ISSN 1827-6660
Vol. 5 N. 1
January – February 2010

International Review of Electrical Engineering (IREE)

PART
A

Contents:

(continued on outside back cover)

PWP
Praise Worthy Prize

International Review of Electrical Engineering (IREE)

Editor-in-Chief:

Santolo Meo
Department of Electrical Engineering
FEDERICO II University
21 Claudio - I80125 Naples, Italy
santolo@unina.it

Editorial Board:

Jorge Luis Aguero	(Argentina)
Drago Ban	(Croatia)
M. El Hachemi Benbouzid	(France)
Frede Blaabjerg	(Denmark)
Bimal K. Bose	(Usa)
Isaak Braslavsky	(Russia)
Piet M.T. Broersen	(The Netherlands)
Hulusi Bülent Ertan	(Turkey)
Carlo Cecati	(Italy)
Dominique Dallet	(France)
Massimo D'Apuzzo	(Italy)
Serge Demidenko	(Malaysia)
Ahmed M. El-Serafi	(Canada)
Ali Emadi	(Usa)
Enric Fossas	(Spain)
Giuseppe Gentile	(Italy)
Jacek F. Gieras	(Usa)
Ferdinand Gubina	(Slovenia)
Thierry Marie Guerra	(France)
Peter Hanggi	(Germany)
Narain Hingorani	(Usa)
David Howe	(U.K.)
Maria Imecs	(Romania)
Vittorio Isastia Cimino	(Italy)
Theodore Laopoulos	(Greece)
Gerard Ledwich	(Australia)
Emil Levi	(U.K.)
Leo Lorenz	(Germany)
Junya Matsuki	(Japan)
Santolo Meo	(Italy)
Linus Michaeli	(Slovak Republik)
Mart Min	(Estonia)
James E. Morris	(Usa)
Istvan Nagy	(Hungary)
Shukla Padma Kant	(Germany)
Po Gyu Park	(Korea)
Michel Poloujadoff	(France)
Jan-Hann C. Pretorius	(South Africa)
Francesco Profumo	(Italy)
Zhaoming Qian	(China)
Kaushik Rajashekara	(Usa)
Muhammad H. Rashid	(Usa)
Alfred Rufer	(Switzerland)
Athanasios N. Safacas	(Greece)
Yong-Hua Song	(U.K.)
Julio Usaola	(Spain)
Cui Xiang	(China)
Inmaculada Zamora	(Spain)
Ahmed Faheem Zobaa	(Egypt)

The *International Review of Electrical Engineering (IREE)* is a publication of the **Praise Worthy Prize S.r.l.**.
The Review is published bimonthly, appearing on the last day of February, April, June, August, October, December.

Published and Printed in Italy by **Praise Worthy Prize S.r.l.**, Naples, February 28, 2010.
Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.

This journal and the individual contributions contained in it are protected under copyright by **Praise Worthy Prize S.r.l.** and the following terms and conditions apply to their use:
Single photocopies of single articles may be made for personal use as allowed by national copyright laws.
Permission of the Publisher and payment of a fee is required for all other photocopying, including multiple or systematic copying, copying for advertising or promotional purposes, resale and all forms of document delivery. Permission may be sought directly from **Praise Worthy Prize S.r.l.** at the e-mail address:
administration@praiseworthyprize.com

Permission of the Publisher is required to store or use electronically any material contained in this journal, including any article or part of an article. Except as outlined above, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without prior written permission of the Publisher. E-mail address permission request:
administration@praiseworthyprize.com

Responsibility for the contents rests upon the authors and not upon the **Praise Worthy Prize S.r.l.**.
Statement and opinions expressed in the articles and communications are those of the individual contributors and not the statements and opinions of **Praise Worthy Prize S.r.l.**. **Praise Worthy Prize S.r.l.** assumes no responsibility or liability for any damage or injury to persons or property arising out of the use of any materials, instructions, methods or ideas contained herein.
Praise Worthy Prize S.r.l. expressly disclaims any implied warranties of merchantability or fitness for a particular purpose. If expert assistance is required, the service of a competent professional person should be sought.

