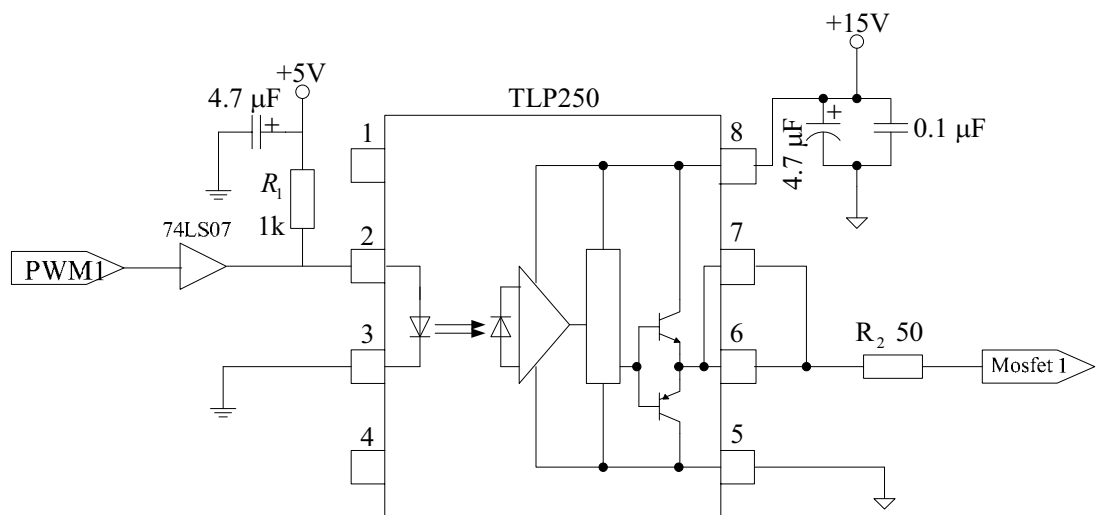


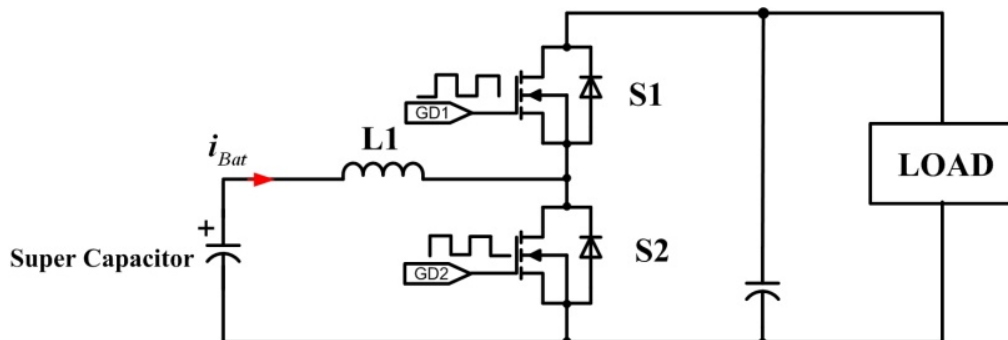
2.2.2.4 วงจรขับเกต (Gate Driver) เพื่อความสะดวกในการต่อใช้งานและให้วงจรขับมีขนาดเล็ก จึงใช้ไอซีสำเร็จรูปเบอร์ TLP 250 ขนาด 8 ขา ซึ่งในวงจรทบทแรงดันขนาด 2 เฟส จะต้องทำการสร้างวงจรขับเกตขึ้นมาทั้งหมด 2 วงจรเพื่อทำหน้าที่ขับเกตของมอสเฟตทั้ง 2 ตัว จากภาพที่ 2-18 สัญญาณอินพุตจากไมโครคอนโทรลเลอร์เข้ามายังขา 2 และขา 3 ของ TLP250 เพื่อจัดไบอัสให้แก่โฟลโตไดโอดที่ต่ออยู่ภายในตัวไอซี TLP250 ระหว่างขา 2 และขา 3 โดยที่ขา 2 ของ TLP250 ต่อเข้ากับ Vcc (+5 V) เพื่อรักษาระดับของแรงดันให้คงที่ ทำให้โฟลโตไดโอดทำงานได้อย่างเต็มที่ ซึ่งจะต่อ Pull up ตัวต้านทาน 1 k Ω ทำหน้าที่ควบคุมกระแสที่ไหลผ่านออปโตคัปเปอเรอร์ โดยสัญญาณเอาต์พุตจะได้ตามคุณสมบัติของไอซี ซึ่ง TLP 250 มีลักษณะเป็นไปตามสัญญาณอินพุตที่ป้อนเข้ามา แต่มอสเฟตกำลังเป็นอุปกรณ์สวิตช์กำลังที่ต้องการแรงดันควบคุมให้มอสเฟตกำลังทำงาน ดังนั้นสัญญาณที่เข้ามาควบคุมจะต้องเป็นสัญญาณพัลส์ที่สามารถทำให้มอสเฟตกำลังทำงานได้และหยุดทำงานได้รวดเร็วตามความต้องการซึ่งจะต้องเป็นสัญญาณพัลส์แบบสี่เหลี่ยม โดยที่ไอซี TLP 250 ถูกจัดวงจรตามคุณสมบัติของไอซีคือจะได้รับการป้อนแรงดันไฟตรง 15 V เข้าที่ขา 8 และต่อกราวด์เข้าที่ขา 5 ของไอซี โดยสัญญาณเอาต์พุตที่จะออกมาจากขา 6 และขา 7 ของไอซีเมื่อเทียบกับกราวด์ที่ขา 5 ของไอซี สัญญาณที่ได้ออกมาเป็นพัลส์จะมีระดับของสัญญาณอยู่ที่ +15 V ตามแหล่งจ่ายไฟที่ป้อนให้กับไอซีและความถี่ที่ได้จะเท่ากับความถี่ของสัญญาณอินพุตที่ป้อนให้กับไอซีและ R2 จะเป็นตัวควบคุมกระแสที่ จะไหลผ่านไปยังขา G ของเพาเวอร์มอสเฟตและเมื่อทำการวัดระดับสัญญาณที่ได้ที่ขา G และขา S ของเพาเวอร์มอสเฟตสัญญาณที่ได้เหมาะสมกับความต้องการของมอสเฟตกำลังที่สามารถทำงานเป็นสวิตช์ได้



