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หมายเหตุ เป็นที่ปรึกษาร่วม

Intelligent Model-Based Control of a Standalone Photovoltaic/Fuel Cell Power Plant With Supercapacitor Energy Storage

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Abstract—A renewable energy hybrid power plant, fed by photovoltaic (PV) and fuel cell (FC) sources with a supercapacitor (SC) storage device and suitable for distributed generation applications, is proposed herein. The PV is used as the primary source; the FC acts as a backup, feeding only the insufficiency power (steady-state) from the PV; and the SC functions as an auxiliary source and a short-term storage system for supplying the deficiency power (transient and steady-state) from the PV and the FC. For high-power applications and optimization in power converters, four-phase parallel converters are implemented for the FC converter, the PV converter, and the SC converter, respectively. A mathematical model (reduced-order model) of the FC, PV, and SC converters is described for the control of the power plant. Using the intelligent fuzzy logic controller based on the flatness property for dc grid voltage regulation, we propose a simple solution to the fast response and stabilization problems in the power system. This is the key innovative contribution of this research paper. The prototype small-scale power plant implemented was composed of a PEMFC system (1.2 kW, 46 A), a PV array (0.8 kW), and an SC module (100 F, 32 V). Experimental results validate the excellent control algorithm during load cycles.

Index Terms—Flatness control, fuel cells, fuzzy control, nonlinear system, photovoltaic, supercapacitor.

NOMENCLATURE

dc	Direct current.
FC	Fuel cell.
PV	Photovoltaic.
SC	Supercapacitor.

C_{Bus}	Total capacitance at dc bus (F).
C_{SC}	Total capacitance of supercapacitor module (F).
i_{Load}	DC bus load current (A).
i_{FC}	Fuel cell current (A).
i_{FCREF}	Fuel cell current reference (set-point) (A).
i_{PV}	Solar cell (photovoltaic) current (A).
i_{PVREF}	Solar cell current reference (set-point) (A).
i_{SC}	Supercapacitor current (A).
i_{SCREF}	Supercapacitor current reference (set-point) (A).
MPPT	Maximum power point tracking.
P_{Load}	Load power (W).
P_{FC}	Fuel cell power (W).
P_{FCo}	Fuel cell output power to dc bus (W).
P_{FCREF}	Fuel cell power reference (set-point) (W).
P_{FCMax}	Maximum fuel cell power (W).
P_{PV}	Solar cell (photovoltaic) power (W).
P_{PVo}	Solar cell output power to dc-bus (W).
P_{PVREF}	Solar cell power reference (set-point) (W).
P_{PVMax}	Maximum solar cell power (W).
P_{SC}	Supercapacitor power (W).
P_{SCo}	Supercapacitor output power to dc-bus (W).
P_{SCREF}	Supercapacitor power reference (set-point) (W).
P_{SCMax}	Maximum supercapacitor power (W).
v_{Bus}	DC bus voltage (V).
v_{FC}	Fuel cell voltage (V).
v_{PV}	Solar cell (photovoltaic) voltage (V).
v_{SC}	Supercapacitor voltage (V).
E_{Bus}	DC bus energy (J).
E_{BusREF}	DC bus energy reference (set-point) (J).
E_{SC}	Supercapacitor energy (J).
E_{SCREF}	Supercapacitor energy reference (set-point) (J).
E_T	Total energy at dc bus and supercapacitor (J).

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r_{FC}	Equivalent series resistance in fuel cell converter (Ω).
r_{PV}	Equivalent series resistance in solar cell converter (Ω).
r_{SC}	Equivalent series resistance in supercapacitor converter (Ω).
u	Input variable vector.
x	State-variable vector.
y	Output vector.
$\phi(\cdot), \varphi(\cdot)$, and $\psi(\cdot)$	Smooth mapping functions.

I. INTRODUCTION

RENEWABLE energy sources are predicted to become competitive with conventional power generation systems in the near future. Unfortunately, they are not very reliable. For example, the PV source is not available during the night or during cloudy conditions. Other sources such as FCs may be more reliable but have economic issues associated with them. Because of this, two or more renewable energy sources are required to ensure a reliable and cost-effective power solution. Such a combination of different types of energy sources into a system is called a hybrid power system [1].

A combination of PV and FC sources forms a good pair with promising features for distributed generation applications [2]. Obviously, the slow response of the PEMFC [3], [4] needs to be compensated with a supercapacitor or a battery. A supercapacitor storage device is preferable due to its high power density, high dynamics, and long lifetime [5].

Many researchers have focused their studies on such systems. Riffonneau *et al.* [6] have studied the energy management of a grid connected PV/battery hybrid power plant. Jiang *et al.* [7] studied control based on an adaptive control with state machine estimation of an FC/Li-Ion battery hybrid power source, and Uzunoglu and Alam [8] have studied control based on a wavelet-based load sharing algorithm of an FC/SC hybrid power source.

A classical boost converter is often used as an FC converter and a PV converter [9], and a classical two-quadrant (bidirectional) converter is often used as a supercapacitor or battery converter. However, the classical converters will be limited when the power increases or at higher step-up ratios. As such, the use of parallel power converters (multiphase converters in parallel) with interleaving may offer better performance [10]. The interleaved converter can benefit both high current and high power density designs. It is ideal for merchant power applications because the reduced input ripple current and reduced output capacitor ripple current lessen the electrical stress on the dc capacitors.

Current work on controlling an FC/SC hybrid power plant is reported in [11], where a linear control using PI compensator was proposed for dc-link stabilization. Design controller

parameters based on linear methods require a linear approximation [12], [13], where this is dependent on the operating point. Because the switching model of the hybrid power plant is nonlinear, it is natural to apply model-based nonlinear control strategies that directly compensate for system nonlinearity without requiring a linear approximation.

In the early 1990s, the flatness control theory was introduced by Fliess *et al.* [14] in a differential algebraic framework. It is simple, clear-cut, and appropriate for robustness, predictive control, trajectory planning, and constraints handling. Recently, this idea has been used in a variety of power electronic systems [15], [16]. Thounthong [16] has proved with real test bench results that the flatness-based control of a PV/supercapacitor power plant is absolutely robust.

The fast response, efficiency, and stability of the operation of hybrid power plants are of particular interest. In this work, a hybrid power generation system is studied, consisting of the following main components: a PV, proton exchange membrane FCs (PEMFC), and an SC as a high-power density device. In this study, a novel framework is proposed for the intelligent fuzzy logic-based flatness control approach of a solar-hydrogen power generation system with a supercapacitor storage device. The rest of the paper is structured as follows: Section II describes the hybrid energy system and modeling of the power plant that is studied in this work. Section III presents the proposed energy management algorithm, the proof of the flat system of the renewable energy power plant, and the control laws and system stability. Section IV presents test bench results for the proposed system. Finally, the paper ends with concluding remarks in Section V.

II. SOLAR/HYDROGEN POWER PLANT

A. Structure of Power Converters Studied

The power converter structure of the system studied in this paper is shown in Fig. 1. The FC and PV converters have four-phase parallel boost converters and the SC converter has four-phase parallel bidirectional converters (two-quadrant converters). For optimization in power converters, these converters connected in parallel, with an *interleaved switching technique*, increase the power processing capability and availability of the power electronic system [10].

For safety and high dynamics, the PV, FC, and SC converters are primarily controlled by inner current regulation loops classically. To ensure system stability, the dynamics of the inner regulation loops are also supposed to be much faster than those of the outer control loops [13]. These current control loops are supplied by three reference signals: i_{SCREF} , i_{PVREF} , and i_{FCREF} , generated by the control laws, presented hereafter.

B. Mathematical Model of the Power Plant

We consider that the PV, FC, and SC currents follow their reference values perfectly. This is a classical assumption used in the cascade control structure in order to estimate the external control loop. However, the assumption error will be compensated by the intelligent external control loop. Then, the inner control loops of the PV, FC, and SC powers can be approximated as a unity gain. The PV power reference p_{PVREF} , the FC

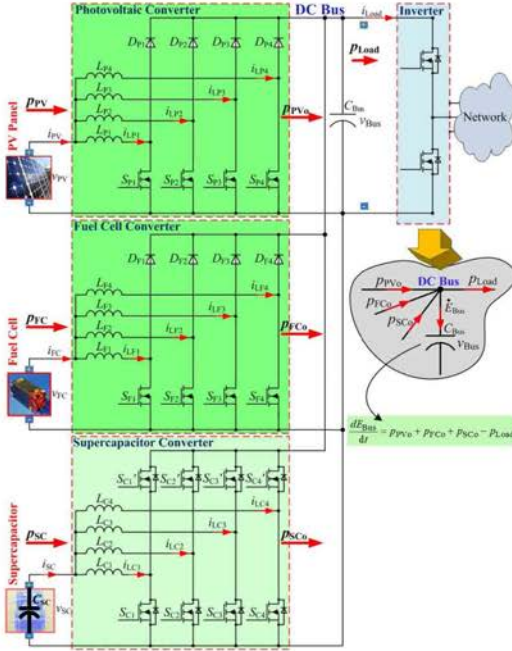


Fig. 1. Proposed circuit diagram of power plant supplied by an FC, a PV, and SC.

power reference p_{FCREF} , and the SC power reference p_{SCREF} are

$$p_{PVREF} = p_{PV} = v_{PV} \cdot i_{PV} \quad (1)$$

$$p_{FCREF} = p_{FC} = v_{FC} \cdot i_{FC} \quad (2)$$

$$p_{SCREF} = p_{SC} = v_{SC} \cdot i_{SC} \quad (3)$$

The PV panel, the FC generator, and the SC storage device function as controlled power sources. We assume here that there are only static losses in these converters, in which r_{PV} , r_{FC} , and r_{SC} represent the only static losses in the PV, the FC, and the SC converters, respectively. In real environment, the losses in converters are varied depending on many factors: temperature, current flow, etc. However, the estimation error will be compensated by the intelligent controller, presented hereafter. So, the dc-bus capacitive energy E_{Bus} and the supercapacitive energy E_{SC} can be written as

$$E_{Bus} = \frac{1}{2} C_{Bus} v_{Bus}^2, \quad E_{SC} = \frac{1}{2} C_{SC} v_{SC}^2. \quad (4)$$

The total electrostatic energy E_T stored in the dc-bus capacitor C_{Bus} and in the supercapacitor C_{SC} can also be written as

$$E_T = \frac{1}{2} C_{Bus} v_{Bus}^2 + \frac{1}{2} C_{SC} v_{SC}^2. \quad (5)$$

As portrayed in Fig. 1, the derivative of dc-bus capacitive energy E_{Bus} is given versus p_{PVo} , p_{FCo} , p_{SCo} , and p_{Load} by the following differential equation:

$$\dot{E}_{Bus} = p_{PVo} + p_{FCo} + p_{SCo} - p_{Load} \quad (6)$$

where

$$p_{PVo} = p_{PV} - r_{PV} \left(\frac{p_{PV}}{v_{PV}} \right)^2 \quad (7)$$

$$p_{FCo} = p_{FC} - r_{FC} \left(\frac{p_{FC}}{v_{FC}} \right)^2 \quad (8)$$

$$p_{SCo} = p_{SC} - r_{SC} \left(\frac{p_{SC}}{v_{SC}} \right)^2 \quad (9)$$

$$p_{Load} = v_{Bus} \cdot i_{Load} = \sqrt{\frac{2E_{Bus}}{C_{Bus}}} \cdot i_{Load} \quad (10)$$

$$p_{SC} = v_{SC} \cdot i_{SC} = \sqrt{\frac{2E_{SC}}{C_{SC}}} \cdot i_{SC}. \quad (11)$$

III. NONLINEAR MODEL-BASED CONTROL OF A POWER PLANT

A. Energy Balance

The main control objectives are stability, high overall efficiency, and fast response. As for supplying energy to the load demanded and the charging storage device, the multivariable control here involves set-point control of the dc-bus voltage v_{Bus} (representing the dc-bus energy E_{Bus} , called “DC link stabilization”) [11] and set-point control of the SC voltage v_{SC} (representing the supercapacitive energy E_{SC}).

The principle behind the proposed hybrid energy management lies in using the SCs (the fastest energy source) to supply the energy required to achieve the dc grid voltage regulation (or the dc bus energy regulation) [11]. Then, the PV and FC, although clearly the main energy source of the system, function as the generator that supplies energy for both the dc bus capacitor C_{Bus} and the C_{SC} to keep them charged.

B. Flatness of the Power Plant Model

For the substantiation of flatness [17], [18], the system explanation from Section II is examined. To regulate the dc-bus voltage v_{Bus} (DC link stabilization) and the SC voltage v_{SC} (state-of-charge), based on the flatness control theory introduced above, the flat outputs y , the control input variables u , and the state variables x are defined as

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} E_{Bus} \\ E_T \end{bmatrix}, \quad u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} p_{SCREF} \\ p_{TREF} \end{bmatrix} \quad (12)$$

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} v_{Bus} \\ v_{SC} \end{bmatrix}$$

where p_{TREF} is the total power from the FC and PV array. From (4) and (5), the state variables x can be written as

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2y_1}{C_{Bus}}} \\ \sqrt{\frac{2(y_2 - y_1)}{C_{SC}}} \end{bmatrix} = \begin{bmatrix} \varphi_1(y_1) \\ \varphi_2(y_1, y_2) \end{bmatrix}. \quad (13)$$

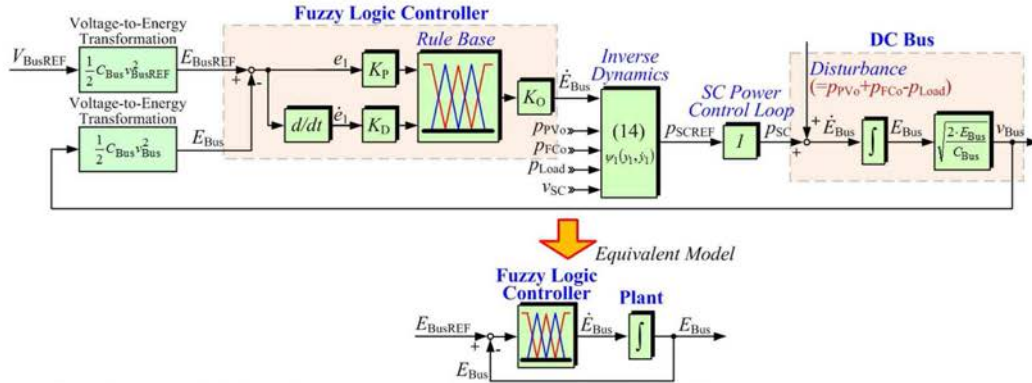


Fig. 2. Control law based on the differential flatness theory of the dc-bus energy regulation for PV/FC/SC hybrid power plant.