International Review of Electrical Engineering (I.R.E.E.), Vol. 5, N. 1
January-February 2010

A Novel Control Strategy of Bidirectional DC-DC Converter for Interfacing Ultracapacitor to Fuel Cell Electric Vehicles System Based on Dynamic Evolution Control

A. S. Samosir, A. H. M. Yatim

Abstract – *Fuel cell electric vehicles gives far more promising performance. They have higher efficiency and lower emissions compared with the internal combustion engine vehicles. The fuel cell has a high energy storage capability, thus enhancing the range of operation for automobile and is a cleaner source of energy. However, the fuel cell has a slow dynamic response, so an auxiliary power source is needed during start up and transient conditions. Ultracapacitor usually used as secondary power source for improving the performance and efficiency of the overall system. Several methods have been devised to connect ultracapacitor to the fuel cell system. If the ultracapacitor is connected in parallel directly with the dc bus, its charge and discharge current cannot be controlled. Once the load changes significantly, the rush current would destroy the ultracapacitor. Therefore, a bidirectional converter needs to be inserted between the dc bus and the ultracapacitor to control the charge and discharge current. This paper proposes a novel control strategy of bidirectional dc-dc converter for interfacing ultracapacitor energy storage to fuel cell electric vehicles system. The controller of bidirectional dc-dc converter system was designed and implemented based on dynamic evolution control. Performance of the proposed dynamic evolution control is tested through simulation and experiment.* ***Copyright © 2010 Praise Worthy Prize S.r.l. – All rights reserved.***

Keywords: *Fuel Cell, Ultracapacitor, Electric Vehicle, Dynamic Evolution Control, Bidirectional Dc-Dc Converter*

Nomenclature

Y	Error function
m	Gain
k	Positive coefficient
α	Duty cycle
V_{err}	Error voltage
V_{ref}	Reference voltage
V_O	Output voltage
V_{UC}	Ultracapacitor voltage
L	Inductor
i_L	Inductor current
t	Time

I. Introduction

An electric vehicle powered by fuel cell gives far more promising performance. The Fuel Cell Electric Vehicles (FCEV) has higher efficiency and lower emissions compared with the internal combustion engine vehicles. Fuel cell has higher energy storage capability thus enhancing the range of operation for automobile and is a cleaner source of energy. Fuel cells also have the added advantage of using hydrogen as fuel which will reduce world's dependence on non-renewable hydrocarbon sources.

Automobiles have changing load requirements during different modes of travel. Further there are braking and acceleration requirements for control of automobile. These demands require that the source of energy should be able to respond to fast changing loads.

Fuel cells have no capability to respond to fast changing loads. Fuel cell has a slow dynamic response. Therefore, auxiliary energy storage is needed for responding the increased load instantly during start up and transient conditions. Among several energy storage devices, ultracapacitor is a good option due to several advantages like high power density, long lifecycle and very good charge/discharge efficiency. Ultracapacitor also have more cycles of charging and discharging during its lifetime. They can also provide large transient power instantly thus capable of providing energy for increased load for automobile requirements like acceleration, or sudden slope. Hence ultracapacitor is a suitable choice for secondary source of energy in electric vehicles applications.

Several methods have been devised to connect energy storage device to the fuel cell. If the ultracapacitor is connected in parallel directly with the dc bus, its charge and discharge current cannot be controlled. Once the load

Manuscript received and revised January 2010, accepted February 2010

changes significantly, the rush current would destroy the ultracapacitor. Therefore, an interface converter needs to be inserted between the dc bus and the ultracapacitor to control the charge and discharge current.

A converter system for connecting ultracapacitor as secondary energy storage to fuel cell electric vehicle systems has been presented in [7]. The ultracapacitor is connected to dc bus of the fuel cell electric vehicle system through a bidirectional DC-DC converter. Controller for interface converter has been designed based on dynamic evolution control. This controller controls ultracapacitor current such that the voltage droop at dc bus is minimized even after a sudden change in load current. In this paper, performance of the proposed dynamic evolution control is verified through simulation and experiment.

