# Hybrid Control Technique Applied in a FC-SC Electric Vehicle Platform

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***Abstract-*** **A Fuel Cell-Supercapacitor Electric Vehicle (FC-SC-EV) with only one power converter generally uses the FC as an average power unit and the SC as a peak power unit. This array requires operating the power converter linked to the FC in operation regions rather than single operation point; as a result traditional averaged modeling and control methods are no longer valid. In this paper, a hybrid control technique is proposed to control the power converter, which is cable to work in operation regions and it can use any inductor current in the converter as a feedback; meanwhile it achieves an excellent output voltage control under disturbances either from supply voltage, load voltage or other perturbations. Experimental results are given for a *1kW* Nexa® power module and interleaved boost converter taken as a benchmark.**

## I. INTRODUCTION

Different electric vehicle (EV) traction configuration has been proposed in literature, for example battery (B) EV, fuel cell (FC) EV, photovoltaic (PV) EV; and several arrays of B, FC and PV linked with supercapacitors (SC), for a comprehensive comparison refer to [14-20]. In particular, FC-EV configuration has received a lot of attention due to the following characteristics:

1. It produces current just when it is supplied by its fuel.
2. It achieves a high energy efficiency between 40-60%, which its load dependent.
3. The Proton Exchange Membrane (PEM) is the best candidate for vehicular applications due to its high power density, small volume and low temperature.
4. FC produces zero or almost zero pollution and noise.

However its load dependency, incapacity to accept regenerative energy, intolerance to the input ripple current, start-up time, and slow load response; makes unviable the single use of FC in traction applications. Therefore different FC-SC-EV configurations has been proposed, Fig. 1 shows the most common configuration. It is necessary to say that a comprehensive fair comparison between different FC-SC configurations is out of the scope of this paper. In this paper configuration *j)* is taken as a benchmark and its characteristics are listed to follow:

1. It uses only one power converter.
2. It uses SC as a peak power buffer during EV acceleration.
3. The SC accepts the regenerative power for the EV breaking period.
4. There is an inherent decoupling between the peak and averaged EV power. As a result the power converter just deals with the averaged power. This behavior is translated in a small size and weight of the power converter.
5. The power converter needs to operate in a wide input voltage operation region caused by the FC load dependency.
6. It is necessary to implement a Power Management Strategy for the appropriate operation of the overall system.

It can be found in literature several papers that deal with characteristic 1-4 and 6 [1-5]. In particular, this paper focuses with characteristic number five of this traction configuration. It has been reported different power converter that can be used as a step-up/down converter for the selected traction configuration. For example Boost, Buck/Boost, Boost interleaved, Half Bridge, Full Bridge, Full Bridge Zero Voltage Switching (ZVS) and/or Zero Current Switching (ZCS) or Push-Pull [6]. Their main differences are the conversion ratio, power ratio, current ripple, uni/bidirectional capacity, efficiency and isolation, in this work the interleaved boost converter was selected as a benchmark [7]. Previous studies have considered that interleaved boost converter is operated in single operation point and standard linear techniques have been applied to its analysis, which limit the viability to use this configuration in operation regions [8].

This paper in an extension of the hybrid-time controller reported in [9-13], this controller is suitable to the new demands of DC-DC converters such as multiple operation

