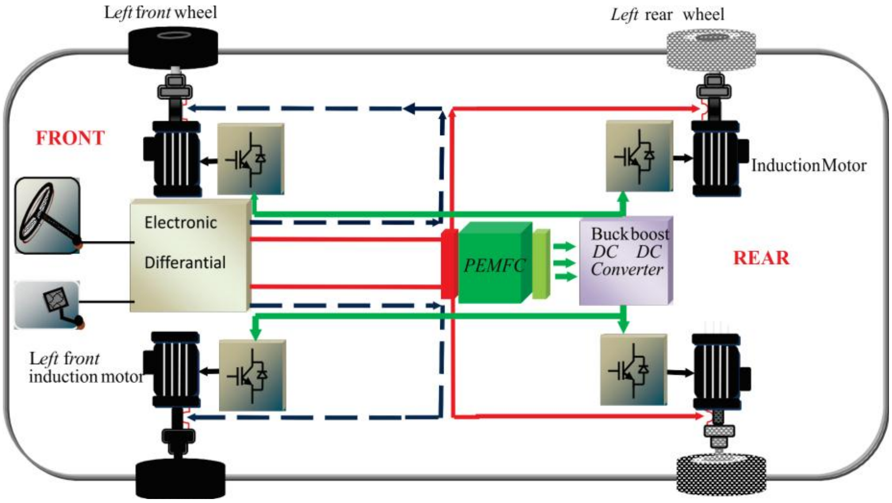

Figure 4. The Fuel cell electric vehicle wheels control shemas.

5. Buck Boost DC-DC Converter for four wheel electric vehicle

DC-DC Buck boosts converters find applications in places where the energy ources is charging, regenerative braking, and backup power are required. The power flow in a bidirectional converter is usually from a low voltage end such as battery or a super capacitor to a high voltage side and is referred to as boost operation [6,5,10]. Figure 5 show the electric vehicle propulsion chain using an DC-DC Buck boosts converters [5,6,10].

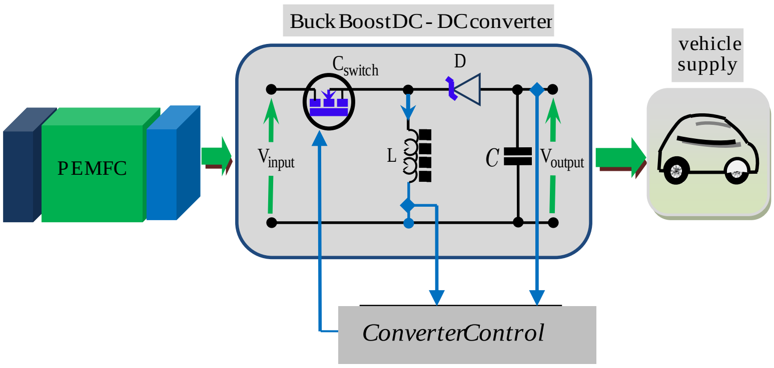

Figure 5. The buck boost DC-DC converter used for electric vehicle supply

6. Simulation Results

In order to analyze the driving wheel system, simulations were carried on MATLAB using the model of figure 4. The following results were given using various slope angle (5%,10% and 15%) and it's divided into two principle phases. The first one: describe the performance test of 4WDEV controlled by DTC-SVM in various seniors. Second phase: shows the slope angle effect on the PEMFC behavior of during all trajectories.

A. Direct torque control scheme with space vector modulation.

The topology studied in this work consists of three phases: the first one is the moving on slope road with an angle of 5 %, in the second the slope road became 10 % one when the speed still constant of 80 Km/h and finally the vehicle is moving up on up the slope road of 15% under the same reference speed, the specified road topology is shown in Figure 6, when the different phase road constraints are described in the table 1.