II. Power Management System

Refer to [7], the fuel cell, which is considered in this research, has a 42V nominal voltage. The bus voltage should be 100V and remain constant. So the fuel cell voltage should be stepped up through a boost converter. The ultracapacitor is connected to the bus through a bidirectional converter. During the start up and transient conditions, the ultracapacitor will supply the load. When the power generated by the fuel cell is more than the power needed for the load, and also during the regenerative braking, the converters charge the ultracapacitor. The ultracapacitor has 165 F capacities, and it can be charged up to 48V. The schematic of the whole system is shown in Fig. 1.

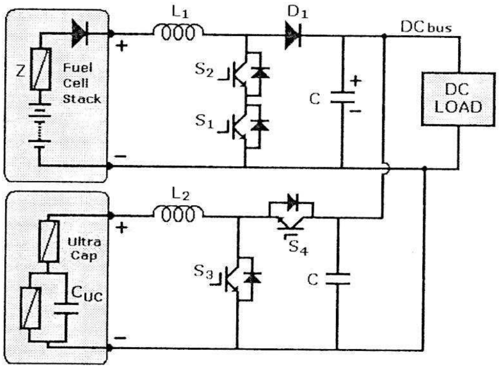

Fig. 1. Interface Converter Topology

III. Dynamic Evolution Control Design

The dynamic evolution control theory has been described in reference [6], [7] and [8].

In dynamic evolution control, the dynamic characteristic of system is forced to make evolution by following an evolution path. With the selected evolution path is an exponential function as shown in Fig. 2, the value of the dynamic characteristic of system will decrease exponentially to zero by equation:

$$Y = Yo \cdot e^{-mt} \qquad (1)$$

where, Y is the dynamic characteristic of system, Yo is the initial value of Y, and m is a design parameter specifying the rate of evolution.

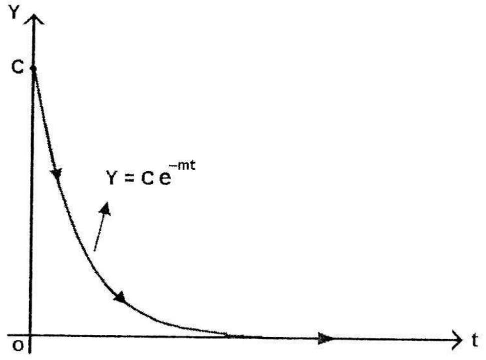

Fig. 2. Dynamic Evolution path

The dynamic evolution function of this controller can be written as:

$$\frac{dY}{dt} + mY = 0, \qquad m > 0 \qquad (2)$$

Synthesis process is done to obtain the control law that guarantees the dynamic characteristic of system decrease to zero by following the evolution path.

In dc-dc power converter, this control law corresponds to the duty cycle equation of the converter. This duty cycle equation $\alpha(V_O,V_{UC},i_L)$, represents α as a function of the state v_O, V_g and i_L. The duty cycle equation $\alpha(V_O,V_{UC},i_L)$ is obtained by analyzed and substituted the dynamic equation of the converter system into the dynamic evolution function (2).

The duty cycle equation is used to calculate the desired value of signal level control V_{ctrl}. The pwm signal is generated by comparing a signal level control V_{ctrl} with a repetitive waveform as shown in Fig. 3. The frequency of the repetitive waveform with a constant peak, which is a sawtooth Vst, establishes the switching frequency. This frequency is kept constant. Therefore, the dynamic evolution control is operated at constant switching frequency.