From (6) to (11), the control input variables $\mathbf{u}$ can be calculated from the flat output $\mathbf{y}$ and its time derivatives

$$\begin{aligned} u_1 &= 2p_{SCLim} \\ &\cdot \left[1 - \sqrt{1 - \left(\frac{\dot{y}_1 + \sqrt{\frac{2y_1}{C_{Bus}}} \cdot i_{Load} - p_{FCo} - p_{PVo}}{p_{SCLim}} \right)^2} \right] \\ &= \psi_1(y_1, \dot{y}_1) \end{aligned} \quad (14)$$

$$\begin{aligned} u_2 &= 2p_{TMax} \cdot \left[1 - \sqrt{1 - \left(\frac{\dot{y}_2 + \sqrt{\frac{2y_1}{C_{Bus}}} \cdot i_{Load}}{p_{TMax}} \right)^2} \right] \\ &= \psi_2(y_1, \dot{y}_2) \end{aligned} \quad (15)$$

where

$$p_{SCLim} = \frac{v_{SC}^2}{4r_{SC}}, \quad p_{TMax} = \frac{v_T^2}{4r_T}. \quad (16)$$

p_{SCLim} is the limited maximum power from the SC converter, v_T is the virtual voltage from the FC and PV power generators, and r_T is the virtual static losses in the FC and PV power converters.

In fact,

$$p_{TMax} = p_{FCMax} + p_{PVMMax} \quad (17)$$

where p_{FCMax} is the maximum FC power and p_{PVMMax} is the maximum PV power.

Thus, it is understandable that $x_1 = \varphi_1(y_1)$, $x_2 = \varphi_2(y_1, y_2)$, $u_1 = \psi_1(y_1, \dot{y}_1)$, and $u_2 = \psi_2(y_1, \dot{y}_2)$. The proposed reduced order model can be studied as a flat system [17], [18].

C. DC Link Stabilization

Fuzzy control algorithms offer many advantages over traditional controls because they give fast convergence, are parameter insensitive, and accept noisy and inaccurate signals [19], [20]. In recent years, it has been used in many control applications where the system is complex [21], [22].

The control objective is to regulate the dc bus voltage v_{Bus} or the dc bus energy $E_{Bus}(= y_1)$. The controller contains a Takagi–Sugeno (T–S) inference engine and two fuzzy inputs: the energy error $e_1(= y_{1REF} - y_1)$ and the differential energy error $\dot{e}_1$, which are carefully adjusted using the proportional gain K_P and the derivative gain K_D , respectively. In addition, the fuzzy output level can be set by the proportional gain K_O (Fig. 2).

Triangular and trapezoidal membership functions are chosen for both of the fuzzy inputs, as shown in Fig. 3(a). There are seven membership functions for each input, including *NB* (Negative Big), *NM* (Negative Medium), *NS* (Negative Small), *Z* (Zero), *PB* (Positive Big), *PM* (Positive Medium), and *PS* (Positive Small). For the singleton output membership function, the zero-order Sugeno model is used, where the membership functions are specified symmetrically, as follows: *NB* = -1 , *NM* = -0.66 , *NS* = -0.33 , *Z* = 0 , *PB* = 1 , *PM* = 0.66 , and *PS* = 0.33 , as presented in Fig. 3(b).

For the rule base, expert suggestions, an experimental approach, and a trial and error technique were used to define the relationships between the inputs and the output. The data representation was in the form of an *IF-THEN* rule, as shown in the following example:

IF e_{1i} is *NS* and $\dot{e}_{1i}$ is *NS*
THEN $z_i(=output)$ is *NB*.

As shown in Fig. 3(c), the total number of rule bases is, therefore, equal to 49 rules. To obtain the output of the controller, the center of gravity method for the *COGS* of the singletons is utilized as

$$U = \frac{\sum_{i=1}^N w_i z_i}{\sum_{i=1}^N w_i} \quad (18)$$

where the weights (w_i) can be retrieved from

$$w_i = \max(e_{1i}, \dot{e}_{1i}). \quad (19)$$

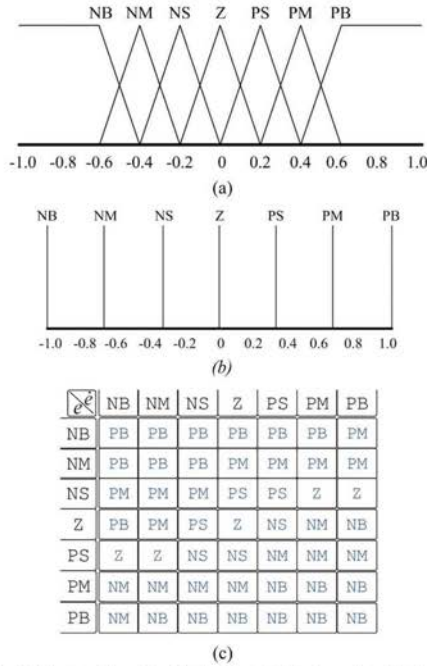


Fig. 3. Rule base and membership functions. (a) Input membership functions. (b) Output membership function. (c) Rule base.

D. Charging Supercapacitor

Because the SC energy storage has a massive size capacity, and the supercapacitive energy is defined as a slower dynamic variable than the dc-bus energy variable. Then, the proposed control law is [23], [24]

$$(\dot{y}_2 - \dot{y}_{2REF}) + K_{21}(y_2 - y_{2REF}) = 0. \quad (20)$$

This yields

$$\dot{y}_2 = \dot{y}_{2REF} + K_{21}(y_{2REF} - y_2) \quad (21)$$

where y_{2REF} is the reference of total electrostatic energy, refer to (5), and K_{21} is the control parameter.

From (20), if we define $e_2 = y_2 - y_{2REF}$, $K_{21} = 1/\tau_S$, we obtain

$$\tau_S \cdot \dot{e}_2 + e_2 = 0. \quad (22)$$

Substituting the expression for $\dot{y}_2$ from (21) into (15) gives the equation for the closed-loop static state feedback, in which one obtains the inverse dynamics

$$\begin{aligned} u_2 &= \psi_2(y_1, \dot{y}_2) = p_{TREF} \\ &= p_{PVDEM} + p_{FCDEM} \end{aligned} \quad (23)$$

where p_{PVDEM} is the PV power demand and p_{FCDEM} is the FC power demand.

The total energy control law (or the SC energy control law) generates a total power reference p_{TREF} , as shown in Fig. 4.

First, p_{TREF} is considered as the PV power demand p_{PVDEM} . It must be limited in level, within an interval maximum p_{PVMax} (maximum power point tracking MPPT) and minimum p_{PVMin} (set to 0 W). Several approaches have been devised for tracking MPP accurately for PV cells [25], [26]. Some of the popular ones are the perturbation and observation algorithm (P&O) method [27]. Based on P&O MPPT, the pseudocode for the PV power saturation function studied here is described in ALGORITHM I, where ΔI_{PV} is the defined PV current step size and Δt_{PV} is the sampling time. Note that this sampling time must be higher than a main program sampling time.

ALGORITHM I: MPPT for PV

BEGIN

READ $p_{PVDEM}(t)$

READ $v_{PV}(t)$

READ $i_{PV}(t)$

$p_{PV}(t) = v_{PV}(t) \times i_{PV}(t)$

$p_{PV}(t - \Delta t_{PV}) = v_{PV}(t - \Delta t_{PV}) \times i_{PV}(t - \Delta t_{PV})$

IF $p_{PV}(t) \geq p_{PV}(t - \Delta t_{PV})$ **THEN**

IF $i_{PV}(t) \geq i_{PV}(t - \Delta t_{PV})$ **THEN**

$i_{PVMMax}(t) = i_{PV}(t) + \Delta I_{PV}$

ELSE

$i_{PVMMax}(t) = i_{PV}(t) - \Delta I_{PV}$

ELSEIF

ELSE

IF $i_{PV}(t) \geq i_{PV}(t - \Delta t_{PV})$ **THEN**

$i_{PVMMax}(t) = i_{PV}(t) - \Delta I_{PV}$

ELSE

$i_{PVMMax}(t) = i_{PV}(t) + \Delta I_{PV}$

ELSEIF

ENDIF

$p_{PVMMax}(t) = v_{PV}(t) \times i_{PVMMax}(t)$

$p_{PVREF}(t) = \min[p_{PVDEM}(t), p_{PVMMax}(t)]$

$v_{PV}(t - \Delta t_{PV}) = v_{PV}(t)$

$i_{PV}(t - \Delta t_{PV}) = i_{PV}(t)$

END

Second, the difference between the total power reference p_{TREF} and the PV power reference p_{PVREF} is the FC power demand p_{FCDEM} . It must be limited in level, within an interval maximum p_{FCMax} and minimum p_{FCMin} (set to 0 W) and limited in dynamics to respect the constraints that are associated



Fig. 5. Photograph of the experimental setup.

- 3) At the same time, the FC power increases with limited dynamics to MPP of around 430 W.
- 4) The input from the SC, which supplies most of the transient power that is required during the stepped load, slowly decreases and the unit remains in a discharge state after the load step because the steady-state load power (approximately 900 W) is greater than the total power supplied by the photovoltaic array and fuel cell. This state is known as the ride-through mode.

After that, at 9:02:10, the load power steps from 900 to 280 W (negative transition) and $V_{SCREF} (= 25 \text{ V}) > v_{SC} (= 17 \text{ V})$. As a result, the SC changes its state from discharging to charging, demonstrating the four phases.

TABLE I
SPECIFICATIONS OF POWER SOURCES AND STORAGE DEVICE

Fuel Cell System (by Ballard Power Systems Inc):		
Rated Power	1,200	W
Rated Current	46	A
Rated Voltage	26	V
Photovoltaic Array (by Ekarat Solar Company):		
Number of Panels in Parallel	4	
Panel Open Circuit Voltage	33.5	V
Panel Rated Voltage	26	V
Panel Rated Current	7.7	A
Panel Rated Power	200	W
Array Rated Power	800	W
Supercapacitor Bank (by Maxwell Technologies Comp): (Cell Model: BCAP1200)		
Number of Cells in Series	12	
Cell Capacity	1,200	F
Cell Maximum Voltage	2.7	V
Bank Capacity (C_{SC})	100	F
Bank Maximum Voltage	32	V

TABLE II
DC-BUS ENERGY CONTROL LOOP PARAMETERS

V_{BusREF}	60	V
C_{Bus}	12200	μF
K_P	0.15	
K_D	0.15	
K_O	-200	
r_{PV}	0.13	Ω
r_{YC}	0.13	Ω
r_{SC}	0.08	Ω
V_{SCMax}	32	V
V_{SCMin}	15	V
$I_{SCRated}$	150	A

TABLE III
SUPERCAPACITIVE ENERGY CONTROL LOOP PARAMETERS

V_{SCREF}	25	V
C_{SC}	100	F
K_{21}	0.1	$\text{W} \cdot \text{J}^{-1}$
p_{FCMin}	0	W
I_{FCMax} (Rated)	46	A
I_{FCMin}	0	A
τ_1	5	s

- 1) First, the FC and PV still supply their total limited maximum powers for driving the load and for charging the SC, intelligently.
 - 2) Second, at 9:02:35 ($v_{SC} = 23.5 \text{ V}$), the SC is nearly charged at 25 V; which then reduces the charging power. As a result, the FC power is reduced to zero.
 - 3) Third, at 9:03:00 ($v_{SC} = 24.5 \text{ V}$), the SC is nearly fully charged at 25 V; as a result, the PV power is reduced.
 - 4) Fourth, at 9:03:20, the SC is fully charged ($V_{SCREF} = v_{SC} = 25.0 \text{ V}$). As a result, the FC and SC powers are zero; the PV source supplies power for the load of 280 W.
- During the experiment, the FC maximum power is limited by the MPPT and the PV maximum power is limited by the MPPT. Exceptionally, one can observe that the power plant is always energy balanced ($p_{Load} = p_{PV} + p_{FC} + p_{SC}$) by the proposed original control algorithm.

The oscilloscope waveforms in Fig. 7 show the dynamic response of the dc bus voltage dynamics to the large load power

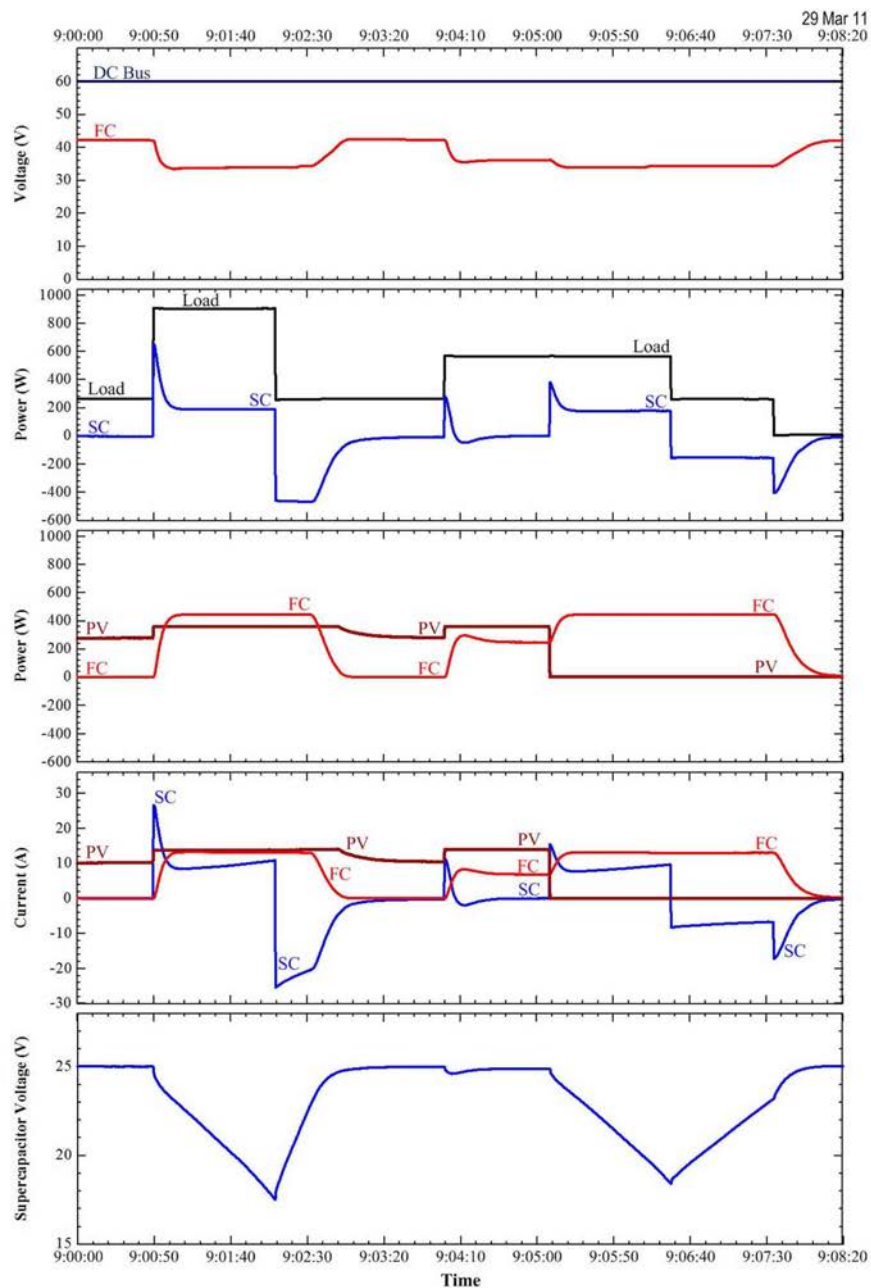


Fig. 6. Experimental results: Power plant response during load cycles.

demands (disturbance) from 0 to 900 W. The oscilloscope screens show the dc bus voltage, the SC voltage, the load power, and the SC power. The PV and FC power dynamics were purposely limited, forcing the SC to supply the transient

load power demand. The proposed fuzzy-logic controller shows good stability and an optimum response (no oscillation and short settling time) for the regulation of the dc bus voltage to the desired reference of 60 V.