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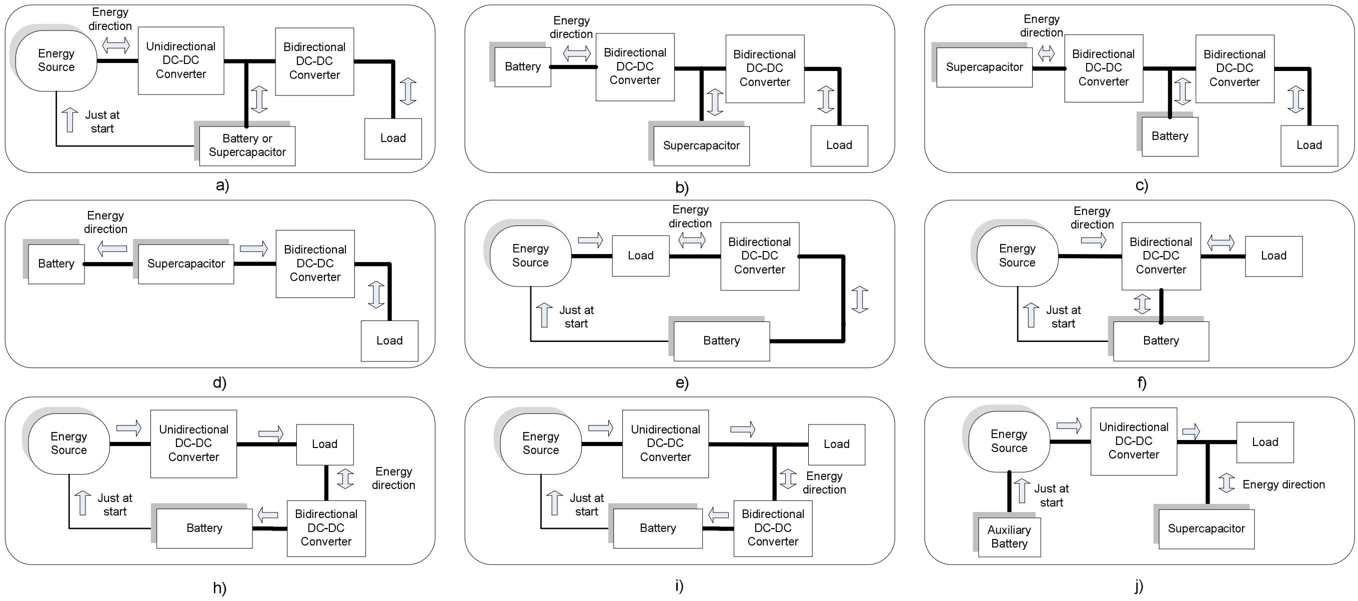



Fig. 1 Different FC-SC-EV configurations have been reported in literature.

points and constant power loads. In this paper the proposed hybrid controller guarantees stability in the selected operation region, meanwhile it achieves an excellent output voltage control under disturbances either from supply voltage, load voltage or other perturbations. The paper is organized as follows. Section II presents preliminaries of the converter, description and implementation considerations of the proposed controller. Section III shows the general response of controller during transient and steady state using numerical simulations, the experimental test bed is reported in Section IV. Conclusion and final comments are presented in the last section.

## II. Description of Converter and Controller Structure

An interleaved boost converter connected to a boost converter and SC is shown in Fig. 2. This arrangement let us to decouple the power needed by the EV in two dynamics: one average (slow dynamic) power supported by the FC and other peak (fast dynamic) maintained by the SC section. Advantages of this configuration are a FC size reduction, increment of power density, and an inherent tolerant-fault capability [8].

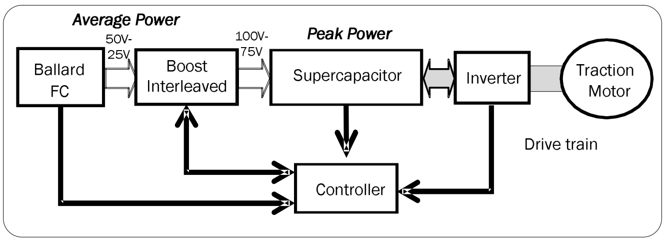



Fig. 2 Proposed fuel cell electric vehicle architecture.

The proposed hybrid controller in this paper it is based on a particular switched control technique and applied to single-cell boost DC-DC converters, introduction and overall description and results are reported. Following this trend, application in single cell DC/DC buck converter is presented in [10], extension of the proposed hybrid controller in interleaved buck and boost converter are given in [11]-[12], respectively. Application of the switched control technique in a three stage cascaded boost converter with single switch applied in FC is reported in [13]. Reference [13] demonstrates that the proposed switched control technique regulates the desired output voltage by using as a current feedback any of the three possible inductor current; and in spite of variations in the input voltage, load, and dynamic reference voltage.