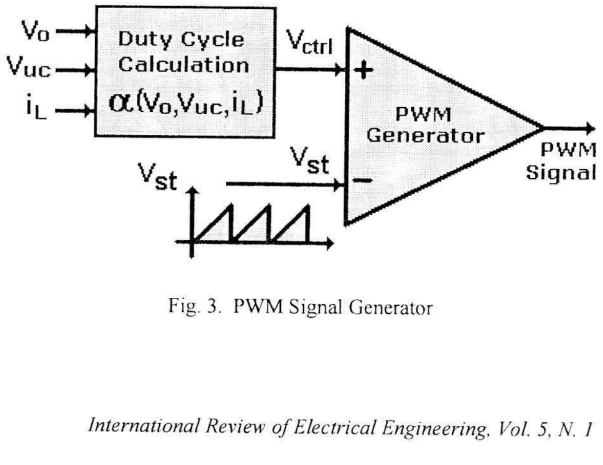

Fig. 3. PWM Signal Generator

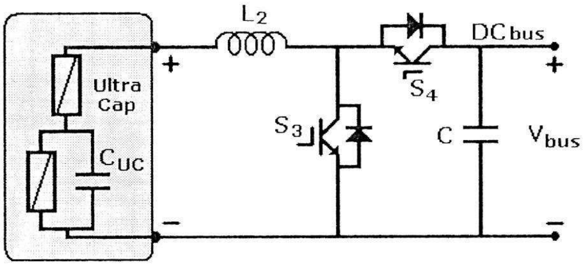

Fig. 4. Bidirectional DC-DC Converter

IV. Synthesis of the Bidirectional DC-DC Converter Controller

A schematic diagram of the bidirectional dc-dc converter, which is interfacing ultracapacitor to the bus, is shown as Fig. 4. The converter can be operated in two modes of operation, namely boost and buck operation. During the boost operation, the converter operates as a boost converter and the power flows from ultracapacitor to dc bus. During buck operation, the converter operates as a buck converter and the power flows from dc bus to the ultracapacitor.

Due to this converter power switches are operated in complementary way, it is sufficient to find out the control law in boost mode of operation only. In fact, the duty cycle of the upper switch, which is responsible for the buck operation, is always $1-\alpha$.

Based on the state-space average model, the voltage and current dynamics of the boost mode of operation are given by:

$$V_{UC} = L\frac{di_L}{dt} + v_O\left[1-\alpha\right] \tag{3}$$

$$C\frac{dv_O}{dt} = i_L\left[1-\alpha\right] - \frac{v_O}{R} \tag{4}$$

where L is the inductance, C the capacitance, R the load resistance, V_{UC} the ultracapacitor voltage, i_L the inductor current, v_O the output voltage, and α the duty cycle, respectively. Rearranging (3), the output voltage of converter can be written as:

$$v_O = V_{UC} + v_O \cdot \alpha - L\frac{di_L}{dt} \tag{5}$$

The dynamic evolution synthesis of the controller begins by defining the state error function (Y). In power electronic application, Y can be selected as a function of error voltage or error current. Refer to [5], with the selected Y is a linear function of error voltage as (6):

$$Y = k \cdot v_{err} \tag{6}$$

The obtained duty cycle α is given by:

$$\alpha = \frac{k\frac{dv_{err}}{dt} + (mk-1)v_{err} + L\frac{di_L}{dt} + V_{ref} - V_{UC}}{v_O} \tag{7}$$

The expression for duty cycle α is the control action for the converter controller.

Duty cycle eq. (7) forces the state error function Y to make evolution by following eq. (1) and decrease to zero with a decrease rate m. Hence the voltage output of converter converges to the converters steady state:

$$v_O = V_{ref} \tag{8}$$

Rearranging the duty cycle equation (7), the duty cycle α can be written as:

$$\alpha = \frac{V_{ref} - V_{UC}}{v_O} + \frac{(mk-1)}{v_O}v_{err} + \frac{k}{v_O}\frac{dv_{err}}{dt} + \frac{L}{v_O}\frac{di_L}{dt} \tag{9}$$

It is interesting to note that the control law in (9) consists of four distinct parts. The first part is the feedforward term $\left(V_{ref} - V_{UC}\right)/v_O$ which is calculated based on the duty cycle at the previous sampling instant. This term compensates for variations in the input voltages.

The second and third terms are like the proportional and derivative terms of the perturbations in the output voltage respectively. But the important things that make this controller action is better than the conventional one are the gain value of proportional and derivative terms are not constant. These gains are varying with the output voltage value. The last term consists of the derivative terms of the inductor current. The gain of this term is also varying with the output voltage value.

From (9), we can see that the input voltage, output voltage and inductor current are involved in control output. The advantage is the dynamic evolution control can compensate all of variation in the input and output voltages also the change of inductor current. It contributes to the better dynamic performance of the controlled system.

V. Simulation Result

A comprehensive simulation analysis was conducted to verify the controller performance. The whole system was simulated in MATLAB SIMULINK.