Table 1.Driving road phases constraints

Phases	Slope road angle [%]	Vehicle Speed[km/h]
Phase 1	5	80
Phase 2	10	80
Phase 3	15	80

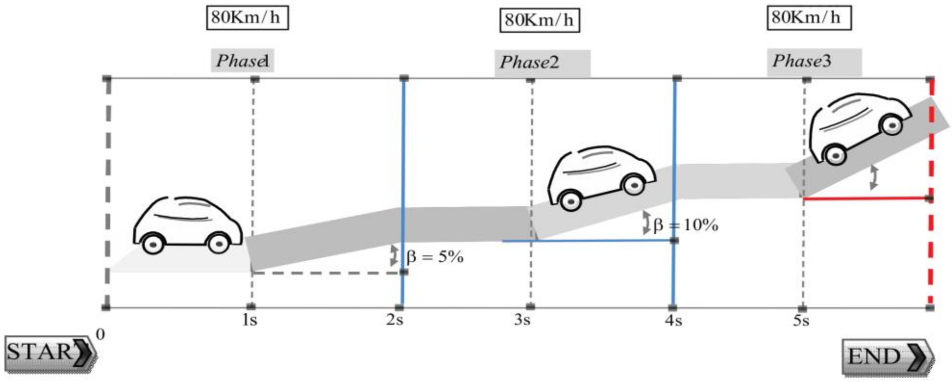

Figure 6. Specified driving road topology.

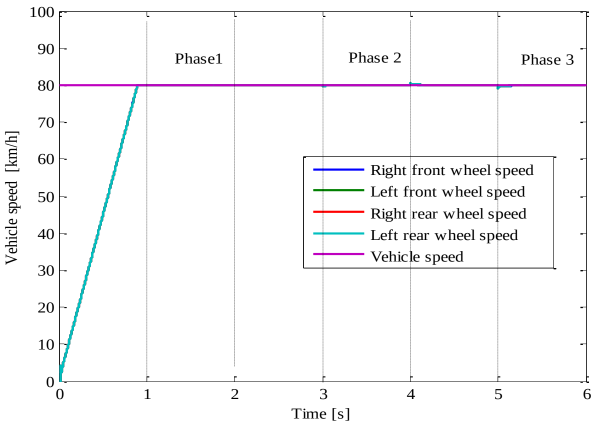

Figure 7. Variation of vehicle speeds in different phases.

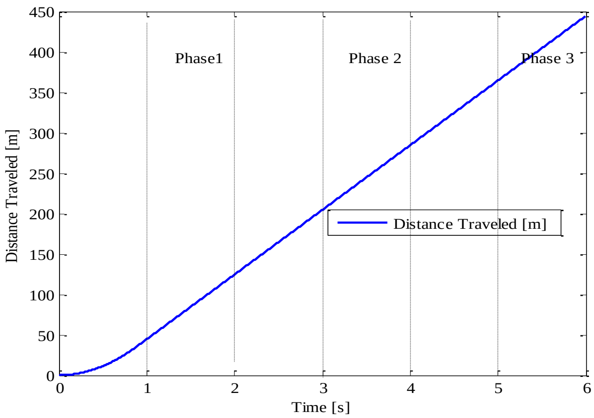

Figure 8. Variation of vehicle speed and traveled distance in different phases.

Figure 7 shows the variation of vehicle linear speed in different stages. Figure 8, present a simple evaluation of distance traveled during time. The total distance traveled by the vehicle over than 420 meters.

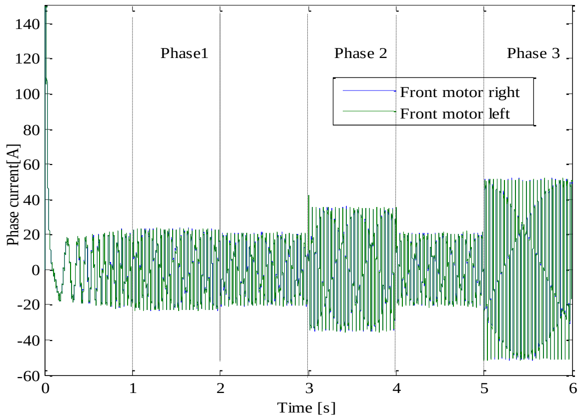

Figure 9. Variation of phase current of the right and left motor in different phases.