ภาพที่ 2-18 วงจรขับเกต

2.3 ตัวแปลงไฟสำหรับแบตเตอรี่ชนิดซูเปอร์คาปาซิเตอร์

2.3.1 การออกแบบวงจรกำลังของวงจรทบทรงดันไฟฟ้ากระแสตรง (2-Quadrant Converter)



ภาพที่ 2-19 วงจรบูสต์คอนเวอร์เตอร์ 2 ทิศทาง

จากภาพที่ 2-19 เป็นส่วนของวงจรทบทรงดันแบบ 2 ทิศทาง มีมอสเฟตกำลังทำหน้าที่เป็นสวิตช์รับคำสั่งการสวิตช์มาจากตัวขับเคลื่อนที่จุด GD1 และ GD2 ในวงจรกำลังจะประกอบไปด้วยการออกแบบส่วนต่างๆ ดังนี้

2.3.1.1 การคำนวณหาค่าตัวเหนี่ยวนำความถี่สูง ในวงจรทบทรงดันไฟฟ้ากระแสตรง ตัวเหนี่ยวนำเป็นอุปกรณ์ที่สำคัญมาก เนื่องจากมีหน้าที่ในการเก็บและคายพลังงานเป็นผลให้ระดับแรงดันทางเอาต์พุตมีค่าสูงกว่าระดับแรงดันที่อินพุตการคำนวณหาค่าของตัวเหนี่ยวนำสามารถหาได้จากสมการ

$$L_{\min} = \frac{D(1-D)^2 R}{2f} \quad (2-16)$$

เมื่อ $L_{\min}$ คือค่าตัวเหนี่ยวนำต่ำสุดที่สามารถใช้งานได้
 f คือความถี่ที่ใช้ในวงจร มีค่า 25 kHz
 R คือค่าความต้านทานโหลดของวงจรหาได้จาก

$$R = \frac{V_{bus}^2}{Po_{\min}} \quad (2-17)$$

เมื่อ V_{bus} คือแรงดันด้านออกของวงจรที่ต้องการมีค่า 60 V
 $Po_{\min}$ คือกำลังทางด้านเอาต์พุตที่ให้ประสิทธิภาพต่ำสุดหาได้จากสมการที่ (2-18)

$$\eta_{\min} = \frac{Po_{\min}}{Pi_{\max}} \quad (2-18)$$

$\eta_{\min}$ คือประสิทธิภาพต่ำสุดของวงจรที่ต้องการคือ 80 เปอร์เซ็นต์
 $Pi_{\max}$ คือกำลังทางดำนอินพุตที่ให้ประสิทธิภาพต่ำสุด หาได้จากสมการที่ (2-19)

$$Pi_{\max} = V_{bat\max} i_{bat\max} \quad (2-19)$$

$V_{bat\max}$ คือแรงดันของแบตเตอรี่สูงสุดคือ 24 V
 $i_{bat\max}$ คือกระแสของแบตเตอรี่สูงสุดคือ 20 A
 แทนค่าลงในสมการที่ (2-19)

$$Pi_{\max} = 24 \times 20 = 480 \text{ W}$$

แทนค่า $Pi_{\max}$ ลงในสมการที่ (2-18) เพื่อหา $Po_{\min}$

$$Po_{\min} = \eta_{\min} Pi_{\max}$$

$$Po_{\min} = \frac{80}{100} \times 480 = 384 \text{ W}$$

แทนค่า $Po_{\min}$ ลงในสมการที่ (2-17)