A further application step of the proposed switched technique is reported in this paper. Here it is shown that he proposed controller can be directly applied in FC-EV application with no regrets in the inherent inductor current-to-duty cycle transfer function minimum phase characteristic. Furthermore, the proposed controller is able to regulate the output voltage and limit input current at the same time, which extend the FC useful working life

Inspired in [10], [12], in this paper, a two loop controller is modified to make the current loop robust against voltage input variations that can be originated by hydrogen income flux changes in the fuel cell. The structure of the controller can be observed in Fig.3. Firstly, it is can be noticed that the inner loop is constituted by a switching controller which uses constant switching surfaces whose value is defined by the outer loop. Two symmetrical surfaces are defined to confine inductors currents within a prescribed region. The value of these surfaces depends strongly on two things: Maximum desired rippling and the hydrogen income flux to the FC. Since the variation of this flux strongly affects the FC output voltage (equivalently, the input voltage in the converter), the voltage conversion radio is dramatically affected, leading in most cases to a fail in accomplishing the converter output voltage regulation. A way to adapt this switching controller to converter input changes is to know in advance the changes in the voltage conversion radio. In this case, a pre-operating identification task must be performed based on hydrogen flux changes that must be measured. Such strategy would be very involved, would require of additional flux measurement and still will not be sufficient to face load changes (changes in power vehicle requirements).

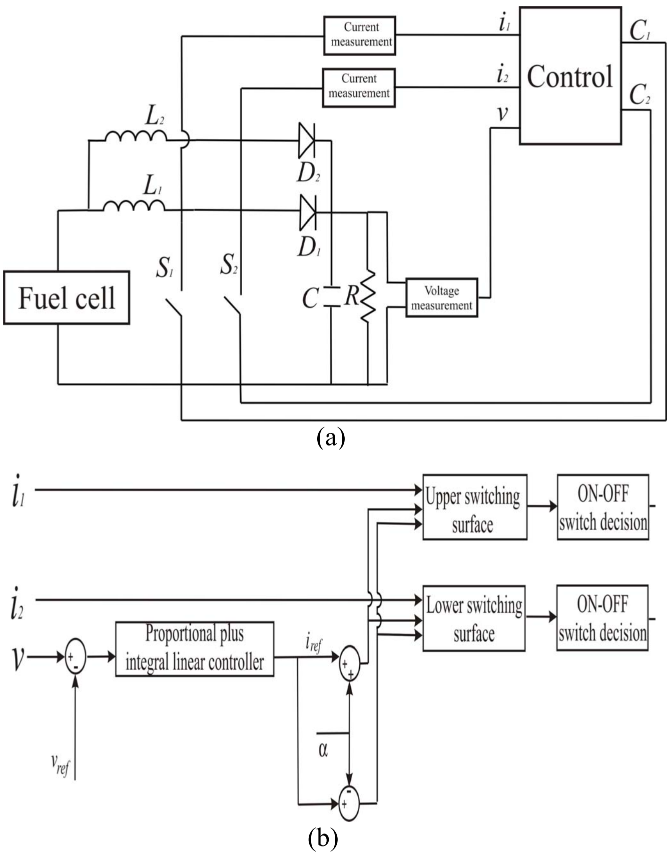



Fig. 3. (a) Conveter -control structure (b) Multiloop Hybrid Controller

In this paper, we propose the use a robust linear controller to define the switching surfaces. Based on the converter output voltage regulation error simple proportional plus integral action is able to face uncertainty in the voltage conversion radio map from multiple sources (e.g. hydrogen flux or load changes). The integral action is tuning to be a slow compensating action with respect to converter dynamics, but with a dynamics comparable with that of fuel cell; leading, in this way, to an efficient voltage tracking. Notice that additional contributions of this work with respect to existing strategies [21] are i) simplicity of the controller (*i.e.* not involved tuning methods or delay computation are required) (ii) the stability of the controller can be ensured using hybrid control tools (see [10]).