The performance of dynamic evolution control under starting condition of fuel cell and regenerative braking are tested. The control goal is to regulate dc bus voltage, Vo = 100V.

The reference of the dc bus voltage is fixed 100V during the operation. Fig. 5 shows the demanded power for a period of time.

The bus voltage and fuel cell voltage is represented in Fig. 6, and the simulation result of i_{UC}, i_{FC}, and i_o are shown in Fig. 7. Demanded power during T1 and T2 is 500W. During T3 the vehicle is braking, and during T4 demanded power is 500 W.

Fig. 7 shows that during the first time span, T1, the fuel cell power is less than the required power, therefore the ultracapacitor will supply the load. In the second time span, T2, fuel cell power has reached the required level, so it will supply the load. Fuel cell starts to supply current.

The current of fuel cell increase to nominal current, along with the ultracapacitor current is decrease. During the third time span, T3, the vehicle is braking. The ultracapacitor will charge during the regenerative braking. In the fourth time span, T4, fuel cell supply power to the load and ultra capacitor backup the difference power between the supplied power from fuel cell and the load demand power.

Fig. 6 shows that in all time spans the dc bus voltage does not droop. The ultracapacitor accomplish to stabilizing the dc bus during the low power of fuel cell and during the transient time. The power generated by fuel cell and ultracapacitor is shown in Fig. 8.

The results show that the ultracapacitor and converter improve the dynamic response of fuel cell system, hence enabling fuel cell powered automobile to accelerate rapidly and also respond to sudden changes in load conditions.