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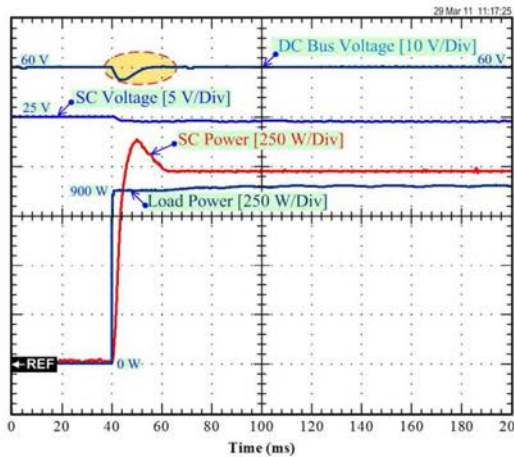


Fig. 7. Experimental results of the dynamic characteristics of the power plant during a step load from 0 to 900 W.

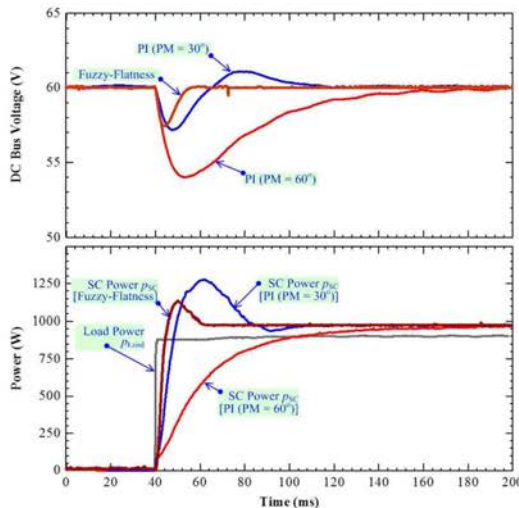


Fig. 8. Comparison of the fuzzy-flatness based control law with a linear PI control law during a large load step.

Finally, to compare the performance of the proposed control law, a traditional linear PI control method presented in [11] was also implemented on the test bench. In order to give a rational comparison between the methods, the parameters of the linear controller K_P and K_I were tuned to obtain the best possible performance. The desired phase margin (PM) was tuned at 30° and 60° . This result was compared to the fuzzy-flatness-based control. Fig. 8 shows experimental results obtained for both controllers during the large load step. The fuzzy-flatness-based control shows good stability and optimum response of the dc-bus voltage regulation to its desired reference of 60 V. Although dynamic response of the linear control law could be improved relative to that shown in the figures, this enhancement comes at the expense of a reduced stability margin (overshoot

and oscillation). From these results, we conclude that fuzzy-flatness-based control provides better performance than the classical PI controller.

V. CONCLUSION

The key contribution of this paper is to authenticate the intelligent fuzzy logic control based on differential flatness estimation of a PV/FC/SC hybrid power plant for standalone applications. The prototype power plant studied was composed of a PEMFC system (1200 W), a PV array (800 W), and an SC module (100 F). Its working principle, analysis, and design procedure were presented. The PV is the main source, while the FC serves as a support source to compensate for the uncertainties of the PV source in the steady state. The SC functions as a storage device (or an auxiliary source) to compensate for the uncertainties of the PV and FC sources in the steady state and transient state.

Using the intelligent fuzzy logic control for dc link stabilization based on the flatness property, we proposed simple solution to the fast response and stabilization problems in the nonlinear power electronic system. This strategy is based on a standard dc link voltage regulation, which is simpler than standard state machines used for hybrid source control, and free of chattering problems. This is the novel concept for this kind of application. Experimental results authenticated the control algorithm and control laws.

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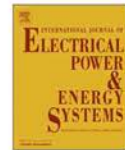
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Performance investigation of linear and nonlinear controls for a fuel cell/supercapacitor hybrid power plant



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ABSTRACT

In this paper, linear proportional–integral (PI) and nonlinear flatness-based controllers for dc link stabilization for fuel cell/supercapacitor hybrid power plants are compared. For high power applications, 4-phase parallel boost converters are implemented with a switching interleaving technique for a fuel cell (FC) converter, and 4-phase parallel bidirectional converters are implemented with a switching interleaving technique for a supercapacitor converter in the laboratory. As controls, mathematical models (reduced-order models) of the FC converter and the supercapacitor converter are given. The prototype small-scale power plant studied is composed of a PEMFC system (the Nexa Ballard FC power generator: 1.2 kW, 46 A) and a supercapacitor module (100 F, 32 V, based on Maxwell Technologies Company). Simulation (by Matlab/Simulink) and experimental results demonstrate that the nonlinear differential flatness-based control provides improved dc bus stabilization relative to a classical linear PI control method.

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1. Introduction

FCs have experienced remarkably rapid growth in the past 10 years because of concerns about environmental emissions from centralized power plants and the uncertainty of global energy supplies. These sources are pollution-free sources of abundant power. In addition, they generate power near the load centers, hence eliminating the need for running high voltage transmission lines through rural and urban landscapes [1,2].

According to recent works on fuel cell characteristics [3–5] and the specific properties of FCs, their output power response is delayed due to the processing time through subsidiary equipment and their slow internal electrochemical and thermodynamic characteristics. Therefore, in order to supply electric power to fluctuating loads by a hybrid FC system, an electric energy storage system is needed to compensate the gap between the output from the FC and the load, in addition to the collaborative load sharing [6]. Previous research works have shown that the hybridization of FC vehicles with batteries [2], with supercapacitors (ultracapacitors) [7], and with batteries/supercapacitors [8,9] provides cost, performance, and operational improvements, as well as fuel economy benefits that are attractive and should be considered by researchers.

The control problem (dc link stabilization) is important in many power electronic applications, such as robust control methods for unified power flow controller [10], control of solar power systems [11], and control for a wind energy conversion system [12]. Traditional methods to solve this problem are regularly based on a linearized model of the power converter and proportional–integral (PI) or proportional–integral–derivative (PID) feedback.

Control, robustness, stability, efficiency, and optimization of distributed generation systems remain an essential area of research. Recent work on controlling a FC/supercapacitor hybrid power plant is reported in [13], where a linear control using PI compensators was proposed for dc link stabilization. This work established a regularly used cascade controller structure for the supercapacitor current and dc bus voltage where the regulation of the supercapacitor current is contained inside the PI control for the dc bus voltage. Thus, design controller parameters based on linear methods require a linear approximation, where this is dependent on the operating point. Because the switching model of the hybrid power plant is nonlinear, it is natural to apply model-based nonlinear control strategies that directly compensate for system nonlinearity without requiring a linear approximation. Studies of some nonlinear controllers for nonlinear systems have been proposed, such as nonlinear robust control of proton exchange membrane fuel cell by state feedback exact linearization [14], or nonlinear control for fuel cell/battery/ultracapacitor hybrid power sources [15]. However, more than 90% of industrial

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Nomenclature

AC	alternating current	p_{SCREF}	supercapacitor power reference (set-point) (W)
DC	direct current	p_{SCMax}	maximum supercapacitor power (W)
FC	fuel cell	v_{bus}	DC bus voltage (V)
SC	supercapacitor	v_{fc}	fuel cell voltage (V)
C_{bus}	total capacitance at DC bus (F)	v_{sc}	supercapacitor voltage (V)
C_{SC}	total capacitance of supercapacitor module (F)	E_{bus}	DC bus energy (J)
i_{load}	DC bus load current (A)	E_{busREF}	DC bus energy reference (set-point) (J)
i_{fc}	fuel cell current (A)	E_{sc}	supercapacitor energy (J)
i_{fcREF}	fuel cell current reference (set-point) (A)	E_{scREF}	supercapacitor energy reference (set-point) (J)
i_{sc}	supercapacitor current (A)	E_T	total energy at DC bus and supercapacitor (J)
i_{scREF}	supercapacitor current reference (set-point) (A)	r_{fc}	equivalent series resistance in fuel cell converter (Ω)
p_{load}	load power (W)	r_{sc}	equivalent series resistance in supercapacitor converter (Ω)
p_{fc}	fuel cell power (W)	$\mathbf{u}$	input variable vector
p_{FCO}	fuel cell output power to DC bus (W)	$\mathbf{x}$	state-variable vector
p_{fcREF}	fuel cell power reference (set-point) (W)	$\mathbf{y}$	output vector
p_{FCMax}	maximum fuel cell power (W)	$\phi(\cdot), \psi(\cdot), \phi(\cdot)$	smooth mapping functions
p_{sc}	supercapacitor power (W)		
p_{SCO}	supercapacitor output power to DC bus (W)		

controllers are still implemented based on linear control algorithms (PI or PID controllers), including the following advantages: clear functionality, applicability, and ease of use [16].

This paper presents a performance comparison between a proposed flatness-based control and a classical linear control for dc link stabilization of an FC/supercapacitor hybrid power source. It will provide a significant contribution to the field of multi-source systems, particularly in nonlinear power electronics applications. The flatness-based control of a FC/supercapacitor power plant will show good convergence of the dc-bus voltage regulation to its desired reference compared the classical PI controller, as studied in previous works [3,9,13]. There are no operating points and linearization models used in the proposed new control system. In Section 2, the FC and supercapacitor converter structure of multi-phase power converters is presented in detail, including a mathematic model of the power plant. The control laws based on the differential flatness property and linear PI control in Section 3 will be explained in detail. Simulation and experimental results will show the system performances of linear and nonlinear control laws. The summary and conclusions are presented in Section 4.

2. Fuel cell/supercapacitor hybrid power plant

2.1. System configuration studied

Normally, an FC system needs a boost dc/dc converter to adapt the FC output low voltage to the desired higher voltage level [17] and a storage device needs a bidirectional dc/dc converter (or two-quadrant converter) [18]. Nevertheless, a single converter will be limited when the power increases or for higher step-up ratios. That way, the use of paralleling power converters with the interleaved technique may offer better performance [19].

The power converter structure of the system studied in this paper is shown in Fig. 1. The FC converter is composed of 4-phase parallel boost converters, and the supercapacitor converter is composed of 4-phase parallel bidirectional converters (2-quadrant converters). These parallel connected converters, with interleaved switching technique, increase the power processing capability and availability of the power electronic system. Interleaved power conversion constitutes one of the most promising alternatives for the following advantages [19,20]:

- (i) ripple cancellation both in the input and output waveforms to the maximum extent,

- (ii) a lower value of ripple amplitude and a high ripple frequency in the resulting input and output waveforms,
- (iii) improvement of the efficiency of the parallel connected converter system if a proper number of converters in the system are activated,
- (iv) fewer output capacitors is due to lower output-ripple current, which results in lower cost and lower power dissipation.

The prototype FC converter (1 kW) and the supercapacitor converter (2 kW) (refer to Fig. 1) were realized in the laboratory. The converter parameters and semiconductor components are detailed in Table 1.

For safety and high dynamics, the FC and supercapacitor converters are primarily controlled by inner current regulation loops, classically [13]. The current controls of these converters are similar to a basic current control of parallel converters. They can be easily realized by linear (PI) controllers [21] or nonlinear (sliding mode) current controllers [22]. To ensure system stability, the dynamics of the inner current regulation loops are also assumed to be much faster than those of the outer control loops [23]. These current control loops are supplied by two reference signals; the supercapacitor current reference i_{scREF} and the FC current reference i_{fcREF} , generated by the control laws, are presented below.

2.2. Mathematical model

We consider that the FC and supercapacitor currents follow their reference values perfectly. Consequently,

$$i_{fc} = i_{fcREF} = \frac{p_{fc}}{v_{fc}} = \frac{p_{fcREF}}{v_{fc}} \quad (1)$$

$$i_{sc} = i_{scREF} = \frac{p_{sc}}{v_{sc}} = \frac{p_{scREF}}{v_{sc}} \quad (2)$$

Then, the FC generator and the supercapacitor storage device function as controlled current sources. We consider here that there are only static losses in these converters, and r_{fc} and r_{sc} represent the static losses in the FC and supercapacitor converters, respectively.