In order to introduce this last contribution, we stated as in [10], that if the nominal frequency (*1/RC*) is small compared to the design switching frequency (*fs*), the output voltage remains constant for short times (i.e. $\mathcal{O}$ (*1/fs*)). Hence the inductor current evolves describing a piece-wise linear trajectory with slopes $m_{off,j} = (V_{out,FC}-V_{out,conv})/L_j < 0$; and $m_{on,j} = V_{out,FC}/L_j > 0$, for $j = 1, 2$. Furthermore, the output filter of the converter serves as a time-scale separation between the current dynamics and the voltage dynamics. Hence if the current is confined by the switched controller in a bounded region of measure *β, e.g. B(i', β)* (*i.e.* a ball centered at *i'* and radius *β*), voltage trajectories will be confined in an other bounded region, which size depend on parameters *R, C.*

The main contribution is summarized in the following theorem:

**Theorem 1**. Let $2\alpha>0$ be the maximum desired current ripple, and $i_{ref} \pm\alpha$ be symmetric switching surfaces, if $m_{off}$ for $i> i_{ref}+\alpha$ for and $m_{on}$ for $i> i_{ref}-\alpha$ *with* $i_{ref} = K_1(V_{out,conv} - V_{ref}) + K_2(V_{out,conv} - V_{ref})d\mu$, hence voltage and current trajectories are β-bounded, with β a design parameter and there exists a finite time $T$ such that for all $t > T$, $i_1 \in B(i_{1\_ref}, \alpha)$, $i_2 \in B(i_{2\_ref}, \alpha)$ and $V_{out,conv} \in B(Vref, \beta)$.

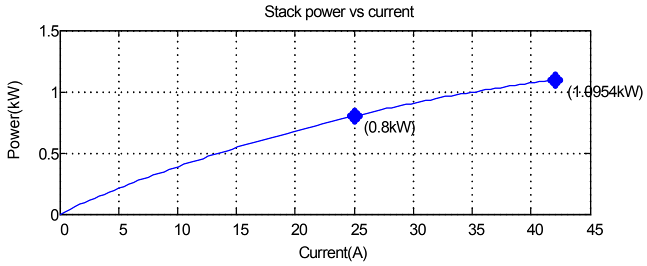
The theorem above states that any current value in a domain $D$, can be leaded to a neighborhood of $[i_{ref,1}, i_{ref,2}, V_{ref}]^T$ in finite time $t > T$. In this way, the sets $B(i_{1\_ref}, \alpha)$, $B(i_{2\_ref}, \alpha)$ and $\in B(Vref, \beta)$ are **globally attractive** and system trajectories will lead to such sets asymptotically. Moreover, the switching rule in Theorem 1 defines a family of switching sequences such that trajectories of converter trajectories are confined for $t > T$, and maximum ripple current converter is guaranteed.

The proof of the theorem can be performed using notions of practical asymptotic stability for switched systems. By showing that every desired voltage can be generated by a linear combination of slopes $m_{off}$ and $m_{on}$. Such fact actually implies that every desired current and therefore voltage, can be generated by finite switching sequence. More over global attractivity of the set $B(Vref, \beta)$ can also be proved along the same idea.

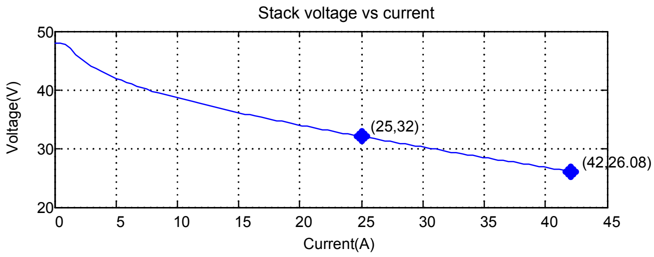
In the following section, illustration of the results stated before are performed using numerical simulations.