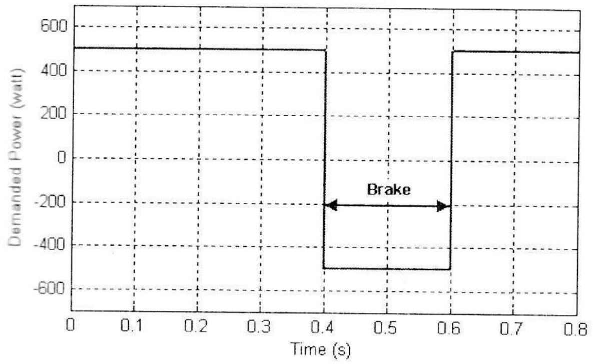

Fig. 5. The demanded power

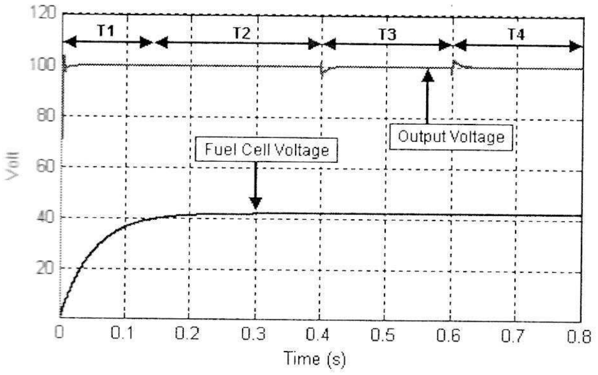

Fig. 6. Fuel cell and dc bus voltage

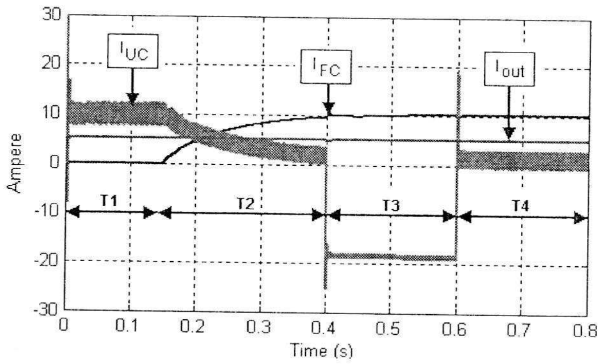

Fig. 7. Simulation result of I_{UC}, I_{FC} and Io

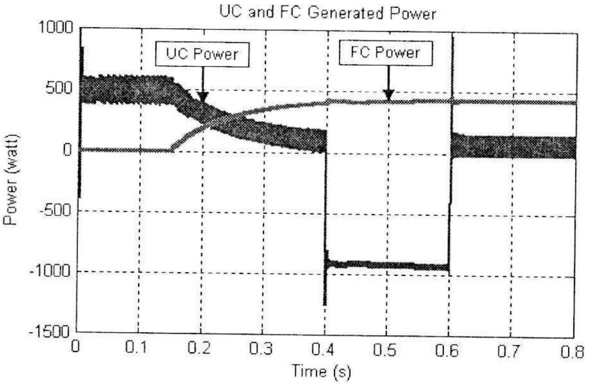

Fig. 8. Power generated by ultracapacitor and fuel cell

VI. Experiment Result

In order to verify the effectiveness of controller, a prototype of system is prepared for experimentation. In this experiment the fuel cell is controlled to feed 3.5A constant current to dc bus. The load demand was switched between 3A and 4A by changing the loading resistor. In this experiment, the objective of controller is to regulate the dc bus voltage at 20V level.

For flexible and rapid prototyping design approach, a TMS320F2812 eZdsp board is used. The TMS320F2812 eZdsp board is employed to implement the dynamic evolution control and the PWM signal generator. Fig. 9 shows the complete hardware set-up for converter system implementation.

Fig. 10 shows simulation result when the step load change was applied to the system. At time 40 ms, a step load change occurs, the load current change from 3A to 4A. as a result of this change, it is shown that the ultracapacitor current change from to 0.8A to –1.2A. It's mean that the condition of ultracapacitor was changed from charging to discharging condition.

Fig. 11 shows experiment result when the step load change was applied to the system. When a step load change occurs, the load current was change from 3A to 4A. As a result, it is shown that the ultracapacitor current change from to 0.8A to –1.2A. It's clear that the controller has been change the condition of ultracapacitor from charging to discharging condition. These results shown that the controller was accomplished in controlling the bidirectional dc-dc converter to charging and discharging the ultracapacitor, in order to regulate the voltage of dc bus.

VII. Conclusion

A new control method for bidirectional dc-dc converter, that interfacing ultracapacitor energy storage to a fuel cell system is presented in this paper. The paper shows that using a bidirectional converter as an interface between fuel cell and ultracapacitor gives better control over fuel cell voltage during transients. The controller allows the ultracapacitor to respond to fast changing loads and then get charged back to its nominal voltage when the fuel cell power is bigger than the demanded load or when vehicle is braking. The fast transient response during a step load transient is confirmed by the experiment.