$$R = \frac{V_{bus}^2}{Po_{\min}} = \frac{60^2}{384} = 9.357 \Omega$$

จากสมการที่ (2-1) D คือดิวิตีไซเคิล หาได้จาก

$$D = 1 - \frac{V_{bat}}{V_{bus}} \quad (2-20)$$

เมื่อ V_{bat} คือ แรงดันอินพุต มีค่า 24 V
 แทนค่าลงในสมการที่ (2-20)

$$D = 1 - \frac{24}{60} = 0.6$$

แทนค่าลงในสมการที่ (2-16) เพื่อหาค่าตัวเหนี่ยวนำ

$$L_{\min} = \frac{0.6(1-0.6)^2 \times 9.375}{2 \times 25 \times 10^3} = 18 \mu\text{H}$$

ดังนั้นจึง เลือกใช้ขดลวดพันบนแกน EE55 คำนวณหาจำนวนรอบของขดลวดได้จาก

$$N = \frac{LI_{\text{peak}}}{B_{\text{max}} S}$$

เมื่อ	N	คือจำนวนรอบของขดลวด
	I_{peak}	คือกระแสสูงสุดที่ไหลในขดลวด มีค่า 10 A
	B_{max}	คือความเข้มฟลักซ์สูงสุดได้จากกราฟ BH Curve มีค่า 0.025 T
	S	คือพื้นที่ของแกน EE55 มีค่า 354 mm^2

$$N = \frac{18 \times 10^{-6} \times 10}{0.012 \times 10^{-6} \times 354} = 42.37 \text{ รอบ}$$

2.3.1.2 การเลือกอุปกรณ์สวิตชิง อุปกรณ์สวิตชิงในวงจรทบทแรงดันไฟฟ้ากระแสตรงควรเลือกอุปกรณ์ที่ทำงานได้ดีที่ความถี่สูง เวลาในการเปลี่ยนสถานะค่อนข้างสั้น ในการวิจัยนี้ได้เลือกใช้มอสเฟตกำลังทำหน้าที่เป็นอุปกรณ์สวิตชิง เพราะนอกจากสามารถทำงานที่ความถี่สูงได้ตั้งแต่ 30 kHz ไปจนถึง 400 kHz เวลาในการสวิตชิ่งอยู่ในช่วงนาโนวินาที และในวงจรขั้วมอสเฟตกำลังนั้นทำได้ง่ายเพราะควบคุมด้วยแรงดันและต้องการกระแสอินพุตค่าต่ำๆ เท่านั้น

โดยได้เลือกใช้เพาเวอร์มอสเฟตเบอร์ IRFP264 ของบริษัท International Rectifier IR มีคุณลักษณะสมบัติต่าง ๆ ที่สำคัญดังนี้ ความต้านทานระหว่างขาเดรนและซอร์ส ขณะนำกระแส $R_{DS(on)} = 0.075 \Omega$ ซึ่งมีค่าต่ำมาก แรงดันตกคร่อมระหว่างขาเดรนและขาซอร์ส (V_{DS}) ที่ทนได้ 250 V กระแสเดรน (I_D) สูงสุดที่สามารถไหลผ่านได้ 38 A เวลาคืนสภาพของเพาเวอร์มอสเฟต $t_{rr} = 620 \text{ ns}$

2.3.1.3 การคำนวณค่าตัวเก็บประจุด้านเอาต์พุต ในวงจรกำลังของวงจรทบทแรงดันไฟฟ้าตัวเก็บประจุด้านเอาต์พุตของวงจรมีหน้าที่ในการเก็บพลังงานในรูปของประจุไฟฟ้าและทำการจ่ายแรงดันออกให้กับเอาต์พุตหรือภาระ (Load) หรือคายประจุไฟฟ้าเมื่ออุปกรณ์สวิตชิง Turn on และทำการเก็บประจุเมื่ออุปกรณ์สวิตชิง Turn off ดังนั้นจำเป็นต้องเลือกตัวเก็บประจุที่สามารถทนแรงดันได้เท่ากับหรือมากกว่าแรงดันเอาต์พุต หากเลือกตัวเก็บประจุที่มีขนาดใหญ่จะมีส่วนช่วยในการลดแรงดันกระเพื่อมทางด้านเอาต์พุต สามารถคำนวณหาตัวเก็บประจุทางด้านเอาต์พุตได้จากสมการที่ (2-21)

$$\frac{\Delta V_{\text{bus}}}{V_{\text{bus}}} = \frac{D}{RCf} \quad (2-21)$$

เมื่อ	$\frac{\Delta V_{bus}}{V_{bus}}$	คือค่า Ripple Factor กำหนดให้ไม่เกิน 1 เปอร์เซ็นต์
	ΔV_{bus}	คือแรงดันกระเพื่อมทางด้านเอาต์พุต
	V_{bus}	คือแรงดันเอาต์พุต มีค่า 60 V
	C	คือค่าตัวเก็บประจุทางด้านเอาต์พุต
	D	คือดิวตี้ไซเคิล หาได้จากสมการที่ (2-5) มีค่า 0.6
	R	คือค่าความต้านทานโหลดของวงจร
	f	คือความถี่ที่ใช้ในวงจร มีค่า 25 kHz