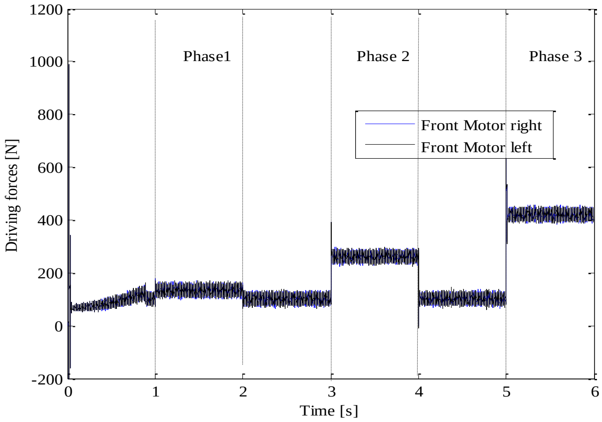

Figure 10. Variation of driving forces of the front motors in different cases.

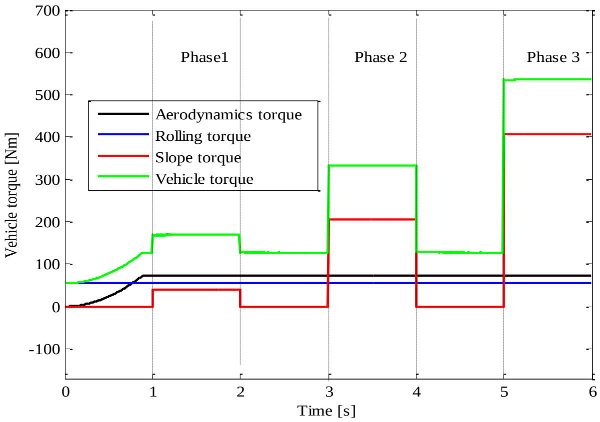

Figure 11. Vehicle resistive torques variation in different phases

Figures 9 and 10 explain the variation of phase current and driving force respectively. In the first step (5%)and to reach 80 Km/h, the 4WDEV demand a current of 22.85 A for each motor which explain the driving force of 163.10 N. In second phase (10%) the current and driving forces demand increase too by means that the vehicle developed efforts became double and developed driving forces as it shown in figs 9 and 10 respectively. The last phases explain the effect of the slope of 15% on four wheels drive developed efforts. The driving wheels forces increase and the current demand undergo triple of the current demand in the first case, the PEMFC use 80 % of his power to satisfy the motorization demand under the slopped road condition which can interpreted physically the augmentation of the globally vehicle resistive torque illustrate in table 2. In the other hand the linear speeds of the four induction motors stay the same and the road drop does not influence the torque control of each wheels. The results are listed in table 2, Figure 11, shows the variation of vehicle torque in different cases.

Table 2. Values of phase current driving force of the right motor in different phases.

Phases	Phase 1	Phase 2	Phase 3
Slope angle %	5	10	15
Current of the right motor [A]	22.85	35.29	51.66
Driving force of the right motor [N]	163.10	286.20	444.70

According to the formulas (1), and table 3, the variation of resistive vehicle torques in different cases as it depicted in table 3. , the vehicle resistive torque was 168.4 N.m in the first case when the power propulsion system resistive one became 331.60 Nm in the second phases (phases 2) , the back and front driving wheels develop more and more efforts to satisfy the traction chain demand which impose an resistive torque equal to 535.00 N.m in the third phase .The result prove that the traction chain under acceleration demand develop the double effort comparing with the first phase case’s by means that the vehicle needs the half of its energy developed in the second phase's compared with the first acceleration phase , table 3. give more detail for variation of globally vehicle resistive torque compared to nominal motor torque in different phases.

Table 3.Variation of vehicle torque in different Phases.