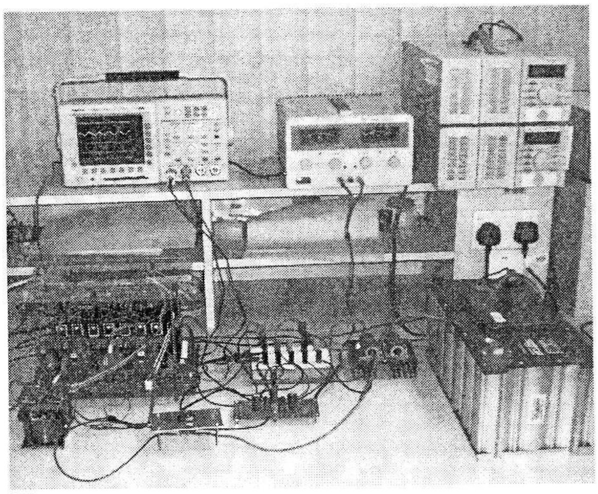

Fig. 9. Complete hardware prototype for implementation

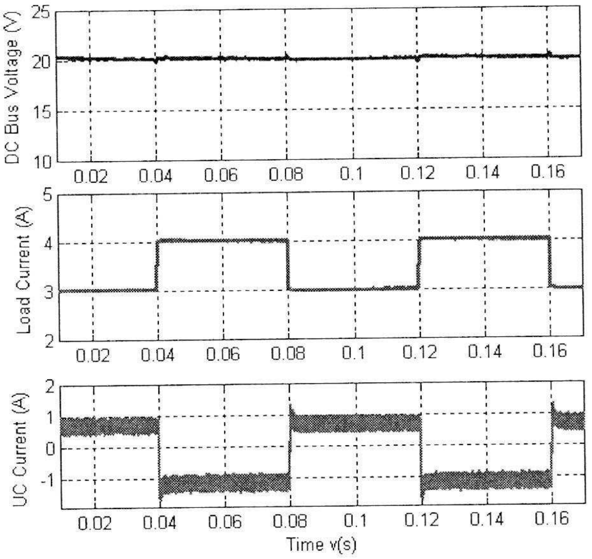

Fig. 10. Simulation result, the load current changes from 3A to 4A

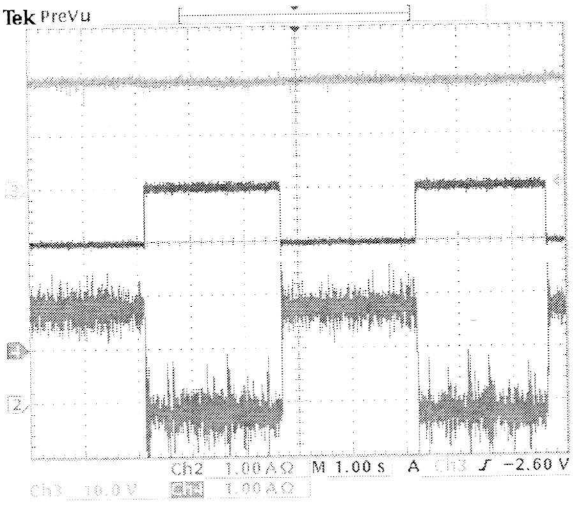

Fig. 11. Experiment result when the load current changes from 3A to 4A (ch.2&4:1A/div, ch.3:10V/div, 1s/div)

Acknowledgment

The authors would like to thank the Ministry of Science, Technology and Innovation (MOSTI) of the Malaysian government for providing the funding for this research.

References

[1] G. Gentile, S. Meo, F. Esposito, Comparison among Different Topologies of DC-DC Converter for Fuel-Cell-Based Inverter System, *11th International Conference EPE-PEMC'2004*, 2-4 September 2004, Riga, Latvia.

[2] S. Meo, A. Perfetto, L. Piegari, F. Esposito, A ZVS Current Fed DC/DC Converter oriented for applications Fuel-Cell-Based, 30th *Annual Conference of the IEEE Industrial Electronics Society (IECON)*, November 2-6, 2004, Busan, Korea.

[3] D. Z. Bo YuWen, X. Jiang, Performance optimization control of the fuel cells electric vehicle driving system, *PowerCon 2002, International Power System Technology Conference*, pp. 149-152, 2002.

[4] A. Drolia, P. Jose, N. Mohan, An Approach to Connect Ultracapacitor to Fuel Cell Powered Electric Vehicle and Emulating Fuel Cell Electrical Characteristics using Switched Mode Converter, *IECON 2003 conference*, pp. 897-901, Nov 2003.

[5] P. Thounthong, S. Rael, B. Davat, Control Strategy of Fuel Cell and Supercapacitors Association for a Distributed Generation System, *Transactions on Industrial Electronics*, pp. 3225 – 3233, Dec 2007.

[6] A. S. Samosir, A. H. M. Yatim, Implementation of new control method based on dynamic evolution control with linear evolution path for boost dc-dc converter, *PECON 2008 conference*, pp. 213-218, Nov 2008.

[7] A. S. Samosir, A. H. M. Yatim, Dynamic Evolution Control of Bidirectional DC-DC Converter for Interfacing Ultracapacitor Energy Storage to Fuel Cell Electric Vehicle System, *AUPEC 2008 conference*, pp. 1-6, Dec 2008.

[8] A. S. Samosir, A. H. M. Yatim, Implementation of new control method based on dynamic evolution control for DC-DC Power Converter, *International Review of Electrical Engineering Journal, vol. 4, no.1*, pp. 1 – 6, February 2009.

[9] M. Amirabadi, S. Farhangi, Fuzzy Control of a Hybrid Power Source for Fuel Cell Electric Vehicle using Regenerative Braking Ultracapacitor, *Power Electronics and motion control conference*, pp. 1389 – 1394, Aug 2006.