แทนค่าในสมการที่ (2-21) เพื่อหา ΔV_{bus}

$$\frac{\Delta V_{bus}}{60} = 0.01$$

ดังนั้น

$$\Delta V_{bus} = 0.01 \times 60 = 0.6V$$

หาค่าตัวเก็บประจุทางด้านเอาต์พุตจากสมการที่ (2-21)

$$C = \frac{D}{Rf \frac{\Delta V_{Bus}}{V_{Bus}}}$$

แทนค่า

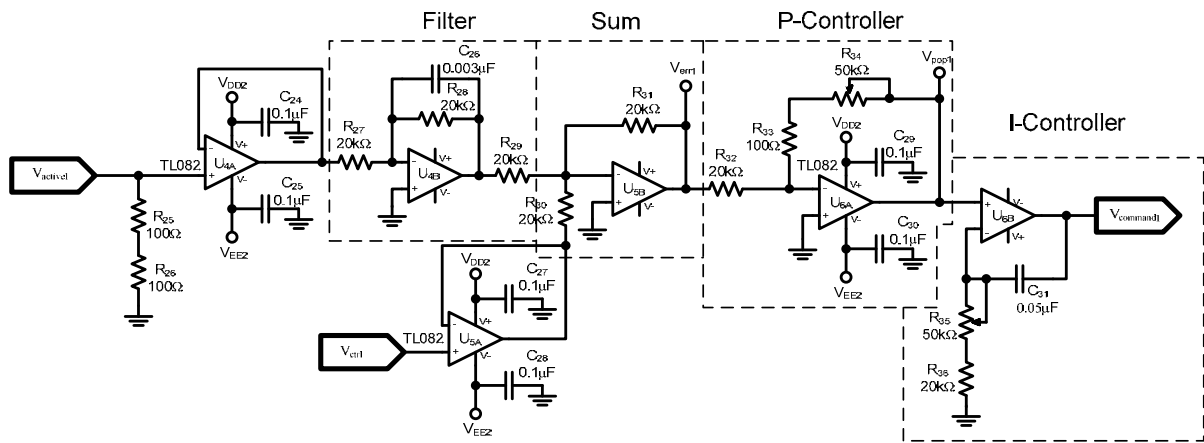
$$C = \frac{0.6}{9.375 \times 25 \times 10^3 \times 0.01} = 256 \mu F$$

ดังนั้นควรเลือกตัวเก็บประจุทางด้านเอาต์พุตของวงจรที่มีค่าสูงกว่า 256 μF และแรงดันที่ทนได้ต้องไม่ต่ำกว่าแรงดันเอาต์พุตที่ 60 V

2.3.2 การออกแบบวงจรควบคุม

วงจรควบคุมกระแสเป็นวงจรที่ทำหน้าที่ควบคุมให้ระดับการจ่ายกระแสคงที่ถึงแม้ว่าภาระจะมีการเปลี่ยนแปลง การจัดวงจรควบคุมแสดงดังภาพที่ 2-20 จุดต่ออินพุต V_{ctrl} เป็นจุดรับสัญญาณคำสั่งจาก dSPACE เพื่อควบคุมการจ่ายกระแสของคอนเวอร์เตอร์ทั้งหมด จุดต่ออินพุต $V_{active1}$ เป็นจุดต่อรับสัญญาณป้อนกลับค่ากระแสจากเซนเซอร์กระแสที่ได้รับการแปลงให้เป็นแรงดันแล้ว จากวงจรตรวจจับกระแสและจุดต่อเอาต์พุต $V_{command1}$ เป็นจุดต่อสัญญาณออกจากตัวควบคุมไปให้วงจรกำเนิดสัญญาณ PWM เพื่อควบคุมการสวิตช์ต่อไป จัดเป็นวงจรกันชนเพื่อป้องกันไม่ให้อุปกรณ์ที่จุด $V_{active1}$ และ V_{ctrl} ซึ่งอาจทำให้แรงดันทั้ง 2 จุดลดลงจนการทำงานของคอนเวอร์เตอร์ผิดพลาดได้ U1B จัดเป็นวงจรกรองแรงดันเพื่อกรองแรงดัน $V_{active1}$ จากเซนเซอร์กระแสให้มีความเรียบมากที่สุด เพราะสัญญาณที่ได้จากเซนเซอร์กระแสมักจะมีการกระเพื่อมตามลักษณะของกระแสจากตัวเหนี่ยวนำความถี่สูงอยู่ ส่วน U2B