Phases	1	2	3
Slope angle %	5	10	15
the Vehicle resistive torque [N.m]	168.40	331.60	535.00
the globally vehicle resistive torque Percent compared with nominal motor torque of 392.46Nm	42.91 %	84.50 %	136.34 %

B. Power electronics and Fuel cell behavior analysis

The PEMFC is able to supply sufficient power to the 4WDEV in different angle slope (5%,10%,15%), which means that the peak power of the PEMFC must be greater than or at least equal to the peak power of the four electric motors. The PEMFC must store sufficient energy to maintain their consumption of air and fuel to economical level during driving. Figures 12, Figure 13, Figure 14, and Figure 15 describes the changes in the PEMFC storage voltage, current, power efficiency respectively in different slope references.

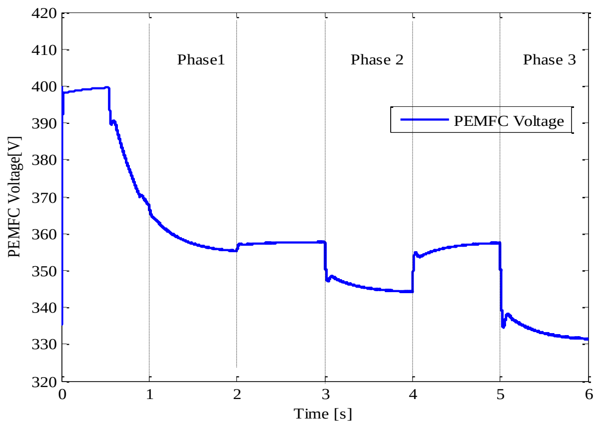

Figure 12. Variation of PEMFC voltage in different phases.

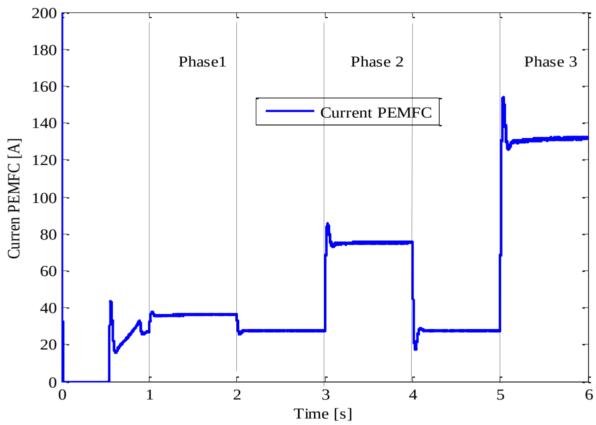

Figure 13. Variation of PEMFC current in different phases.

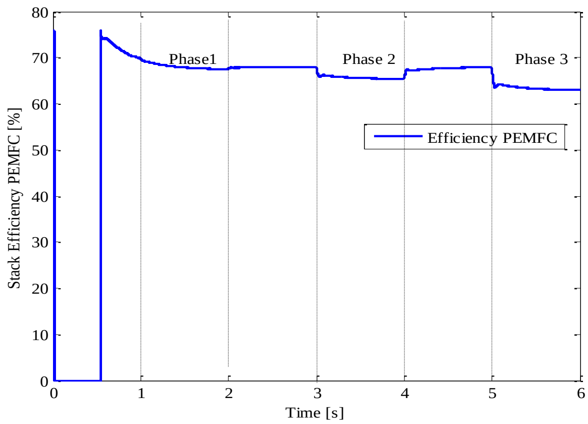

Figure 14. Evaluation of PEMFC efficiency in all trajectory.

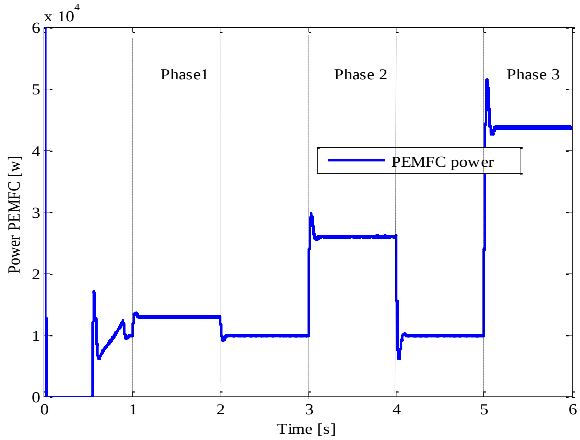

Figure 15. Variation of PEMFC power in different topologies consideration.