## III. NUMERICAL RESULTS

Besides the complexity of the converter (*2n,* where $n = 2$), only one loop was used to control the input and ripple current loops; it was used a proportional ($K_p$) and integral gain ($K_i$) in the current loop (set to *1.4* and *0.6* respectively); and one voltage loop with $K_p = 0.4$ and $K_i = 0.3$ to control the output voltage. *The controller gains were remained constant for the overall set of experiments.* Fig. 3a) shows the output voltage in closed-loop with a dynamic reference $V_{in}$ maintained constant in *50V*, and the Fig. 4b) shows the input current reflected to the FC in the same working condition. It is observed the characteristic current in each cell, which are in contra phase. This response is obtained due to the adaptive digital controller slides on the initial equilibrium surface of




(a)

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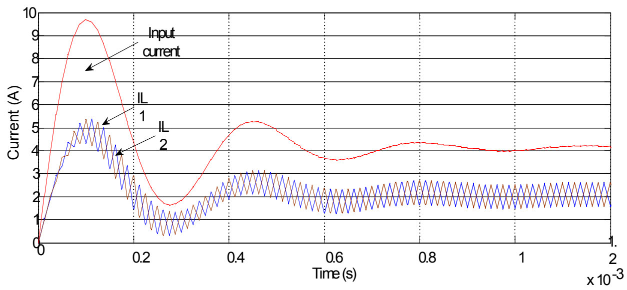
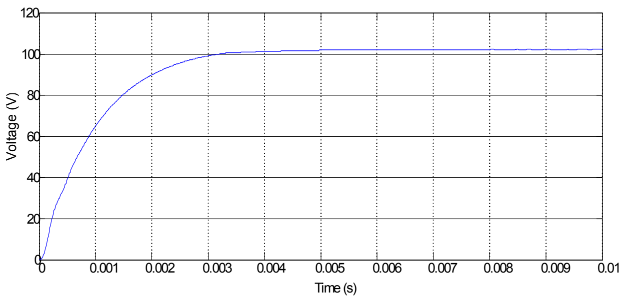



(d)

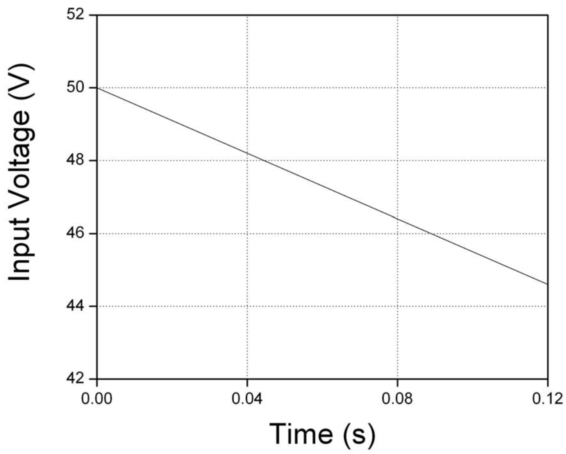
Fig. 4 Proposed fuel cell electric vehicle architecture.

the reference voltage. As a result is produced a maximum variation of 0.2% of the desired voltage.

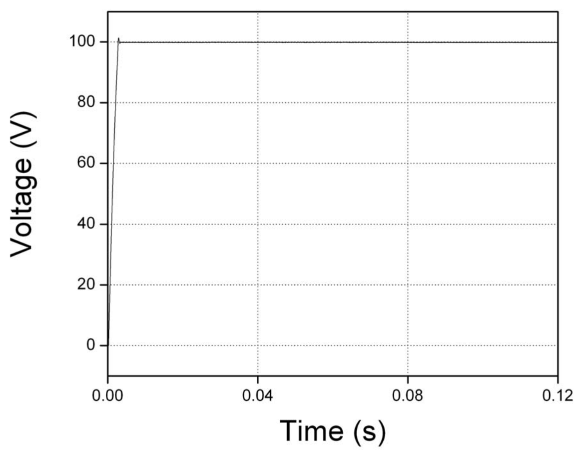
On the other hand, Fig 5 shows the performance of the proposed controller under dramatic hydrogen consumption of FC, leading to a corresponding voltage variation. In this case, the input voltage varies as a ramp changing from 50 to 44 v under a very short period of time (t = 0.12 sec). It can be observed that the controller is able to regulate the output voltage by changing the corresponding current reference in face of power consumption. Moreover, observe that suitable current distribution is achieved in every converter branch.