เป็นวงจรเป็นวงจรรวมสัญญาณระหว่างสัญญาณคำสั่ง V_{ctrl} กับสัญญาณ $V_{active1}$ แต่เนื่องจาก $V_{active1}$ ถูกกลับเฟสสัญญาณเพราะเป็นการป้อนกลับค่ากระแสแบบลบ ทำให้เอาต์พุตที่จุด V_{err1} เป็นผลต่างของ $V_{ctrl}-V_{active1}$ ส่งต่อไปยังตัวควบคุมกระแสแบบ PI



ภาพที่ 2-20 วงจรควบคุมกระแสของตัวแปลงไฟสำหรับแบตเตอรี่

จากการคำนวณทำให้ได้ค่า K_p ของ P-Controller และค่า T_i ของ I-Controller ในภาพที่ 2-20 ที่ทำให้ได้การตอบสนองต่อคำสั่ง V_{ctrl} ได้ในเวลาที่ต้องการ ณ จุดที่ค่า $K_p = 0.285$ และค่า $T_i = 2.085\text{ms}$ ดังนั้นสามารถคำนวณหาค่าอุปกรณ์ต่างๆ ได้ดังนี้

จากสมการโอนย้ายของวงจรควบคุมแบบ PI แบบอิสระต่อกัน

$$\frac{V_{command1}(s)}{V_{err1}(s)} = K_p \left(1 + \frac{1}{T_i s} \right) \quad (2-22)$$

เมื่อ $V_{command1}(s)$ คือแรงดันเอาต์พุตของตัวควบคุมแบบ PI

$V_{err1}(s)$ คือแรงดันผลต่างของ $V_{ctrl}-V_{active1}$

โดยที่อัตราขยายของ K_p หาได้จากสมการ

$$K_p = \frac{R_{33}+R_{34}}{R_{32}} \quad (2-23)$$

ในการออกแบบเลือกค่าความต้านทาน $R_{32} = 20\text{ k}\Omega$ และ $R_{33} = 100\text{ }\Omega$ หาค่า R_{34} โดยแทนค่าลงสมการที่ (2-23)

$$R_{34} = 0.285 \times 20\text{ k}\Omega - 100\text{ }\Omega = 5.6\text{ k}\Omega$$

เพื่อลดความผิดพลาดที่อาจเกิดขึ้นจากตัวอุปกรณ์ในการใช้งานจริงเลือกใช้ R_{34} เป็นตัวต้านทานปรับค่าที่สามารถปรับค่าครอบคลุมค่าความต้านทาน $5.6\text{ k}\Omega$ เพื่อปรับให้ได้ค่าที่ใกล้เคียงที่สุด โดยเลือกใช้ตัวต้านทานปรับค่า $50\text{ k}\Omega$

ในส่วนของ I-Controller คำนวณหาค่าอุปกรณ์ได้จากสมการ

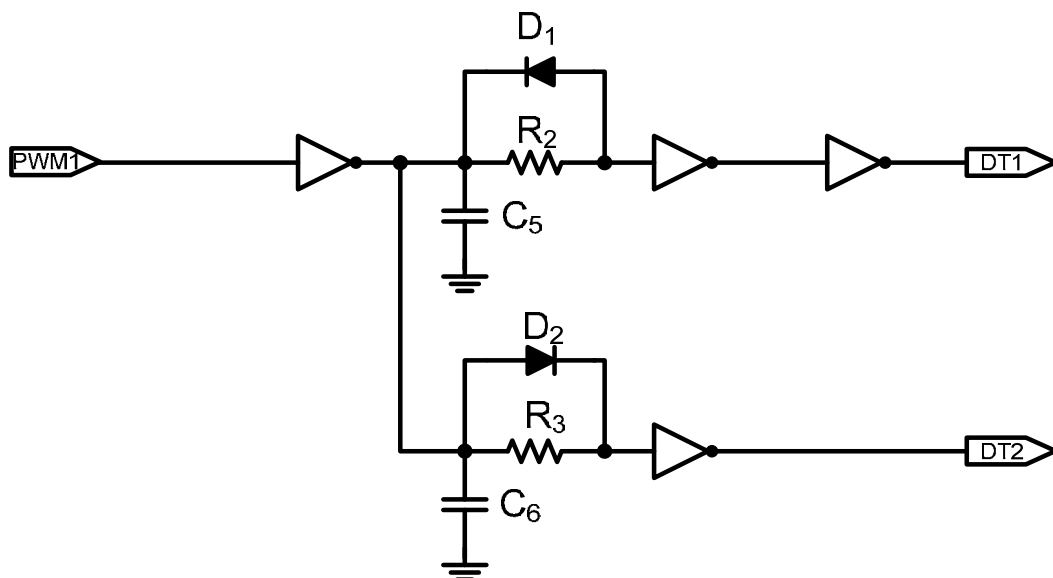
$$T_i = (R_{35} + R_{36})C_{31} \quad (2-24)$$