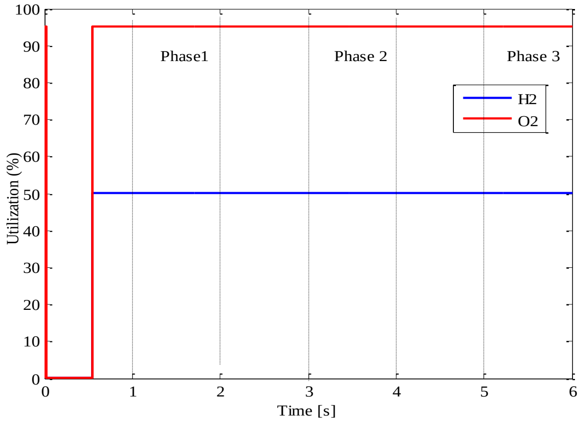

Figure 16. Uses of H_2 and O_2 in different phases.

It is interesting to manage the power distribution in the electrical traction under different slope as it described in Figure 15. The PEMFC provides about 12.89 Kw in the first phase. In the second phase (phase 2:) the demanded power PEMFC increased too which explain by air and fuel consumption. In third phase the PEMFC continue to produce energy to over go the third slope of 15%, it seems that the generating power depend only on road state and the fuel/air state in the PEMFC as it shown in Figure 16 and Figure 17,18. Figure 19 which describe utilization of Air and Fuel in different slope trajectory. The data results are summarized in tables 4 and 5.

Table 4. Values of PEMFC power in different phases

Phase	Phase 1	Phase 2	Phase 3
Slope angle %	5	10	15
PEMFC power [kw]	12.89	26.13	43.77
Percentage of the PEMFC compared with globally PEMFC power [%]	15.99	32.41	54.30

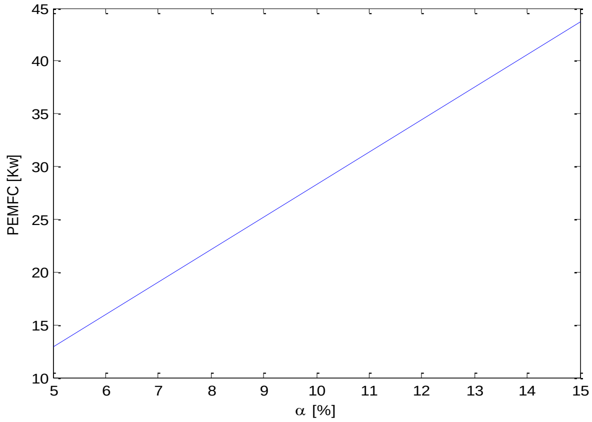

Figure 17. Evaluation in PEMFC power depending on the slope angle.

Table 5. Values of PEMFC stack consumption for air and fuel respectively.

Phase	Phase 1	Phase 2	Phase 3
Slope angle %	5	10	15
Stack consumption of Air [lpm]	108.20	225.30	391.40
Stack consumption of Fuel [lpm]	45.54	93.66	163

It i's appear clearly that when the 4WDEV is moving on slope angle of 5% the PEMFC air consumption is 108.20 lpm and the PEMFC fuel consumption is 45.54 lpm, in the second phases the consumption of air and fuel is almost the double. In the last phase the fuel consumption is 163 lpm and the air consumption is 391.40 lm, is almost the triple compared to the first cases. We can say that when the slope angle increase the hydrogen reserve decrease according to the slope degree. in this situation the autonomy value is affected too.