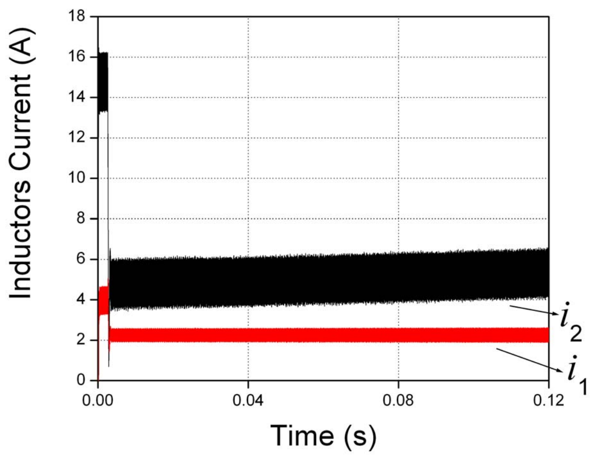
## IV. Conclusions

This paper shows the viability of the hybrid controller to control an interleaved boost converter into a FC-EV application. A simple controller scheme has been proposed that is able to shown stability in operation regions rather that operations points. This characteristic is extremely important in application such as FC- EV, where some devices such as ICE traction motor are turned off and on in terms of the power management strategy. As a consequence of this working mode, the reflected converter´s load changes are seen as impulsive loads, which can become on unstable behavior in traditional controllers based on averaging techniques. The controller has the feature of being robust against system uncertainty and easy to implement. Its capabilities have been illustrated via numerical simulations.




(a)






(c)

Fig. 5 Control performance under dramatic changes on the FC output voltage.

## REFERENCES


[1] P. Thounthong,; V. Chunkag, P. Sethakul, B. Davat, M. Hinaje , "Comparative Study of Fuel-Cell Vehicle Hybridization with Battery or Supercapacitor Storage Device," *IEEE Transactions on Vehicular Technology,* vol.58, no.8, pp.3892-3904, Oct. 2009.

[2] J. Bauman, M. Kazerani, "A Comparative Study of Fuel-Cell–Battery, Fuel-Cell–Ultracapacitor, and Fuel-Cell–Battery–Ultracapacitor Vehicles," *IEEE Transactions on Vehicular Technology,* vol.57, no.2, pp.760-769, March 2008.

[3] Bo Chen, Yimin Gao M. Ehsani, J.M. Miller, "Design and control of a ultracapacitor boosted hybrid fuel cell vehicle," in *Proc. IEEE Vehicle Power and Propulsion Conference, 2009. VPPC '09*. pp. 696-703, 7-10 Sept. 2009.

[4] E. Schaltz, A. Khaligh, P.O. Rasmussen,, "Influence of Battery/Ultracapacitor Energy-Storage Sizing on Battery Lifetime in a Fuel Cell Hybrid Electric Vehicle," *IEEE Transactions on Vehicular Technology,* vol.58, no.8, pp.3882-3891, Oct. 2009.

[5] S.M. Lukic, Jian Cao, R.C. Bansal, F. Rodriguez, A. Emadi, "Energy Storage Systems for Automotive Applications," *IEEE Transactions on Industrial Electronics,* vol.55, no.6, pp.2258-2267, June 2008.