The dc-bus capacitive energy E_{bus} and the supercapacitive energy E_{sc} can be written as:

$$E_{bus} = \frac{1}{2} C_{bus} v_{bus}^2 \quad (3)$$

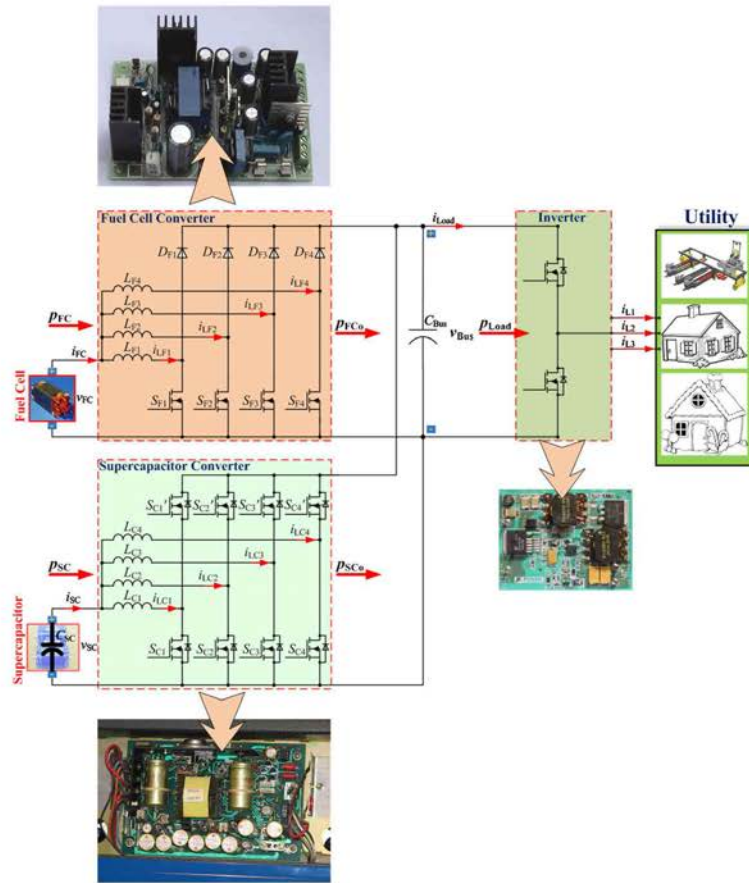


Fig. 1. Proposed circuit diagram of a distributed cogeneration system supplied by a fuel cell and supercapacitor, where $p_{Load} (= v_{Bus} \times i_{Load})$, $p_{FC} (= v_{FC} \times i_{FC})$, $p_{SC} (= v_{SC} \times i_{SC})$, p_{FCo} and p_{SCo} are the output powers to the DC link from the converters of fuel cell and supercapacitor, respectively.

Table 1
Converter parameters and semiconductor devices.

Fuel cell converter	
Inductors $L_{F1} = L_{F2} = L_{F3} = L_{F4}$	420 μ H
MOSFETs $S_{F1} = S_{F2} = S_{F3} = S_{F4}$	IRFP264N: 250 V, 38 A
Diodes $D_{F1} = D_{F2} = D_{F3} = D_{F4}$	RURG3020: 200 V, 30 A
Supercapacitor converter	
Inductors $L_{SC1} = L_{SC2} = L_{SC3} = L_{SC4}$	290 μ H
MOSFETs	IRFP264N: 250 V, 38 A
$S_{C1} = S_{C2} = S_{C3} = S_{C4} = S_{C1} = S_{C2} = S_{C3} = S_{C4}$	

$$E_{SC} = \frac{1}{2} C_{SC} v_{SC}^2 \quad (4)$$

The total electrostatic energy E_T stored in the dc-bus capacitor C_{Bus} and in the supercapacitor C_{SC} can also be written as:

$$E_T = \frac{1}{2} C_{Bus} v_{Bus}^2 + \frac{1}{2} C_{SC} v_{SC}^2 \quad (5)$$

As depicted in Fig. 1, the dc-bus capacitive energy E_{Bus} is given versus p_{FCo} , p_{SCo} , and p_{Load} by the following differential equation:

$$\dot{E}_{Bus} = p_{FCo} + p_{SCo} - p_{Load} \quad (6)$$

where

$$p_{FCo} = p_{FC} - r_{FC} \left(\frac{p_{FC}}{v_{FC}} \right)^2 \quad (7)$$

$$p_{SCo} = p_{SC} - r_{SC} \left(\frac{p_{SC}}{v_{SC}} \right)^2 \quad (8)$$

$$p_{Load} = v_{Bus} \cdot i_{Load} = \sqrt{\frac{2E_{Bus}}{C_{Bus}}} \cdot i_{Load} \quad (9)$$

$$p_{SC} = v_{SC} \cdot i_{SC} = \sqrt{\frac{2E_{SC}}{C_{SC}}} \cdot i_{SC} \quad (10)$$

3. Control algorithm

3.1. Energy management

Several researchers have studied different topologies for the energy management of multi-power sources. Schaltz et al. [24] studied two energy-management strategies of an FC/battery/supercapacitor hybrid power source for vehicle applications. Feroldi et al. [25] studied control based on an efficiency map of an FC/supercapacitor hybrid power source for vehicle applications. Jiang et al. [26] studied control based on adaptive control with a state machine estimation of a FC/Li-Ion battery hybrid power source. Uzunoglu and Alam [27] studied control based on a wavelet-based load sharing algorithm of an FC/supercapacitor hybrid power source, and Thounthong et al. studied a regulated dc-bus voltage FC/supercapacitor hybrid source (based on a basic linear controller) [13], a FC/supercapacitor hybrid source (based on a fuzzy logic controller) [28], and an unregulated dc-bus voltage FC/battery hybrid source (based on a linear controller) [29]. Nevertheless, in these kinds of structures, the control, robustness, stability, efficiency, and optimization of fuel cell hybrid sources remain an essential area of research.

As recommended in [2,3], one must operate an FC with slow dynamics in order to prevent the *fuel starvation phenomenon* and thus improve its stack lifetime. The slow dynamics of an FC can be compensated by faster dynamics from storage devices. In contrast to batteries, supercapacitors have lower energy density but higher power density and provide very fast current charge/discharge cycles because of their low equivalent series resistance. Supercapacitors can provide more cycles than batteries and are well suited to very high dynamic cycles [30,31].

The energy management strategy based on dynamic classification aims at distributing the global power mission of the system (such as a fuel cell vehicle or uninterruptible power supply (UPS) or a fuel cell power plant) into the sources in such a way that each source is optimally used. According to the two points mentioned above, a fuel cell generator is controlled as a lower dynamic power source. A supercapacitor is a higher dynamic power source, which provides the micro-cycles and the fast dynamic power supply [13].

In this kind of system, as depicted in Fig. 1, there are two-voltage variables or two-energy variables to be regulated:

- First, the dc bus voltage v_{bus} is the most important variable.
- Second, the supercapacitor voltage v_{sc} (state-of-charge SOC) must be regulated.

Therefore, the basic principle of the proposed hybrid energy management lies in using the supercapacitors (the faster energy source) to supply the energy required to achieve the dc bus voltage regulation (or the dc bus energy regulation, called “DC link stabilization”) [13]. Then, the fuel cell, although obviously the main energy source of the system, functions as the generator (with dynamic limitations) that supplies energy for both the dc bus capacitor C_{bus} and the supercapacitors C_{sc} to keep them charged.

3.2. Nonlinear control of DC link stabilization

Differential flatness theory (nonlinear control) was first introduced by Fliess et al. [32]. This allowed an alternate representation of the system where trajectory planning and nonlinear controller design is clear-cut. The advantages of the differential flatness approach are that the trajectories of the system are estimated in a straightforward manner by the trajectories of a flat output and its derivatives without integrating any differential equation. These ideas have been used lately in a variety of nonlinear systems across various engineering disciplines including:

- A process of stirred tank chemical reactor [33],
- Vehicle steering control [34],
- Control of a high-speed linear axis driven by pneumatic muscle actuators [35],
- Control of cathode pressure and oxygen excess ratio of a PEM fuel cell system [36],
- Steering control of a two-level quantum system [37],
- Reactive power and dc voltage tracking control of a three-phase voltage source converter [38],
- Control of open-channel flow in an irrigation canal [39],
- Current control for three phase three-wire boost converters [40],
- Design of a guidance algorithm for the hypersonic phase of a lifting-body vehicle [41],
- Control of a space robot with arbitrarily oriented joint axes and two momentum wheels at the base [42].

Then, this section gives a brief theory of differential flatness [32,43,44]. A system of ordinary differential equations (11) is said to be differentially flat if there exist variables (denoted by flat outputs, y) such that:

$$\dot{x} = f(x, u) \quad (11)$$

$$x = [x_1, x_2, \dots, x_n]^T, \quad x \in \mathbb{R}^n \quad (12)$$

$$u = [u_1, u_2, \dots, u_m]^T, \quad u \in \mathbb{R}^m \quad (13)$$

$$y = [y_1, y_2, \dots, y_m]^T, \quad y \in \mathbb{R}^m \quad (14)$$

where x is the state variables, u is the vector of input (control) variables, and $(n, m) \in \mathbb{N}$.

These variables are functions of the states, inputs and finite derivatives of the inputs of the form:

$$y = \phi(x, u, \dot{u}, \dots, u^{(\alpha)}) \quad (15)$$

where α is a finite number of derivatives.

All the states and inputs can be expressed in terms of the flat outputs and their derivatives by equations of the type:

$$x = \varphi(y, \dot{y}, \dots, y^{(\beta)}) \quad (16)$$

$$u = \psi(y, \dot{y}, \dots, y^{(\beta+1)}) \quad (17)$$

where β is a finite number of derivatives.

If the output variables of interest can be proven to be flat outputs y , reference control design y_{REF} becomes straightforward. The dynamics of the resulting linear error dynamics can be specified (control law) [38,40].

$$0 = (y_i^{(\beta+1)} - y_{i,REF}^{(\beta+1)}) + K_\beta (y_i^{(\beta)} - y_{i,REF}^{(\beta)}) + \dots + K_0 (y_i - y_{i,REF}) \quad (18.1)$$

where $K_\beta, \dots, K_0$ are the set of controller parameters. Then, there is no differential equation of the form:

$$0 = \zeta(y, \dot{y}, \dots, y^{(\beta)}) \quad (18.2)$$

where $\delta (= \beta + 1)$ is a finite number of derivatives.

Note that the vector functions $\phi(\cdot)$, $\varphi(\cdot)$, $\psi(\cdot)$, and $\zeta(\cdot)$ are assumed to be smooth. The flat outputs y and their derivatives provide an alternate representation of the system dynamics such that if the flat output profiles are known as a function of time, then one can obtain the profiles of all the system states and the corresponding inputs. This property is used to calculate the flat output trajectories, which are then mapped to the inputs u . Clearly, an advantage of the differential flatness approach is that the trajectories of the system, i.e. (x, u) , are estimated in a straightforward

manner by the trajectories of $\mathbf{y}$ and their derivatives without integrating any differential equations [37].

Based on the flatness control law introduced above, the dc-bus electrostatic energy E_{Bus} stored in C_{Bus} is assumed to be the flat output component. Thus, one defines a flat output $y_1 = E_{\text{Bus}}$, a control variable $u_1 = p_{\text{SCREF}}$, and a state variable $x_1 = v_{\text{Bus}}$. From Eq. (3), the state variable x_1 can be written as:

$$x_1 = \sqrt{\frac{2y_1}{C_{\text{Bus}}}} = \varphi_1(y_1) \quad (19)$$

From (6), the control variable u_1 can be calculated from the flat output y_1 and its time derivatives:

$$u_1 = 2 \cdot P_{\text{SCLimited}} \cdot \left[1 - \sqrt{1 - \left(\frac{\dot{y}_1 + \sqrt{\frac{2y_1}{C_{\text{Bus}}}} \cdot i_{\text{Load}} - p_{\text{FCO}}}{P_{\text{SCLimited}}} \right)^2} \right] = \psi_1(y_1, \dot{y}_1) \quad (20)$$

where

$$P_{\text{SCLimited}} = \frac{v_{\text{SC}}^2}{4r_{\text{SC}}} \quad (21)$$

$P_{\text{SCLimited}}$ is the limited maximum power from the supercapacitor converter.

It is apparent that $x_1 = \varphi_1(y_1)$ and $u_1 = \psi_1(y_1, \dot{y}_1)$ correspond to (16) and (17). Consequently, the mathematical model (the reduced order model) of the hybrid system can be considered as a flat system.

A desired reference for the dc-bus energy is represented by $y_{1\text{REF}}$. A linearizing feedback control law achieving an exponential asymptotic tracking of the trajectory is given by the following expression [45]:

$$(\ddot{y}_1 - \ddot{y}_{1\text{REF}}) + K_{11}(\dot{y}_1 - \dot{y}_{1\text{REF}}) + K_{12} \int_0^t (y_1 - y_{1\text{REF}}) d\tau = 0 \quad (22)$$

where the set of controller parameters (K_{11}, K_{12}) is chosen such that the roots of the closed loop characteristic polynomial, in the complex variable s :

$$p(s) = s^2 + \lambda_1 s + \lambda_0 \quad (23)$$

is a Hurwitz polynomial.

Obviously, the tracking error, $e_1 = y_1 - y_{1\text{REF}}$, satisfies:

$$e_1 + K_{11}\dot{e}_1 + K_{12}e_1 = 0 \quad (24)$$

An optimum choice of the design controller parameters is obtained by matching the characteristic polynomial, $p(s)$, to a desired characteristic polynomial, with pre-specified root locations. We may set as a desired characteristic polynomial:

$$p(s) = s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (25)$$

$$K_{11} = 2\zeta\omega_n \quad (26)$$

$$K_{12} = \omega_n^2 \quad (27)$$

where ζ and ω_n are the desired dominant damping ratio and natural frequency.

Substituting the expression for $\dot{y}_1$ into (20) gives the equation for the closed-loop static state feedback supercapacitor power:

$$u_1 = 2 \cdot P_{\text{SCLimited}} \cdot \left[1 - \sqrt{1 - \left(\frac{(\dot{y}_{1\text{REF}} - K_{11}e_1 - K_{12} \int_0^t e_1 d\tau) + p_{\text{Load}} - p_{\text{FCO}}}{P_{\text{SCLimited}}} \right)^2} \right] = p_{\text{SCREF}} \quad (28)$$

The control system is stable for $K_{11}, K_{12} > 0$ ($\zeta, \omega_n > 0$). However, based on the power electronic constant switching frequency ω_s and the cascade control structure, the outer control loop (here, the dc-bus energy control) must operate at a cut-off frequency $\omega_E \ll \omega_p$ (a cut-off frequency of the supercapacitor power loop) $\ll \omega_s$. Once the flat outputs are stabilized, the whole system is stable because all the variables of the system are expressed in terms of the flat outputs.

Thus, the nonlinear control law of the dc link stabilization detailed above is portrayed in Fig. 2. The nonlinear control law generates a supercapacitor power reference p_{SCREF} . This signal is limited to a converter maximum power p_{SCMAX} and a minimum power p_{SCMIN} , in which $p_{\text{SCMAX}} \leq p_{\text{SCLimited}}$. p_{SCREF} is then divided by the measured supercapacitor voltage v_{SC} . The supercapacitor power is limited to maintain the supercapacitor current within the nominal values; the reference power is set to zero when the supercapacitor voltage is outside the interval $[V_{\text{SCMIN}}, V_{\text{SCMAX}}]$, as presented in the block "SuperC Current Limitation Function" [13]. This results in a supercapacitor current reference i_{SCREF} .