[10] K. Jin, X. Ruan, M. Yang, M. Xu, A Hybrid Fuel Cell Power System, *IEEE Transactions on Industrial Electronics*, pp. 1212 – 1222, April 2009.

[11] H. Tao, J. L. Duarte, M. A. M Hendrix, Line-Interactive UPS Using a Fuel Cell as the Primary Source, *IEEE Transactions on Industrial Electronics*, pp. 3012 – 3021, Aug. 2008.

[12] M. Ortuzar, J. Moreno, J. Dixon, Ultracapacitor-Based Auxiliary Energy System for an Electric Vehicle: Implementation and Evaluation, *IEEE Transactions on Industrial Electronics*, pp. 2147 – 2156, Aug. 2007.

[13] M. Tekin, D. Hissel, M. C. Pera, J. M. Kauffmann, Energy-Management Strategy for Embedded Fuel-Cell Systems Using Fuzzy Logic, *IEEE Transactions on Industrial Electronics*, pp. 595 – 603, Feb. 2007.

[14] A. F. Burke, Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles, *Proceedings of the IEEE*, pp. 806 – 820, April 2007.

[15] M. Ortuzar, J. Moreno, J. Dixon, Ultracapacitor-Based Auxiliary Energy System for an Electric Vehicle: Implementation and Evaluation, *IEEE Transactions on Industrial Electronics*, pp. 2147 – 2156, Aug. 2007.

[16] J. Moreno, M. E. Ortuzar, J. Dixon, Energy management system for a hybrid electric vehicle, using ultracapacitors and neural networks, *IEEE Transactions on Industrial Electronics*, pp. 614 – 623, April 2006.

[17] S. Choe, J. Ahn, J. Lee, S. Baek, Dynamic Simulator for a PEM Fuel Cell System With a PWM DC/DC Converter, *IEEE Transactions on Energy Conversion*, pp. 669 – 680, June 2008.

[18] X. Yu, M. R. Starke, L. M. Tolbert, B. Ozpineci, Fuel cell power conditioning for electric power applications: a summary, *IET Electric Power Applications*, pp. 643 – 656, Sept. 2007.

[19] W. Friede, S. Rael, B. Davat, Mathematical model and characterization of the transient behavior of a PEM fuel cell, *IEEE Transactions on* Power Electronics, pp. 1234 – 1241, Sept. 2004.

Authors' information

Energy Conversion Department,
Faculty of Electrical Engineering,
Universiti Teknologi Malaysia.
Email: saudi.ahmad@gmail.com

Ahmad Saudi Samosir was born in Belawan, Indonesia in 1971. He obtained his Bachelor degree in electrical engineering from University of North Sumatera Indonesia in 1995 and Master degree in electrical power engineering from Bandung Institute of Technology Indonesia in 1999.

He is currently a PhD research student in Department of Energy Conversion, Universiti Teknologi Malaysia. His areas of interest research include renewable energy, control technique and application of power converters.

Abdul Halim Mohd Yatim received the B.Sc. degree in Electrical and Electronic Engineering from Portsmouth Polytechnic, Portsmouth, U.K., in 1981, and the M.Sc. and Ph.D. degrees in power electronics from Bradford University, Bradford, U.K., in 1984 and 1990, respectively. Since 1982, he has been a member of the faculty at the Universiti Teknologi Malaysia, Johor, Malaysia, where he currently is a Professor and Deputy Dean of the Faculty. His areas of interest research include power quality, renewable/alternate energy, power electronics application and drives. He was a Commonwealth Fellow during 1994–1995 at Heriot Watt University, Edinburgh, U.K., and a Visiting Scholar at the Virginia Power Electronics Centre, Virginia Polytechnic Institute and State University, Blacksburg, in 1993. Dr. Yatim is a Corporate Member of the Institution of Engineers Malaysia. He is a Registered Professional Engineer with the Malaysian Board of Engineers. He currently holds the Interim Chapter Chair of the Malaysian Section of the IEEE Industrial Electronics/Industry Applications/Power Electronics Joint Societies.