[6] W.-S Liu, J.-F. Chen, T.-J. Liang, R.-L. Lin, C.-H. Liu,, "Analysis, Design and Control of Bi-Directional Cascaded Configuration for a Fuel Cell Hybrid Power System," *IEEE Transactions on Power Electronics,* in press.

[7] F. Bryan, D.R. Nuttall, A.J. Forsyth, Yonghua Cheng, J. Van Mierlo, P. Lataire,; , "A Low-Cost Battery-Less Power Train for Small Fuel Cell Vehicle Applications," in *Proc. IEEE Vehicle Power and Propulsion Conference, 2007. VPPC 2007,* pp.43-49, 9-12 Sept. 2007.

[8] P. Thounthong, P. Sethakul, S. Rael, B. Davat, "Modeling and control of a fuel cell current control loop of a 4-phase interleaved step-up converter for DC distributed system," in *Proc. IEEE Power Electronics Specialists Conference, 2008. PESC 2008,* pp.230-236, 15-19 June 2008.

[9] León Austria-González, F. J. Perez-Pinal, Ilse Cervantes, "Hybrid Multi-objective Control of DC-DC converters," in *Proc. IEEE Vehicle Power and Propulsion Conference, 2008. VPPC '09*, Harbin, China, Sept. 2008.

[10] I. Cervantes, F.J. Perez-Pinal, A. Mendoza-Torres,, "High performance hybrid control for buck converters," in *Proc. 13th European Conference on Power Electronics and Applications, 2009. EPE '09,* pp.1-7, 8-10 Sept. 2009.

[11] F.J. Perez-Pinal, I. Cervantes, J. Leyva-Ramos, L.H. Diaz-Saldierna, , "Control of single active switch cascade boost converter for fuel cell applications," in *Proc. 13th European Conference on Power Electronics and Applications, 2009. EPE '09,* pp.1-6, 8-10 Sept. 2009

[12] I. Cervantes, A. Mendoza-Torres, A.R. Garcia-Cuevas, F.J. Perez-Pinal , "Switched control of interleaved converters," in *Proc. IEEE Vehicle Power and Propulsion Conference, 2009. VPPC '09*, pp.1156-1161, 7-10 Sept. 2009.

[13] F.J. Perez-Pinal, I. Cervantes, "Multi-objective control for cascade boost converter with single active switch," in *Proc. IEEE International Electric Machines and Drives Conference, 2009. IEMDC '09,* pp.1858-1862, 3-6 May 2009.

[14] *"Modern Electric Vehicle Technology,"* C.C. Chan and K.T. Chu, Oxford Science Publications, 2001.

[15] "*Propulsion systems for hybrid vehicles,*" John M. Miller, IEE, 2004.

[16] *"Handbook of Automotive Power Electronics and Motor Drives,"* Ali Emadi, CRC Press, 2005.

[17] Ali Emadi, Tutorial Notes: Modern Automotive Systems: Power Electronics and Motor Drive Opportunities and Challenges, in *Proc. IEEE, International Electric Machines and Drives Conference, IEMDC ´05, Laredo Texas, USA,* 2005.

[18] C. C. Chan, A. Bouscayrol, K. Chen, "Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling," *IEEE Transactions on Vehicular Technology,* vol.59, no.2, pp. 589-598, Feb. 2010.

[19] *"Handbook of Fuel Cells- Fundamentals, Technology and Applications"*, Edited by Wolf Vielstich, Hubert A. Gasteiger, Arnold Lamm. Volume 4: Fuel Cell Technology and Applications, John Wiley and Sons, Ltd, 2003.

[20] A. Emadi, Young Joo Lee, K. Rajashekara, "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles," *IEEE Transactions on Industrial Electronics,* vol.55, no.6, pp. 2237-2245, June 2008.

[21] K.I. Hwu, Y.T. Yau. "Perfomance enhacement of boost converter based on PID controller plus linear-to nonlinear Translator" IEEE Trans. Power Electronics, vol 25, no. 5, May 2010.