3.3. Linear control of DC link stabilization

In order to compare the performance of the flatness-based control, a traditional linear PI control method presented in [13] is also implemented on the hybrid test stand. Here, we briefly review this approach. A desired reference for the dc-bus energy is represented by $y_{1\text{REF}}$. A linear feedback PI control law is given by the following expression:

$$p_{\text{SCREF}} = K_p(y_{1\text{REF}} - y_1) + K_i \int_0^t (y_{1\text{REF}} - y_1) d\tau \quad (29)$$

where K_p, K_i are the set of controller parameters. Note that, in power electronics applications, the system composes of many spike signals coming from the high frequency switching of power switching devices. If using a PID controller, differentiation (D) increases the high-frequency gain. A pure differentiator is not proper or causal. When a spike change (or a noisy environment) of the disturbance occurs, differentiation results in a theoretically infinite control signal, called "chaos phenomenon". A filter to the differentiator may be added [46] in consideration of high frequency noise suppression. This is the reasons that in power electronics applications a PI controller (a PID controllers part omitted or switched off) is widely chosen instead of a PID controller [11,12,47].

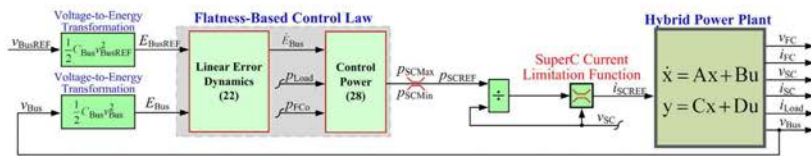


Fig. 2. DC link stabilized fuel cell/supercapacitor hybrid source based on differential flatness control law.

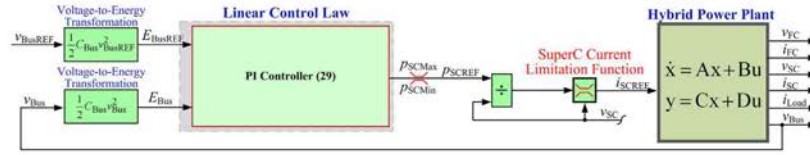


Fig. 3. DC link stabilized fuel cell/supercapacitor hybrid source based on linear PI control law.

Therefore, because the supercapacitor current loop is much faster than the dc link voltage loop (so that it can be considered as a pure unity gain, refer to (6)), the open loop transfer function associated with the dc link voltage regulation can be written as

$$\frac{E_{Bus}(s)}{E_{BusREF}(s)} = \frac{PI-Controller}{(K_p + \frac{K_i}{s})} \cdot \frac{E_{Bus}/P_{SC}}{1} \cdot \frac{P_{SC}/P_{SCREF}}{T_p s + 1} \quad (30)$$

where T_p is the time constant of an equivalent first-order delay of the supercapacitor power regulation loop (or the supercapacitor current regulation loop). Thus, the linear control law of the dc link stabilization detailed above is portrayed in Fig. 3. It is similar to the nonlinear control law (refer to Fig. 2), where the PI controller also generates a supercapacitor power reference p_{SCREF} .

3.4. Performance comparison between linear control and nonlinear control law for DC link stabilization

In order to compare the performance of the flatness-based control and the linear PI control laws, the simulation and test bench were implemented. Simulations with Matlab/Simulink were performed using a reduced-order model of the power plant, as portrayed in Fig. 1. The parameters of the power plant were $V_{BusREF} = 60$ V, $C_{Bus} = 7800$ μ F; $r_{FC} = 0.13$ Ω ; $r_{SC} = 0.08$ Ω ; and $T_p = 2.2$ ms. The supercapacitor module (100 F, 32 V, based on Maxwell Technologies Company) was obtained by means of 12 cells BCAP1200 (capacitance: 1200 F; maximum voltage: 2.7 V) connected in series, as shown in Fig. A2.

The nonlinear controller gains used were $K_{11} = 450$ rad s^{-1} and $K_{12} = 22,500$ rad² s^{-2} , so that the system damping ratio ζ was equal to 1.5, and the natural frequency ω_n was equal to 150 rad s^{-1} . As a result, the cutoff frequency (ω_c) of the closed-loop dc-bus energy was equal to 60 rad s^{-1} , which is lower than the cutoff frequency (ω_p) of the supercapacitor power loop of 600 rad s^{-1} ($T_p = 2.2$ ms), so that the system was stable.

Fig. 4 presents waveforms that are obtained during the large load step. They show the dc bus voltage (the state x_1 , representing the flat output y_1), the supercapacitor voltage, the load power, and the supercapacitor power. The initial state is in no-load power, and the supercapacitor storage device is full of charge, i.e., the supercapacitor voltage = 25 V; as a result, the supercapacitor power is zero. The simulation results in Fig. 4(a) and the real test bench results in Fig. 4(b) were carried out in order to compare the responses to a large load step from 0 W to 880 W at $t = 30$ ms. The results reveal that, corresponding to the dynamics (25) of the observation error, the dynamic response is affected by this kind of oversized perturbation. The small oscillations in v_{Bus} are due to a large proportional gain K_{12} and the vast load step. The value of K_{12} can be reduced to attenuate the oscillations; however, this leads to a slower transition. The simulation also results show excellent concurrence with the experimental data. It should be noted here that the perfect large power load step is very difficult to perform, as can be seen in Fig. 4(b). One can also estimate that the static losses (r_{SC}) in the supercapacitor converter are around 120 W in Fig. 4(b). Therefore, the present mathematical model of the hybrid power plant

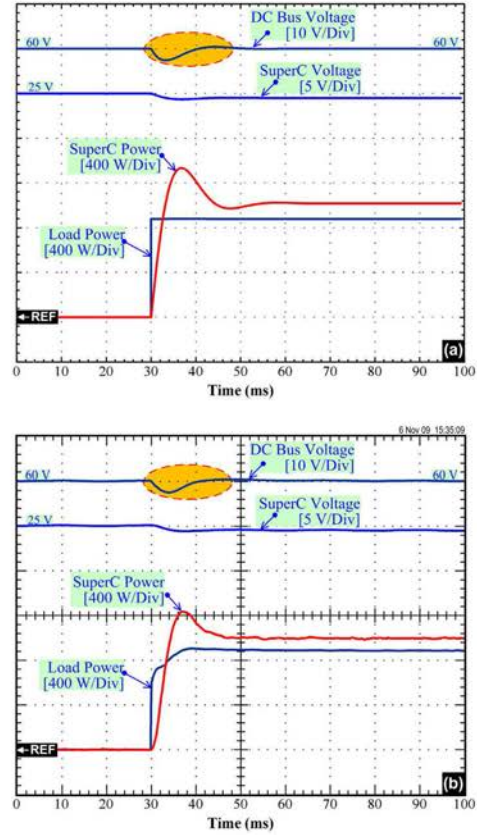


Fig. 4. Flatness-based control law. Response to a large load step from 0 W to 880 W at $t = 30$ ms. (a) Simulation results. (b) Experimental results.

precisely predicts the dynamics of the system when compared to experiment; consequently, the simulation model is a valuable tool for control algorithm validation.

Finally, in order to give a reasonable comparison between the methods, the parameters of the linear controller K_p and K_i were tuned to obtain the best possible performance, and this result is compared to the flatness-based control. In this paper, the symmetrical optimum (SO) is studied [48], [49]. A SO design criterion obtains a controller that forces the frequency response of the system as close as possible to that for low frequencies. The method has the advantage of maximizing the phase margin. As phase margin is maximized for given frequency, the system can tolerate

more delays, which is important for systems having delays. This method optimizes the control system behavior with respect to disturbance input. The method has well established tuning rules and has good disturbance rejection. The resulting performance gives an overshoot of around 43%, settling time around $16.3 \cdot T_p$ and a phase margin of 30° – 60° . Then, by using the SO method, $K_p = 459 \text{ W J}^{-1}$ and $K_i = 40,000 \text{ W (J s)}^{-1}$, so that the desired phase margin is equal to 40° .

Figs. 5 and 6 show simulation and experimental results obtained for both controllers during the large load step. The flatness-based control shows good convergence of the dc bus voltage regulation to its desired reference of 60 V. Although dynamic response of the linear control law could be improved relative to that shown in the figures, this enhancement came at the expense of a reduced stability margin. From these results, we conclude that the flatness-based control provides better performance than the classical PI controller.

Note that, for the specification of the voltage regulation, the dc bus voltage sag is about 5% for a step load change from light load to $\frac{3}{4}$ of nominal load. The dc bus voltage regulation based on the differential flatness approach could be reduced the dc bus voltage sag to 2% or lower by tuning the nonlinear controller gains (K_{11} and K_{12}). In this study, $K_{11} = 450 \text{ rad s}^{-1}$ and $K_{12} = 22,500 \text{ rad}^2 \text{ s}^{-2}$, so that the system damping ratio ζ was equal to 1.5, and the natural frequency ω_n was equal to 150 rad s^{-1} . In order to obtain the higher dynamics or lower voltage drop, the natural frequency ω_n may be increased. Although lower voltage sag could be improved by increasing the defined natural frequency ω_n , this enhancement came at the expense of a reduced stability margin.

3.5. Charging supercapacitor

Again, based on the flatness-base control, we consider the total electrostatic energy E_T stored in the dc bus capacitor C_{Bus} and the supercapacitor C_{SC} as a flat output variable y_2 ; refer to (5),

$$y_2 = E_T = E_{\text{Bus}} + E_{\text{SC}} = \frac{1}{2} C_{\text{Bus}} v_{\text{Bus}}^2 + \frac{1}{2} C_{\text{SC}} v_{\text{SC}}^2 \quad (31)$$

Thus, one defines a control variable $u_2 = p_{\text{FCREF}}$, and a state variable $x_2 = v_{\text{SC}}$. From (4), the state variable x_2 can be written as:

$$x_2 = \sqrt{\frac{2(y_2 - y_1)}{C_{\text{SC}}}} = \varphi_2(y_1, y_2), \quad (32)$$

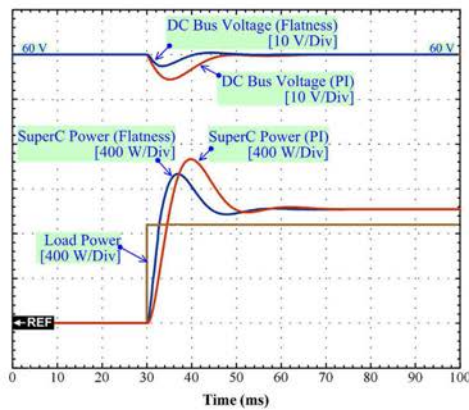


Fig. 5. Simulation results: Comparison of the flatness-based control law with a linear PI control law. Response to a large load step from 0 W to 880 W at $t = 30 \text{ ms}$.

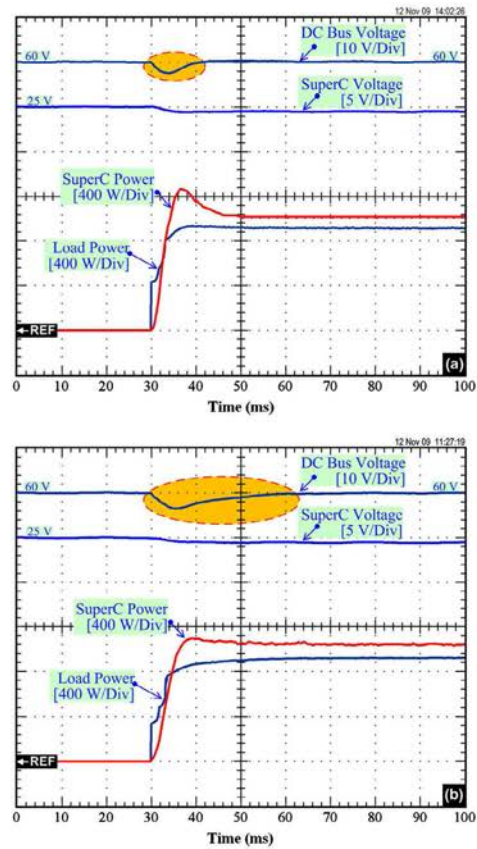


Fig. 6. Experimental results: Comparison of the flatness-based control law with a linear PI control law. Response to a large load step from 0 W to 920 W at $t = 30 \text{ ms}$. (a) Flatness-based control law. (b) Linear PI control law.

From (6), the control variable u_2 can be calculated from the flat output y_2 and its time derivatives:

$$u_2 = 2p_{\text{FLimited}} \cdot \left[1 - \sqrt{1 - \left(\frac{\dot{y}_2 + \sqrt{\frac{2y_1}{C_{\text{Bus}}}} \cdot i_{\text{Load}}}{p_{\text{FLimited}}} \right)^2} \right] = \psi_2(y_1, \dot{y}_2) \quad (33)$$

where

$$p_{\text{FLimited}} = \frac{v_{\text{FC}}^2}{4r_{\text{FC}}} \quad (34)$$

p_{FLimited} is the limited maximum power from the fuel cell converter.

It is apparent that $x_2 = \varphi_2(y_1, y_2)$ and $u_2 = \psi_2(y_1, \dot{y}_2)$ correspond with (16) and (17). Consequently, the mathematical model (the reduced order model) of the hybrid system can be considered as a flat system.

Based on the flatness control law for the total energy regulation (or the supercapacitor energy regulation), a desired reference for the total energy is represented by $y_{2\text{REF}}$. Since the supercapacitor energy storage has an enormous size capacity and the supercapac-

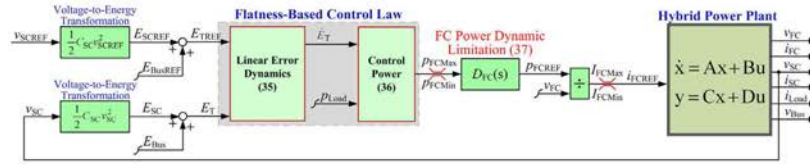


Fig. 7. Supercapacitor charging based on differential flatness-based control law.