การออกแบบในงานวิจัยเลือกใช้ค่าความต้านทาน $R_{36} = 20 \text{ k}\Omega$ และค่าของตัวเก็บประจุ $C_{31} = 0.05 \text{ }\mu\text{F}$ คำนวณหาค่า R_{35} โดยแทนค่าลงในสมการที่ (2-24)

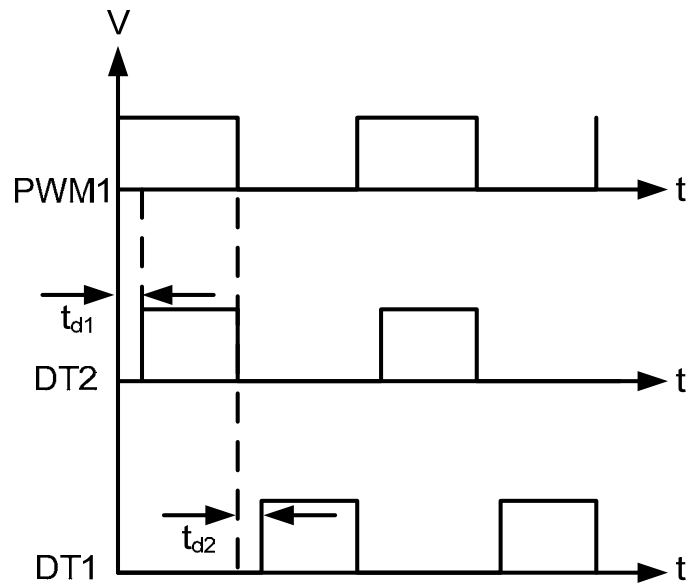
$$2.085\text{ms} = (R_{35} + 20\text{k}\Omega)0.05\mu\text{F}$$

$$R_{35} = \frac{2.085\text{ms}}{0.05\mu\text{F}} - 20\text{k}\Omega = 21.7\text{k}\Omega$$

2.3.2.1 วงจรเดดไทม์ (Dead time circuit) วงจรดังภาพที่ 2-21 ทำหน้าที่ในการหน่วงสัญญาณคำสั่งสวิตช์เพื่อป้องกันไม่ให้ชุดสวิตช์ทั้ง 2 ตัวในแต่ละเฟสทำงานพร้อมกัน โดยสัญญาณคำสั่งสวิตช์จะถูกหน่วงด้วยตัวต้านทานและตัวเก็บประจุในขอบขาขึ้นเท่านั้น ก็เพียงพอที่จะป้องกันไม่ให้เกิดการลัดวงจรของสวิตช์ทั้ง 2 ชุด และเมื่อสัญญาณอินพุตเป็น High หลังจากผ่าน NOT GATE ก็จะเปลี่ยนสถานะเป็น Low ตัวเก็บประจุซึ่งมีแรงดันสูงอยู่ก็จะคายประจุผ่านตัวต้านทาน เมื่อระดับแรงดันที่ตัวเก็บประจุต่ำถึงระดับที่ NOT GATE มองเป็นสถานะ Low สัญญาณเอาต์พุตเป็น High ช่วงนี้จะไม่มีการหน่วงเวลา เพราะกระแสไหลผ่านไดโอดมาชาร์จตัวเก็บประจุแล้วเติมทันที ทำให้เอาต์พุตของ NOT GATE อีกตัวเป็น Low การปรับค่าความต้านทานจะทำให้ระยะการหน่วงเวลาเปลี่ยนไปลักษณะการหน่วงของ Dead time แสดงดังภาพที่ 2-22



ภาพที่ 2-21 วงจรเดดไทม์ (Dead time circuit)



ภาพที่ 2-22 เดดไทม์ของการขับมอสเฟต

จากภาพที่ 2-21 เป็นวงจรเดดไทม์ จุดต่อ PWM1 เป็นจุดรับสัญญาณที่ได้จากวงจรกำเนิดสัญญาณ PWM ส่วนทางด้านเอาต์พุตจุดต่อ DT1 และ DT2 เป็นส่วนที่ได้ถูกกำหนดเดดไทม์แล้วเพื่อส่งต่อไปยังวงจรขับเคลื่อนต่อไป

จากข้อมูลของไอซี NOT GATE เบอร์ 74LS14 ที่ใช้ในวงจรเดดไทม์ สัญญาณอินพุตที่ทำให้เอาต์พุตเป็นลอจิก “1” คือแรงดันอินพุต 1.6 V มอสเฟตกำลังที่ใช้มีเวลาในการคืนสภาพ (t_{rr}) 620 นาโนวินาที คิดเวลาที่อีกตัวหนึ่งทำงานได้เต็มที่และอีกตัวหนึ่งหยุดทำงานสนิท ควรหาช่วงเวลาทั้งหมด $2t_{rr}$ ดังนั้นเวลาหน่วงมีค่า 620 นาโนวินาที $\times 2 = 1,240$ นาโนวินาที หรือ 1.24 ไมโครวินาที ในวงจรเดดไทม์นี้คิดเวลาหน่วงประมาณ 2 ไมโครวินาที เลือกใช้ค่า $C_5 = 3$ nF คำนวณหาค่า R_2 ได้จาก

$$V_{C5} = V_{CC} (1 - e^{-t_{d2}/R_2 C_5})$$

เมื่อ V_{C5} คือ แรงดันที่ตกคร่อม C_5 ที่ทำให้อินพุตเป็นสถานะ high คือ 1.6 V
 V_{CC} คือ แรงดันไฟเลี้ยงวงจรมีค่า 5 V