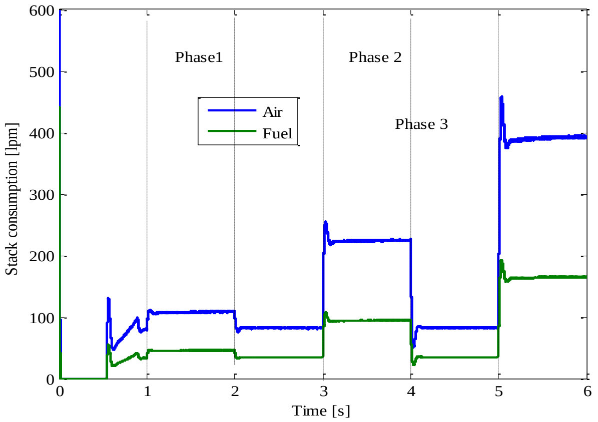

Figure 18. Consumption of the fuel and air for PEMFC in different phases.

It's appear clearly that the temperature change did not affect the performance of the PEMFC, for against the change of pressure caused a sharp decrease in PEMFC efficiency. This allows us to say that the temperature effect is very important on PEMFC performances. It is very interesting to discuss Nerst voltage. The temperature variation decrease the Nerst voltage and when the pressure increase the Nerst voltage decrees against the Nerst voltage remains constant equal to 1.172 V (Without variation).

Table 6. The relationship between the power electronics characteristics and the distance traveled

	Phase1	*Phase2*	*Phase3*
Slope angle [%]	5	10	15
$P_{consumed}PEMFC[Kw]$	12.89	26.13	43.77
Stack efficiency en [%]	61.06	65.53	63.26
Consumption of Air [lpm]	108.20	225.30	391.40
Consumption of Fuel[lpm]	45.54	93.66	163

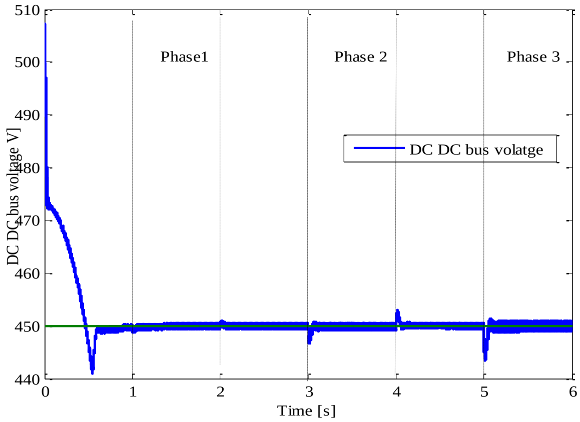

Figure 19. Variation of DC-DC bus voltage in different phases.

This power of DC-DC bus voltage is controlled by the Buck Boost DC-DC converter for three phases. After the test of the buck boost DC-DC converter robustness under several cycles, when the slope pass from 5 to 15 %, the demanded voltage is 450 V. the buck boost converter is not only a robust converter which ensure the power voltage transmission but also a good PEMFC recharger in deceleration state that help to perfect the vehicle autonomous with no voltage ripple, the table 7 give voltage ripple in different cases in electrical traction system when the ripple rate changes are affected with the phase's states.

Table 7. Evaluation of voltage ripple of the Buck-boost .

Phases	1	2	3
Slope angle [%]	5	10	15
The voltage ripple [V]	0.55 %	0.93%	1.03%

7. Conclusion

The vehicle energy management focused in this paper has demonstrated that the 4WDEV behavior controlled by DC-DC converter for utility vehicles can be improved using novel energy policy based on PEMFC and direct torque control strategy. The PEMFC output power depends on the electronic differential reference and the driver decision. According to this study, we conclude that the several slope variations do not affect the performances of the buck boost DC-DC converter output voltage. The control strategy gives good dynamic characteristics of the 4WDEV propulsion system. This study enables the prediction of PEMFC dynamic behavior under slope variation, which is an interesting, result taking into consideration, for the design of new commercialized electric vehicle.

8. References

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Appendix

Parameters of the electric vehicle mechanical load

elements	name	value	elements	name	value
r	tire radius	0.32m	ρ_{air}	Air density	1.2Kg/m^3
m	total mass	1300Kg	C_d	aerodynamic coefficient	0.32
f_r	rolling resistance	0.01	A_f	frontal surface area	2.60 m^2
g	gravity		v	vehicle speed	80Km/h
β	road slope angle				