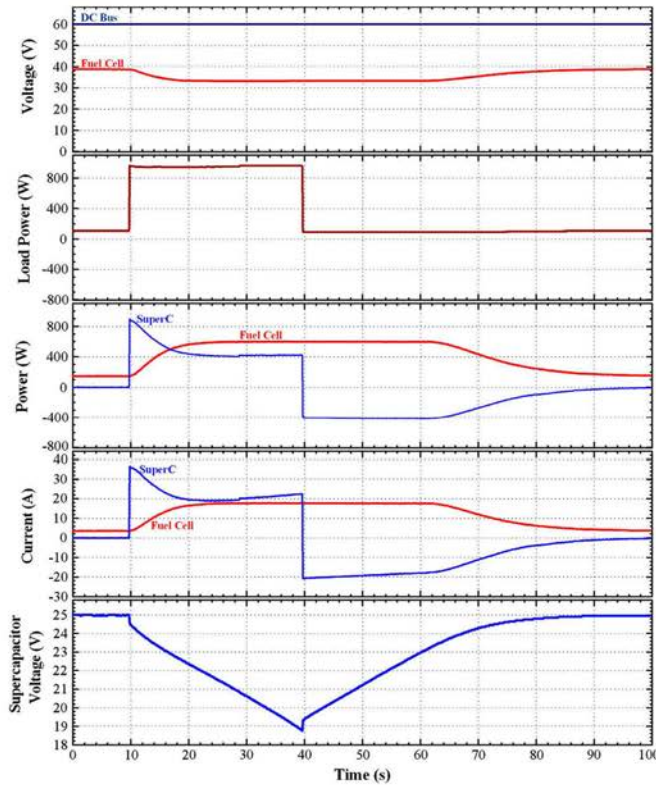


Fig. 8. Experimental results of differential flatness-based control law: hybrid source response during load cycle.

itor energy is defined as a slower dynamic variable than the dc-bus energy variable, the total energy control law is defined as:

$$\dot{y}_2 - \dot{y}_{2REF} + K_{21}(y_2 - y_{2REF}) = 0 \quad (35)$$

Substituting the expression for $\dot{y}_2$ into (33) gives the equation for the closed-loop static state feedback fuel cell power

$$u_2 = 2p_{FCLimited} \cdot \left[1 - \sqrt{1 - \frac{(\dot{y}_{2REF} + K_{21}(y_{2REF} - y_2) + p_{Load})}{p_{FCLimited}}} \right] = p_{FCREF} \quad (36)$$

with $K_{21} > 0$ enforcing tracking convergence.

Fig. 7 depicts the supercapacitor charging algorithm. The total energy control law generates the FC power reference p_{FCREF} . It must

be limited in level, within an interval maximum p_{FCMax} (corresponding to a rated power of the FC, so $p_{FCMax} \leq p_{FCLimited}$) and minimum p_{FCMin} (set to 0 W) and limited in dynamics, which enables the safe operation of the FC with respect to the constraints that are associated with the FC (the prevention of the fuel starvation phenomenon in the FC stack [10]). Here, the second order delay $D_{FC}(s)$ is selected as the FC power dynamic limitation.

$$D_{FC}(s) = \frac{1}{\left(\frac{s}{\omega_{n1}}\right)^2 + \frac{2\zeta_1 s}{\omega_{n1}} + 1} \quad (37)$$

where ω_{n1} and ζ_1 are the regulation parameters. Then, the fuel cell power reference p_{FCREF} is divided by the measured fuel cell voltage v_{FC} . This results in a fuel cell current reference i_{FCREF} . For safety, the fuel cell current reference i_{FCREF} must be limited in level within an

interval [maximum fuel cell current I_{FCMax} (corresponding to a fuel cell rated current), minimum FC current I_{FCMin} (set to 0 A)].

It should be noted here that, for charging the supercapacitor, only the nonlinear control law has been studied, because the differential flatness-based control law shows better performance than the linear control approach.

3.6. System performance of hybrid power source control based on flatness control

The small-scale fuel cell/supercapacitor hybrid power plant implemented in the laboratory is described in Appendix A. For the dc-bus voltage stabilization, the control system parameters are $v_{BusREF} = 60$ V; $C_{Bus} = 7800$ μ F; $r_{FC} = 0.13$ Ω ; $r_{SC} = 0.08$ Ω ; $T_p = 2.2$ ms; $V_{SCMax} = 32$ V; $V_{SCMin} = 15$ V; $I_{SCRated} = 150$ A; $K_{11} = 450$ rad s⁻¹; and $K_{12} = 22,500$ rad² s⁻². For the supercapacitor voltage regulation, the control system parameters are $v_{SCREF} = 25$ V (full of charge); $C_{SC} = 100$ F; $K_{21} = 0.1$ J W⁻¹; $p_{FCMax} = 600$ W; $p_{FCMin} = 0$ W; and $I_{FCMax} = 46$ A (rated), $I_{FCMin} = 0$ A. The parameters for the fuel cell power dynamic delay are $\omega_{h1} = \text{rad s}^{-1}$ and $\zeta_1 = 1$. This value was experimentally determined to be the highest power slope of our fuel cell system, where no fuel starvation occurs. It must be noted here that, for the small-test bench, the FC maximum power p_{FCMax} was set at 600 W; in fact, the rated fuel cell power considered here is 1200 W.

For simulation, the model is tuned to the real system of the 1.2-kW Nexa PEMFC (refer to Fig. A2), using experimental data

$V_{FC} = f(I_{FC})$ and taking 50 operating points to fit the polarization curve (polynomial curve fitting) in a least-squares sense. The stack voltage versus current is governed by the following equation:

$$V_{FC} = a_{6FC}I_{FC}^6 + a_{5FC}I_{FC}^5 + a_{4FC}I_{FC}^4 + a_{3FC}I_{FC}^3 + a_{2FC}I_{FC}^2 + a_{1FC}I_{FC} + a_{0FC} \quad (38)$$

where $a_{6FC} = 5.5991 \times 10^{-8}$; $a_{5FC} = -7.8814 \times 10^{-6}$; $a_{4FC} = 4.2503 \times 10^{-4}$; $a_{3FC} = -0.0114$; $a_{2FC} = 0.1664$; $a_{1FC} = -0.6023$; and $a_{0FC} = 42.62$.

Figs. 8 and 9 present waveforms that are obtained during the load cycle: experimentation and simulation. They show the dc bus voltage (the state variable x_1 , representing the flat output y_1), the FC voltage, the load power, the supercapacitor power, the FC power, the supercapacitor current, the FC current, and the supercapacitor voltage (the state variable x_2 , or the supercapacitor state-of-charge).

The initial state has a load power = 100 W, and the supercapacitor storage device is full of charge, i.e., $v_{SC} = 25$ V; as a result, the supercapacitor power is zero, and the FC power is equal to 100 W for the load power demanded. At $t = 10$ s, the load power steps to a constant value of 1000 W; synchronously, the final FC power increases with a limited slope (second order dynamics) to a limited maximum power of 600 W. Thus, the supercapacitor, which supplies most of the transient power that is required during stepped load, remains in a discharge state after the stepped load

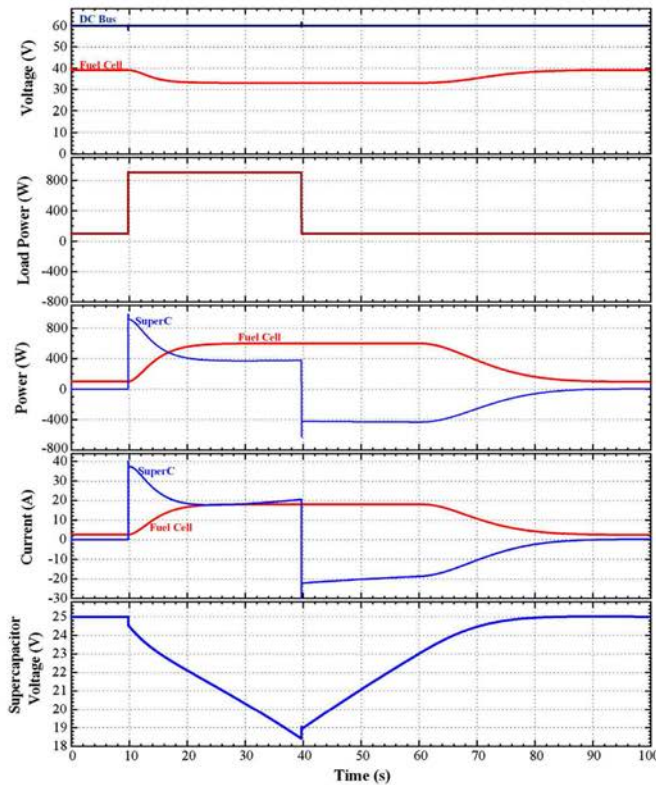


Fig. 9. Simulation results of differential flatness-based control law: hybrid source response during load cycle.

because the steady-state load power (1000 W) is greater than the FC limited maximum power (600 W).

Subsequently, at $t = 40$ s, the load power steps from 1000 W to 100 W. As a result, the supercapacitor changes its state from discharging to charging, demonstrating the three phases. First, the FC supplies its limited maximum power of 600 W for driving the load and for charging the supercapacitor. Second, at $t = 62$ s ($v_{SC} = 23.2$ V), the supercapacitor is nearly fully charged at 25 V, which then reduces the charging power. Third, at $t = 90$ s, the supercapacitor is fully charged, and the supercapacitor charging power is zero. Finally, the FC supplies the constant load power of 100 W.

One can observe that the dc-bus voltage waveform is stable during the constant load power, the large positive load step, and the large negative load step, which is of major importance when employing supercapacitors to improve the dynamic performance of the whole system using the differential flatness-based control law.

4. Conclusion

The key contribution of this paper is to study two dc link stabilization methods (linear and nonlinear) for the control of fuel cell/supercapacitor power plants. The prototype power plant studied was composed of a PEMFC system (the Nexa Ballard FC power generator: 1.2 kW, 46 A) and a supercapacitor module (100 F, 32 V, based on Maxwell Technologies Company). The low voltage dc bus considered here was 60 V. Simulation (by Matlab/Simulink) and experimental results demonstrated the comparisons. The present mathematical model of the hybrid power plant precisely predicts the dynamics of the system when compared to experimental results; accordingly, the simulation model is an essential tool for control algorithm corroboration.

Differential flatness-based control of a FC/supercapacitor power plant of the load rejection transient offers superior voltage response, with smaller voltage dip and shorter recovery time, regardless of the voltage reference setting. This is frequently cited advantage of the nonlinear flatness control [38],[40]. However, the PI controller, being a standard industrial controller solution at present, will continue to be compared to various novel forms of voltage controllers that will emerge in the future (including fuzzy flatness controllers). It is important that, in such cases, a detailed comparative analysis of the system performance is always performed. Comparison based on a single operating point or a single transient is more than obviously insufficient.

However, the flatness-based control requires a load current measurement to estimate the load power in order to obtain the differential flatness property. For the linear control, there is no load current measurement. For future work, a load observer will be used to avoid the measurement of the load current.

Acknowledgments

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Appendix A. Test bench description of fuel cell/supercapacitor hybrid power plant

The small-scale test bench of the hybrid power plant was implemented in our laboratory, as presented in Fig. A1. The FC system used in this effort was a PEMFC system (1.2 kW, 46 A, based on

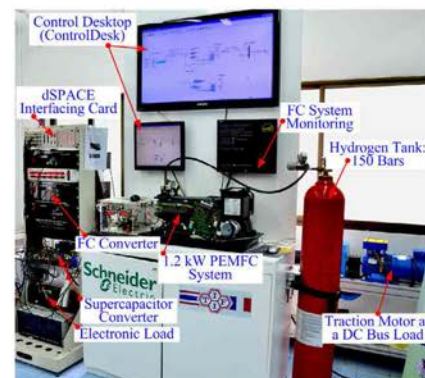


Fig. A1. Experimental setup of the fuel cell/supercapacitor hybrid power plant.



Fig. A2. Supercapacitor module (100 F, 32 V) used in the test bench.

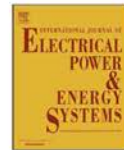
Ballard Power Systems Company). It was supplied with pure hydrogen with a regulated pressure of 10 bars from bottles under a pressure of 150 bars and with clean and dry air from a compressor. The supercapacitor module (100 F, 32 V, based on Maxwell Technologies Company) was obtained by means of 12 BCAP1200 cells (capacitance: 1200 F; maximum voltage: 2.7 V) connected in series, as shown in Fig. A2.

Measurements of the FC current i_{FC} , the supercapacitor current i_{SC} , the load current i_{Load} , the dc bus voltage v_{bus} , the FC voltage v_{FC} , and the supercapacitor voltage v_{SC} were carried out by means of zero-flux Hall effect sensors. The FC and supercapacitor current regulation loops were realized with analog circuits to function at a high bandwidth. The control loops, which generate current references i_{FCREF} and i_{SCREF} , were implemented in the real time card dSPACE DS1104, through the mathematical environment of Matlab–Simulink, with a sampling frequency of 25 kHz.

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Nonlinear single-loop control of the parallel converters for a fuel cell power source used in DC grid applications



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ABSTRACT

This paper presents an innovative control law for a multiphase interleaved converter in the distribution of power supply in fuel cell (FC) generators. Traditionally, to control the DC output power, voltage, or current in a converter, a linear multiple-loop feedback control technique is used. The nonlinear multiple-loop feedback control approach offers several techniques that help to improve the system response. In this paper, an alternative nonlinear single-loop feedback control scheme is proposed. This scheme is based on the differential flatness concept, which provides a solution to achieve the preferred response using a less sophisticated algorithm. To validate the proposed technique, a prototype of a FC power converter (a 600-W two-phase interleaved boost DC–DC converter) was constructed in the laboratory, and the control algorithm was implemented to control the prototype using a dSPACE 1104 controller card. The control scheme exhibited excellent experimental results for use with a 1.2-kW Nexa Ballard polymer electrolyte membrane fuel cell (PEMFC) regarding the steady state and dynamic responses as well as the control robustness.

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Introduction

Renewable energy sources are predicted to become competitive with conventional power generation systems in the near future. As shown in Fig. 1, FCs, which play an important role in supporting electricity demand because of their significant advantages of energy efficiency and emission control, normally require a converter to regulate the DC output voltage when applied to variable power loads [1–3].

In such applications, a parallel DC–DC converter shown in Fig. 2 is a competitive option. The DC–DC converter operates under a feedback control to regulate the output voltage and to enable load sharing. This DC–DC converter with closed-loop control is essentially a nonlinear system. However, the common technique used to control the current and voltage in this nonlinear DC–DC converter is the use of two-loop feedback PI compensators, as shown in Fig. 3(a) (the outer loop is for voltage control and the inner loop is for current control), which is based on linear control theory [4,5].

The subsequent development of nonlinear control techniques, such as the sliding mode control (SMC) and the differential flatness

control approaches shown in Fig. 3(b), has introduced effective means of controlling responses and improving system robustness [6–11]. Multiple-loop feedback control, which is primarily used in complex systems, can increase the sophistication in the design. Two loops are generally required because that is the minimum number of loops required for a set of voltage and current controls.