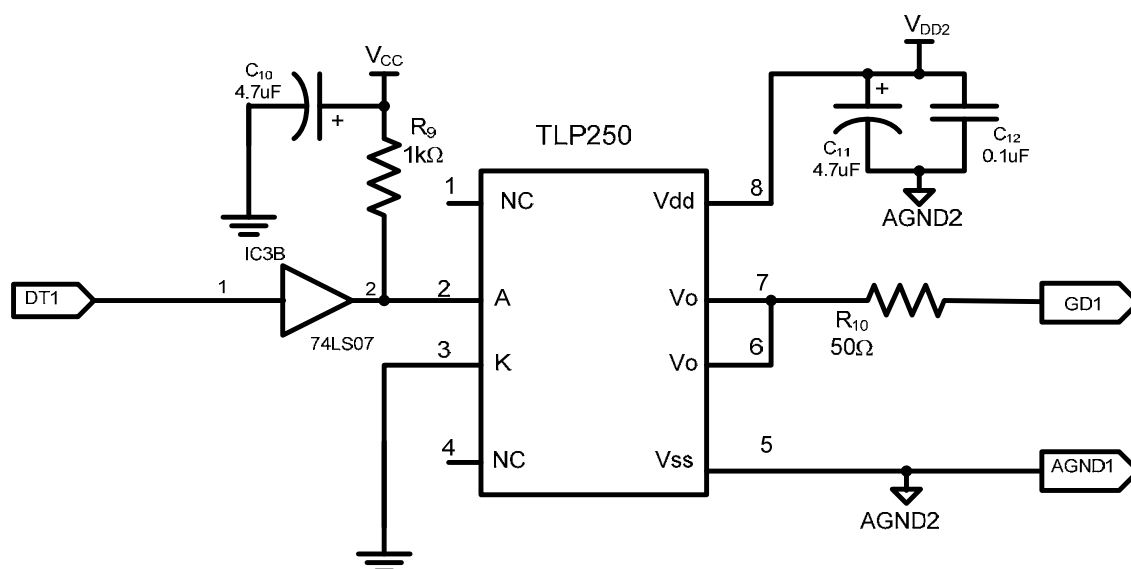
แทนค่าลงในสมการด้านบน

$$1.6 = 5 (1 - e^{-2 \times 10^3 / R_2 \times 3 \times 10^{-9}})$$

$$R_2 = -0.67 \times 10^3 \frac{\log e}{\log 0.68} = 1.74 \text{ k}\Omega$$

ในการใช้งานจริง เลือกใช้งาน R_2 มีค่า 2 Ω ซึ่งทำให้ค่าเดดไทม์ที่ได้จริงมีค่า 2.31 ไมโครวินาที

2.3.2.2 วงจรขับนำเกต ด้วยไอซี TLP250 สัญญาณที่ผ่านการมอดูเลตตามความกว้างของพัลส์หรือสัญญาณ PWM มีลักษณะเป็นสัญญาณพัลส์สี่เหลี่ยม สัญญาณนี้ถูกส่งไปยังวงจรถับนำเกตด้วยไอซีสร้างสัญญาณขับนำเกตเบอร์ TLP250 เพื่อควบคุมการทำงานของมอสเฟต วงจรสร้างขับนำเกตแสดงดังภาพที่ 2-23 จากวงจรสัญญาณด้านเข้าเป็นสัญญาณที่ถูกส่งมาจากวงจรถูกกำเนิดสัญญาณ PWM มีขนาดแรงดัน 0 V ถึง 5 V สัญญาณนี้ถูกส่งเข้าไปไบแอสให้ LED ใน TLP250 นำกระแสโดยมีความต้านทาน R_9 ทำหน้าที่จำกัดกระแสในการไบแอสและใช้ไอซีบัฟเฟอร์ 74LS07 เป็นตัวป้องกันไฟ 5 V ที่จะเกิดการไหลย้อนกลับของแรงดันเข้าไปในวงจรถูกกำเนิดสัญญาณ PWM เมื่อ LED นำกระแส ส่งผลทำให้ทรานซิสเตอร์ชนิด NPN ทางด้านเอาต์พุตของ TLP250 นำกระแส แรงดันที่ขา 7 ของ TLP250 เทียบกับกราวด์เท่ากับ $V_{DD2}(15V)$ และแรงดันที่ V_{GS} ของมอสเฟตเท่ากับ $V_{DD2} (15 V)$ เทียบกับกราวด์เมื่อแรงดัน V_{GS} มีค่าเป็นบวกสามารถทำให้มอสเฟตนำกระแสได้ ส่วนในกรณีที่แรงดันอินพุตน้อยกว่า 0.7 V LED ภายใน TLP250 หยุดนำกระแสส่งผลให้ทรานซิสเตอร์ชนิด NPN ทางด้านเอาต์พุตของ TLP250 หยุดนำกระแสเช่นเดียวกัน แต่ทรานซิสเตอร์ชนิด PNP จะนำกระแสส่งผลให้ ที่สภาวะนี้แรงดันที่ขา 7 ของ TLP250 เทียบกับกราวด์มีค่าประมาณ 0 V เมื่อแรงดันที่ V_{GS} มีค่าเป็น 0 V ก็จะทำให้มอสเฟตหยุดนำกระแสได้