This paper presents an alternative nonlinear single-loop feedback control based on the differential flatness principle, as shown in Fig. 3(c). This type of feedback control reduces the complexity compared to the common multiple-loop feedback control approach. The most important advantage of the single-loop feedback control is to increase the bandwidth of the feedback control system. The bandwidth of the single-loop feedback control should be limited to about 1/4–1/5 of the switching frequency. On the other hand, the bandwidth of the second loop of the two-loop feedback control should be 1/16–1/25 times of the switching frequency in order to prevent the disturbance, which may impact the stability of the controller [12]. However, the complexity of the single-loop control equations can be easily calculated the duty ratios by a controller. By applying the single-loop feedback control based on the differential flatness concept, the dynamic response of the inductor current and the total static energy changes according to its reference; as a result, the inductor current of any phase is maintained

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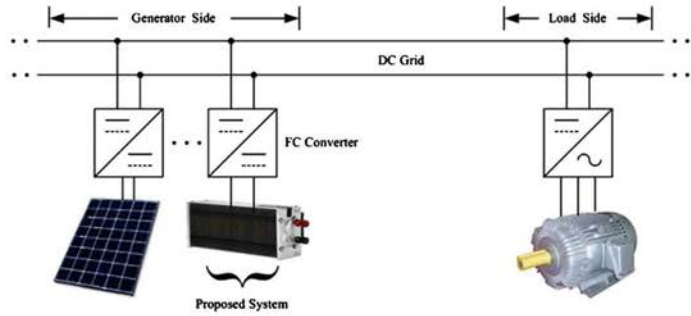


Fig. 1. DC distributed system supplied by renewable energy.

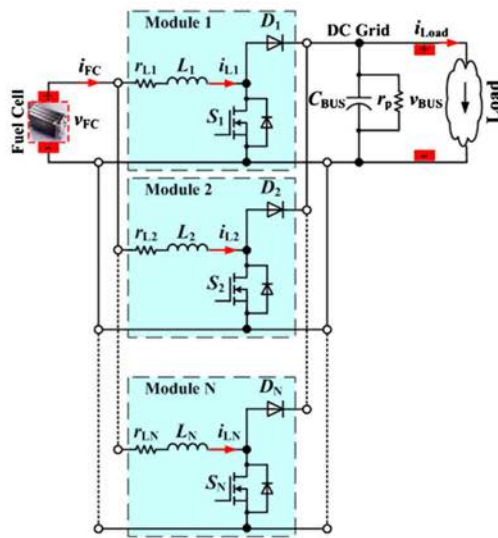


Fig. 2. FC converter: parallel boost converters for FC applications.

by balancing the currents against each other. Moreover, the system is to be controllable and observable under the operation of the differential flatness strategy.

The content of this paper is organized as follows. The structure and model describing the multiphase step-up converter with the parallel switching technique is presented in Section 'Power converter modeling'. A brief introduction to the differential flatness principle and strategies that are used to control the inductor current and the total static energy trajectories are presented in Section 'Control strategy'. The experimental setup and results that validate the proposed control method are described in Section 'Experimental validation'. Finally, the concluding remarks are presented in Section 'Conclusion'.

Power converter modeling

Principally, high-current low-voltage converters are required by reason of the electrical properties of FCs [2,3]. A conventional step-up converter is generally chosen as a FC converter. Nevertheless,

when the power expands the conventional converters will be limited. To overcome this limitation, the utilization of a parallel power converter (multiphase converters in parallel) with an interleaved technique can provide improved performance [9,10]. However, the previous researches [9,10] implemented the converter using a multiple-loop control approach. As a basic principle, the interleaved technique consists of phase shifting the control signals of various converter cells N in parallel [2,7]. The schematic diagram of the proposed multiphase interleaved boost converter for FC applications is shown in Fig. 2. In the case of ideal converters, with the equivalent series and parallel resistances representing losses, the state equation of the converter and the output voltage shown in Fig. 2 are given as:

$$\frac{di_{LK}}{dt} = \frac{1}{L_K} [v_{FC} - r_{LK}i_{LK} - (1 - d_K)v_{BUS}] \quad (1)$$

$$\frac{dv_{BUS}}{dt} = \frac{1}{C_{BUS}} \left[\sum_{K=1}^N (1 - d_K)i_{LK} - \frac{v_{BUS}}{r_p} - i_{LOAD} \right] \quad (2)$$

where $K = \{1, 2, 3, \dots, N\}$, d_K is the duty cycle of the pulsewidth modulation (PWM) converter, v_{FC} is the FC voltage, i_{FC} is the FC current, L_K is the input inductance, i_{LK} is the inductor current in branch K , i_{LOAD} is the load current, v_{BUS} is the DC bus voltage, C_{BUS} is the total output capacitance at the DC bus, and r_{LK} is the series resistance of inductor L_K . Note that r_{LK} and r_p represent the static losses in each boost converter module. The method to obtain these resistances is given in [11].

Control strategy

Differential flatness principle

The concept of the differential flatness principle was first introduced by Fliess et al. [13]. This concept allowed an alternate representation of the system involving the use of trajectory planning and nonlinear systems applied across the various implemented engineering concepts, as demonstrated in the following examples: the control of the cathode pressure and the oxygen excess ratio of a PEMFC system [14]; the control of an inverted pendulum and a vertical takeoff and landing in avionic applications [13]; the current control for three-phase three-wire boost converters [15]; and the reactive power and DC output voltage tracking control of a three-phase voltage source converter [16]. Because the flatness-based control is a model based method, we expect it to have some sensitivity to error in the model parameters. In addition, in [16], the authors demonstrated that the flatness-based control is robust and can provide an improved dynamic tracking performance relative to a classical linear control technique (e.g., a PI controller).

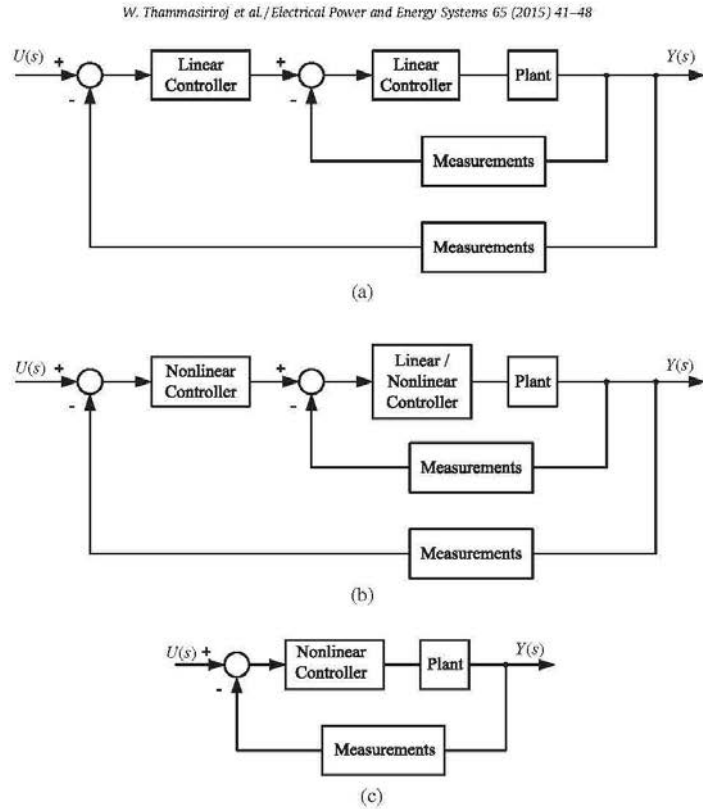


Fig. 3. Control structures for a power electronics converter: (a) linear two-loop feedback control, (b) nonlinear two-loop feedback control, and (c) nonlinear single-loop feedback control.

Briefly, a nonlinear system is flat [17–18] if there exists a set of differentially independent variables (equal in number to the number of inputs) such that all state variables $\mathbf{x}$ and flat input variables $\mathbf{u}$ can be expressed in terms of those flat output variables $\mathbf{y}$ and a finite number of their time derivatives without integrating the differential equations [13]. Especially, the system is flat if the system has state variables $\mathbf{x} \in \mathbb{R}^n$, flat input variables $\mathbf{u} \in \mathbb{R}^m$, and flat output variables $\mathbf{y} \in \mathbb{R}^m$ that can be found of the form [13]:

$$\mathbf{y} = \phi(\mathbf{x}, \mathbf{u}, \dot{\mathbf{u}}, \dots, \mathbf{u}^{(q)}) \quad (3)$$

such that

$$\mathbf{x} = \varphi(\mathbf{y}, \dot{\mathbf{y}}, \dots, \mathbf{y}^{(p)}) \quad (4)$$

$$\mathbf{u} = \psi(\mathbf{y}, \dot{\mathbf{y}}, \dots, \mathbf{y}^{(p+1)}) \quad (5)$$

with $\text{rank}(\phi) = m$, $\text{rank}(\psi) = m$, and $\text{rank}(\varphi) = n$.

Flatness of the power converters

To control the energy in the system, the total static energy of the system is defined as a flat output y_T , which can be expressed as:

$$y_T = \sum_{k=1}^N \frac{1}{2} L_k i_{Lk}^2 + \frac{1}{2} C_{BUS} v_{BUS}^2 \quad (6)$$

From (1) and (2), if we assume the losses of the system become zero ($r_{Lk} = 0$ and $r_p \approx \infty$) and substitute into (6), the first and second order differential equations of y_T can be written as:

$$\dot{y}_T = v_{FC} \sum_{k=1}^N i_{Lk} - v_{BUS} i_{Load} \quad (7)$$

$$\ddot{y}_T = v_{FC}^2 \left(\sum_{k=1}^N \frac{1}{L_k} \right) - v_{FC} v_{BUS} \left(\sum_{k=1}^N \frac{1-d_k}{L_k} \right) \quad (8)$$

Therefore, the state variable v_{BUS} can be given by

$$v_{BUS} = \varphi(i_{Lk}, y_T, \dot{y}_T, \ddot{y}_T) \quad (9)$$

where i_{Load} is a function of v_{BUS} , and v_{FC} is approximately constant compared with the other variables.

To control the inductor current balance between the converters, we assume i_{L1} to be a reference inductor current and define another flat output variable y_K :

$$y_K = i_{L1} - i_{LK}, \quad \forall K \in \{2, \dots, N\} \quad (10)$$

For this system, we choose the flat output vector from (6) and (10):

$$\mathbf{y} = [y_T, y_2, \dots, y_N]^T \quad (11)$$

Then, we define the state variables $\mathbf{x}$ as follows:

$$\mathbf{x} = [i_{L1}, i_{L2}, \dots, i_{LN}, v_{BUS}]^T \quad (12)$$

The summation of all the inductor currents is the FC current:

$$i_{FC} = i_{L1} + i_{L2} + \dots + i_{LN} \quad (13)$$



Obviously, the control system is stable for $\lambda_{K1}, \lambda_{K2} > 0$ ($\zeta_K, \omega_K > 0$). Fig. 4 depicted the proposed control law of the inductor currents detailed above.

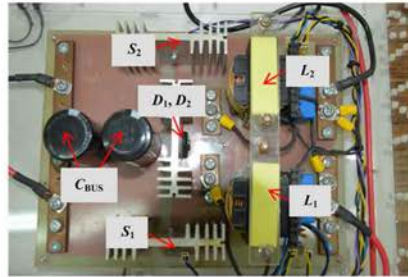


Fig. 5. Prototype of the two-phase parallel boost converter.

Second, the desired reference trajectory is the total energy reference trajectory $y_{T REF}$. The following equation expresses a linear closed-loop control law achieving an asymptotic error tracking $y_T - y_{T REF}$ of the trajectory.

$$(\ddot{y}_T - \ddot{y}_{T REF}) + \lambda_{T1}(\dot{y}_T - \dot{y}_{T REF}) + \lambda_{T2}(y_T - y_{T REF}) + \lambda_{T3} \int (y_T - y_{T REF}) d\tau = 0 \quad (28)$$

where the set of controller parameters $(\lambda_{T1}, \lambda_{T2} \text{ and } \lambda_{T3})$ is chosen. If we define $e_T = y_T - y_{T REF}$, we obtain

$$\ddot{e}_T + \lambda_{T1}\dot{e}_T + \lambda_{T2}e_T + \lambda_{T3} \int e_T d\tau = 0 \quad (29)$$

As mentioned earlier, a desired characteristic polynomial $c_T(s)$ is optimized by the designed root locations. The desired characteristic equation and controller parameters are expressed as:

$$c_T(s) = (s + p)(s^2 + 2\zeta_T\omega_T s + \omega_T^2) \quad (30)$$

$$\lambda_{T1} = 2\zeta_T\omega_T + p \quad (31)$$

$$\lambda_{T2} = 2\zeta_T\omega_T p + \omega_T^2 \quad (32)$$

$$\lambda_{T3} = \omega_T^2 p \quad (33)$$

where ζ_T , ω_T and p are the desired damping ratio, angular frequency and pole of the compensator, respectively. By using this control law, the DC bus voltage always tracks its reference.

To control the system using differential flatness properties, the calculated references are replaced into their measured values to calculate the duty cycles in (20) and (21). The duty cycles d_1 and d_2 are therefore expressed by:

$$d_1 = \frac{1}{((L_1 + L_2)\dot{i}_{LK REF} + \frac{C_{BUS}v_{BUS REF}v_{FC}}{i_{load}})} \left[L_1 v_{BUS REF}^2 \left(-\dot{i}_{load} + 2\dot{i}_{LK REF} + \frac{L_2 \dot{i}_{LK} \ddot{y}_{2REF}}{v_{FC}} \right) + \frac{L_1 C_{BUS} v_{BUS REF}^2}{2\dot{i}_{load}} \left(-\frac{2\dot{i}_{LK}}{\dot{i}_{load}} + \frac{v_{FC}}{L_1} + \frac{v_{FC}}{L_2} + \dot{y}_{2REF} + \frac{\ddot{y}_{T REF}}{v_{BUS REF}} \right) \right] \quad (34)$$

$$d_2 = \frac{1}{((L_1 + L_2)\dot{i}_{LK REF} + \frac{C_{BUS}v_{BUS REF}v_{FC}}{i_{load}})} \left[L_2 v_{BUS REF}^2 \left(-\dot{i}_{load} + 2\dot{i}_{LK REF} - \frac{L_1 \dot{i}_{LK} \ddot{y}_{2REF}}{v_{FC}} \right) + \frac{L_2 C_{BUS} v_{BUS REF}^2}{2\dot{i}_{load}} \left(-\frac{2\dot{i}_{LK}}{\dot{i}_{load}} + \frac{v_{FC}}{L_1} + \frac{v_{FC}}{L_2} - \dot{y}_{2REF} + \frac{\ddot{y}_{T REF}}{v_{BUS REF}} \right) \right] \quad (35)$$

Even though, the duty cycles shown in (34) and (35) seem to be more complicated than the results of the classical multiple-loop strategies, the duty cycles can be easily substituted and calculated by a controller. However, the single-loop control can reduce the design complexity of the multiple-loop ones by the systematic design as shown before.

Finally, the FC power dynamic limitation enables safe operation of the FC [9]. To obtain a linear transfer function, a second-order filter $G_F(s)$ is selected for controlling the FC power dynamics.

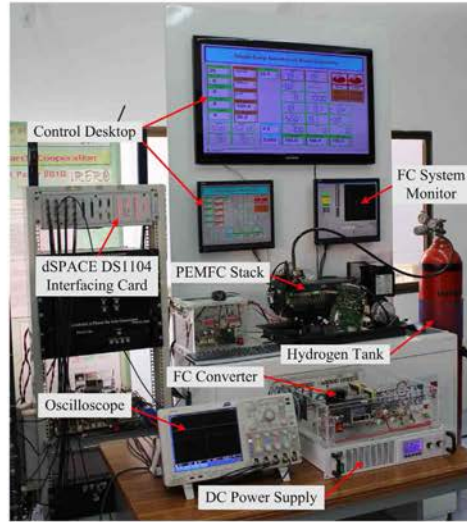


Fig. 6. System test bench.

Table 2
Flatness control and dynamic limitation parameters.

Parameters	Descriptions	Values
ζ_2	Damping ratio of $c_2(s)$	1
ω_2	Natural frequency of $c_2(s)$	157 rad s ⁻¹
ζ_T	Damping ratio of $c_T(s)$	1
ω_T	Natural frequency of $c_T(s)$	314 rad s ⁻¹
p	Desired pole of $c_T(s)$	628 rad s ⁻¹
ζ_F	Damping ratio of $G_F(s)$	1
ω_F	Natural frequency of $G_F(s)$	0.4 rad s ⁻¹

$$G_F(s) = \frac{1}{\left(\frac{s}{\omega_F}\right)^2 + \frac{2\zeta_F}{\omega_F}s + 1} \quad (36)$$

where ω_F and ζ_F are the regulation parameters.

In addition, the reference of the FC current $i_{FC REF}$ and the inductor current $i_{LK REF}$ can approximately be expressed by

$$i_{FC REF} = \frac{v_{BUS} \dot{i}_{load}}{v_{FC} - \sum_{k=1}^N \frac{1}{i_{LK}}} \quad (37)$$

$$i_{LK REF} = \frac{i_{FC REF}}{N} \quad (38)$$

Experimental validation

Description of the test bench

The parameters of the two-phase interleaved converter are detailed in Table 1 and portrayed in Fig. 5. A small-scale test bench as illustrated in Fig. 6 was implemented in the laboratory. The PEMFC system (a Nexa Ballard PEMFC power generator: 1.2 kW, 26 V, 46 A) was used as the DC power supply of the system to test the system characteristics and determine the steady state behaviors. A separate constant DC power supply was used to test the transient response and control system robustness. The feedback control loop detailed in Fig. 4 was implemented through the

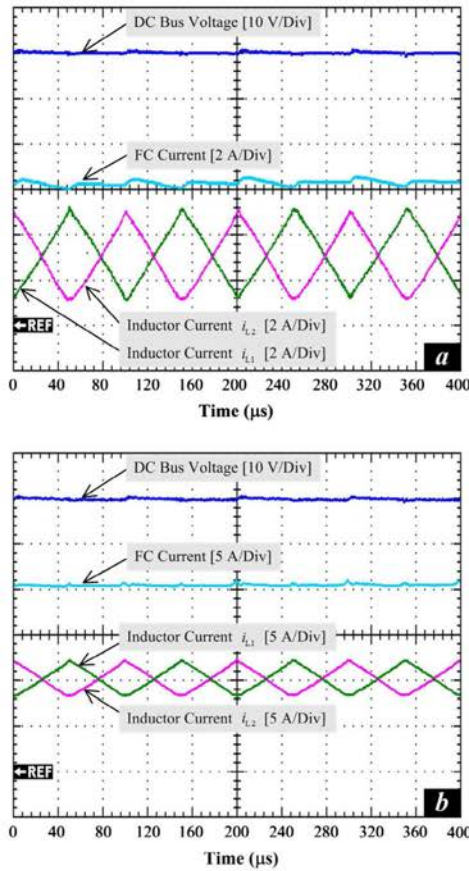


Fig. 7. Steady-state characteristics of the converter at the load powers of (a) 200 W, and (b) 600 W.

controller card dSPACE DS1104 platform as shown in Fig. 6. The converter operated at a switching frequency of 10 kHz. The nonlinear controller parameters used for controlling the system energy and balancing the inductor currents are listed in Table 2.

Experimental results

- (1) *Steady state test using the FC converter supplied by a PEMFC:* The experimental waveforms in Fig. 7 describe the steady-state responses of the interleaved converters at the output power reference of 200 W in Fig. 7(a) and 600 W in Fig. 7(b). Summation of the two inductor currents resulted in the FC current exhibiting lower current ripple compared to its original inductor currents. This result highlights the advantage of multiphase DC–DC converters. The upper trace displays the output DC voltage that met the set point of 60 V. Note that the two phases of the inductor current shared an equal average current value with the out-of-phase waveforms. Moreover, these two phase current waveforms cancel each other and thus reduce the FC input-ripple current caused by the interleaved switching technique. It should

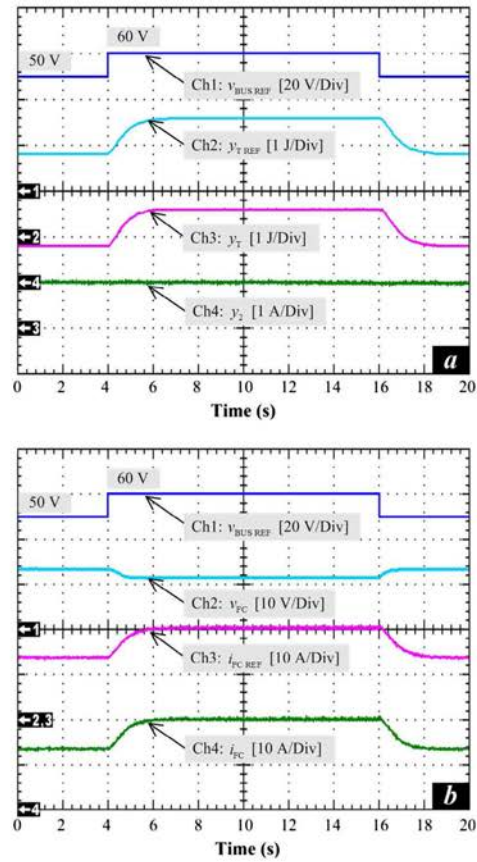


Fig. 8. Dynamic responses when the DC bus voltage reference $v_{BUS REF}$ is changed from 50 V to 60 V at $t = 4$ s and from 60 V to 50 V at $t = 16$ s. (a) Flat output variable and its reference. (b) FC voltage and current and its reference.

be note that if the output power level decreases the converter may go into discontinuous conduction mode (DCM). To avoid DCM, the converter must have bidirectional capability by replacing the output diodes with controlled switches. However, it is beyond this paper.

- (2) *Dynamic performance test using the FC converter supplied by a PEMFC:* As shown in Fig. 8, the test started with the DC bus voltage reference of 50 V (Ch1). Subsequently, at $t = 4$ s it was stepped up to 60 V and remained for 12 s before stepping back to 50 V thereafter. In Fig. 8(a), Ch2 and Ch3, which represents the total static energy reference and measured total static energy, respectively, exhibited a good result of the tracking system. Likewise, in Fig. 8(b), Ch3 and Ch4, which represents the FC current and its reference, were both in phase; as a result, the flat output y_2 [Ch4 in Fig. 8(a)] is nearly zero. Therefore, the response of the inductor currents in the converter verified the highly controlled response using the flatness properties with only one loop control structure. However, Ch4 in Fig. 8(b) shows a variation of the FC current depending on the output voltage because the resistive load was constant during the experimentation.

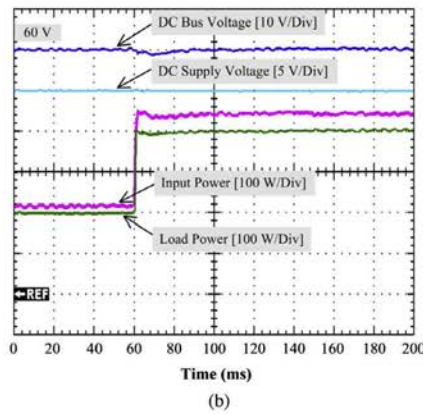
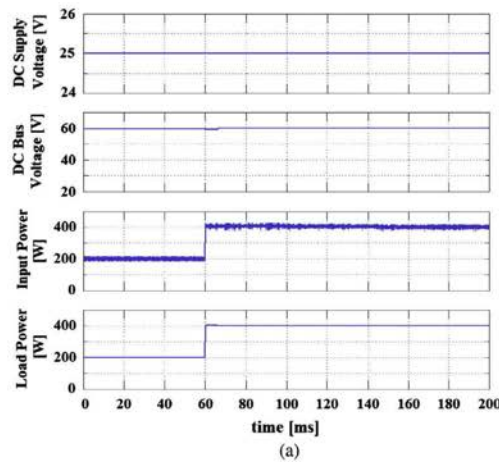


Fig. 9. The dynamic characteristics of the power converter during a step load change from 200 W to 400 W at $t = 60$ ms. (a) Simulation waveforms, (b) Experimental waveforms.

(3) **Control robustness test using the FC converter supplied by a DC power supply:** Because the FC generator has slow dynamics by nature, it is dangerous to perform dynamic testing on an FC stack [19–22]. Therefore, instead of a FC, this dynamic testing was supplied by a 25-V DC power supply. The simulation and oscilloscope waveforms in Fig. 9(a) and (b) shows the dynamic response of the dc bus voltage dynamics to the load power demands (disturbance) from 200 W to 400 W. The proposed controller demonstrates good stability and an optimum response (no oscillation and a short settling time) for the regulation of the dc bus voltage to the desired reference of 60 V.

To substantiate the robustness and dynamic regulation of the dc-bus voltage using the proposed control scheme, Fig. 10 illustrates waveforms that were obtained during the presence of a large load step. Using the exact model resulted in the rapid response in the output voltage loop to reject the perturbation. Despite the errors in the converter model, the system was still able to function, and the waveforms obtained in Fig. 10(a) were quite similar to

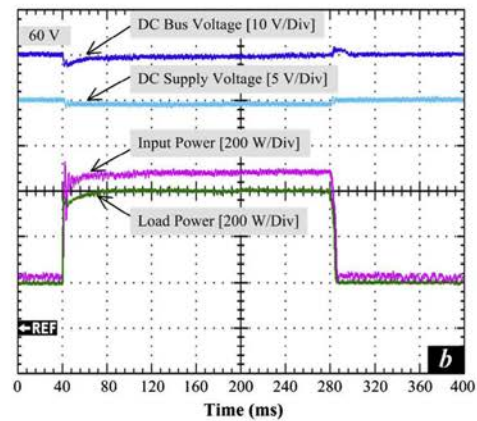
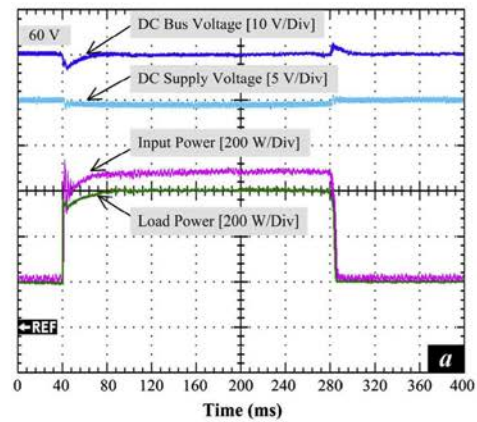


Fig. 10. Comparison of the DC bus voltage regulation (DC link stabilization) of the power plant during a large load step. (a) Exact model ($r_{L1} = 0.10 \Omega$, $r_{L2} = 0.12 \Omega$, $r_p = 250 \Omega$). (b) Error model (robustness) ($r_{L1} = r_{L2} = 0 \Omega$ and $r_p \approx \infty \Omega$).

those measured in Fig. 10(b). The DC bus voltage ripple swing could be easily improved by increasing either the capacitance C_{BUS} or the angular frequency.

This paper profoundly presents the concept and experiments of the single-loop control. However, the multiple-loop control was previously presented in the reference [9]. Additionally, the dynamic response of this strategy (switching frequency = 10 kHz) is faster than the experimental results shown in the reference (switching frequency = 25 kHz) as the reason explained before.

Conclusion

In this paper, a nonlinear single-loop feedback control scheme based on the differential flatness concept was proposed for use in a multiphase parallel converter. This scheme offers an alternative solution that reduces the sophistication of the algorithm design while effectively achieving the preferred response. Validation of the proposed scheme was achieved by demonstrating control of a prototype set of a fuel cell stack with a 600-W two-phase boost converter connected in parallel, which was implemented through

a dSPACE 1104 controller card. Three aspects of the control scheme were verified, including steady state response, dynamic response, and control robustness. The experiments exhibited overall good results, which implied that this designed scheme has the potential to be applied in FC generator applications, as well as in a hybrid power source system, such as hybrid electric vehicles.

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Abstract: This paper presents a new energy control algorithm for dc-grid stabilization in weak transportation networks that employ supercapacitors as the energy storage unit. For safety reason and higher voltage conversion gain, a ground isolated converter based on a dual active bridge topology is presented. Using a nonlinear control approach based on the flatness property, we propose a simple solution to dynamic and stabilization problems in the power electronics systems of transportation networks. Furthermore, high dynamics in the disturbance rejection are achieved, which is the key contribution described in this paper. To validate the proposed method, a hardware system is modeled using digital estimation with a DS1103 dSPACE controller platform. We analyze a prototype small-scale network that uses a 1 kW six-pulse rectifier as a dc main station and a 250 F, 32 V supercapacitor bank as an energy storage substation. Finally, the utility of the control algorithm is validated using experimental results measured during motoring mode, ride-through, and braking mode drive cycles.

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TRANSPORTATION RESEARCH PART C: EMERGING TECHNOLOGIES | 1

Energy Management of a Ground Isolated Magnetic Coupling Converter for Supercapacitor Based Transportation Applications

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ABSTRACT

This paper presents a new energy control algorithm for dc-grid stabilization in weak transportation networks that employ supercapacitors as the energy storage unit. For safety reason and higher voltage conversion gain, a ground isolated converter based on a dual active bridge topology is presented. Using a nonlinear control approach based on the flatness property, we propose a simple solution to dynamic and stabilization problems in the power electronics systems of transportation networks. Furthermore, high dynamics in the disturbance rejection are achieved, which is the key contribution described in this paper. To validate the proposed method, a hardware system is modeled using digital estimation with a DS1103 dSPACE controller platform. We analyze a