ภาพที่ 2-23 วงจรถับนำเกตโดยใช้ไอซีเบอร์ TLP250

จากภาพที่ 2-23 จุดต่ออินพุตของวงจร จุด DT1 เป็นจุดรับสัญญาณจากวงจรถูกกำเนิดสัญญาณ PWM และที่เอาต์พุตของวงจร จุด GD1 เป็นจุดต่อสัญญาณไปยังสวิตช์แต่ละตัวโดยจุดนี้จะเทียบกับจุด AGND1 ต่อจุด GD1 เข้าที่ขาเกตของ S1 และจุด AGND1 เข้าที่ขาซอร์สจากภาพเป็นวงจรถับนำเกตจำนวน 1 ชุด ดังนั้นในการใช้งานต้องสร้างวงจรลักษณะเดียวกันนี้ทั้งหมด 2 ชุด

2.4 การบริหารจัดการพลังงานในระบบจ่ายไฟฟ้ากระแสตรงแบบผสมด้วยเซลล์เชื้อเพลิง เซลล์แสงอาทิตย์และแบตเตอรี่ชนิดซูปเปอร์คาปาซิเตอร์

2.4.1 วงจรกำลังสำหรับแหล่งจ่ายไฟแบบผสม

โครงสร้างการต่อวงจรกำลังของแหล่งจ่ายไฟแบบผสมนี้แสดงได้ดังภาพที่ 2-24 [24] ตัวแปลงไฟสำหรับเซลล์เชื้อเพลิงคือวงจรบูสที่ขนานกัน 4 ชุด (หัวข้อ 2.1) ตัวแปลงไฟสำหรับเซลล์แสงอาทิตย์คือวงจรบูสที่ขนานกัน 2 ชุด (หัวข้อ 2.2) ตัวแปลงไฟสำหรับซูปเปอร์คาปาซิเตอร์คือวงจรแปลงไฟแบบ 2 ทิศทาง (2-Quadrant Converter) ที่ขนานกัน 4 ชุด (หัวข้อ 2.3)

เพื่อเป็นการป้องกันและการทำงานที่มีความเร็วสูง ตัวแปลงไฟของเซลล์เชื้อเพลิง เซลล์แสงอาทิตย์และซูปเปอร์คาปาซิเตอร์จะถูกควบคุมด้วยวงปิดของการควบคุมกระแสของแต่ละตัว ดังอธิบายไปแล้วในหัวข้อ 2.1 2.2 และ 2.3 เพื่อแน่ใจว่าระบบทำงานที่มีเสถียรภาพ (Stability) ความเร็วของวงปิดระบบควบคุมกระแสซึ่งเป็นระบบควบคุมวงในสุด (inner current regulation loops) จะต้องทำงานที่ความเร็วสูงกว่าระบบควบคุมวงปิดของระบบควบคุมวงนอก (outer control loops) [25] ระบบควบคุมกระแสจะรับคำสั่งอ้างอิง (References) สามสัญญาณคือกระแสคำสั่งของซูปเปอร์คาปาซิเตอร์ i_{SCREF} กระแสคำสั่งของเซลล์เชื้อเพลิง i_{FCREF} และกระแสคำสั่งของเซลล์แสงอาทิตย์ i_{PVREF} กระแสคำสั่งทั้งสามนี้จะถูกกำเนิดมาจากตัวควบคุมบริหารจัดการพลังงานทั้งระบบ ซึ่งจะนำเสนอต่อไปนี้

2.4.2 แบบจำลองทางคณิตศาสตร์ของแหล่งจ่ายไฟแบบผสม

เราพิจารณาให้กระแสของเซลล์เชื้อเพลิง กระแสของเซลล์แสงอาทิตย์และกระแสของซูปเปอร์คาปาซิเตอร์ทำงานตามกระแสคำสั่งอย่างรวดเร็ว ดังนั้น

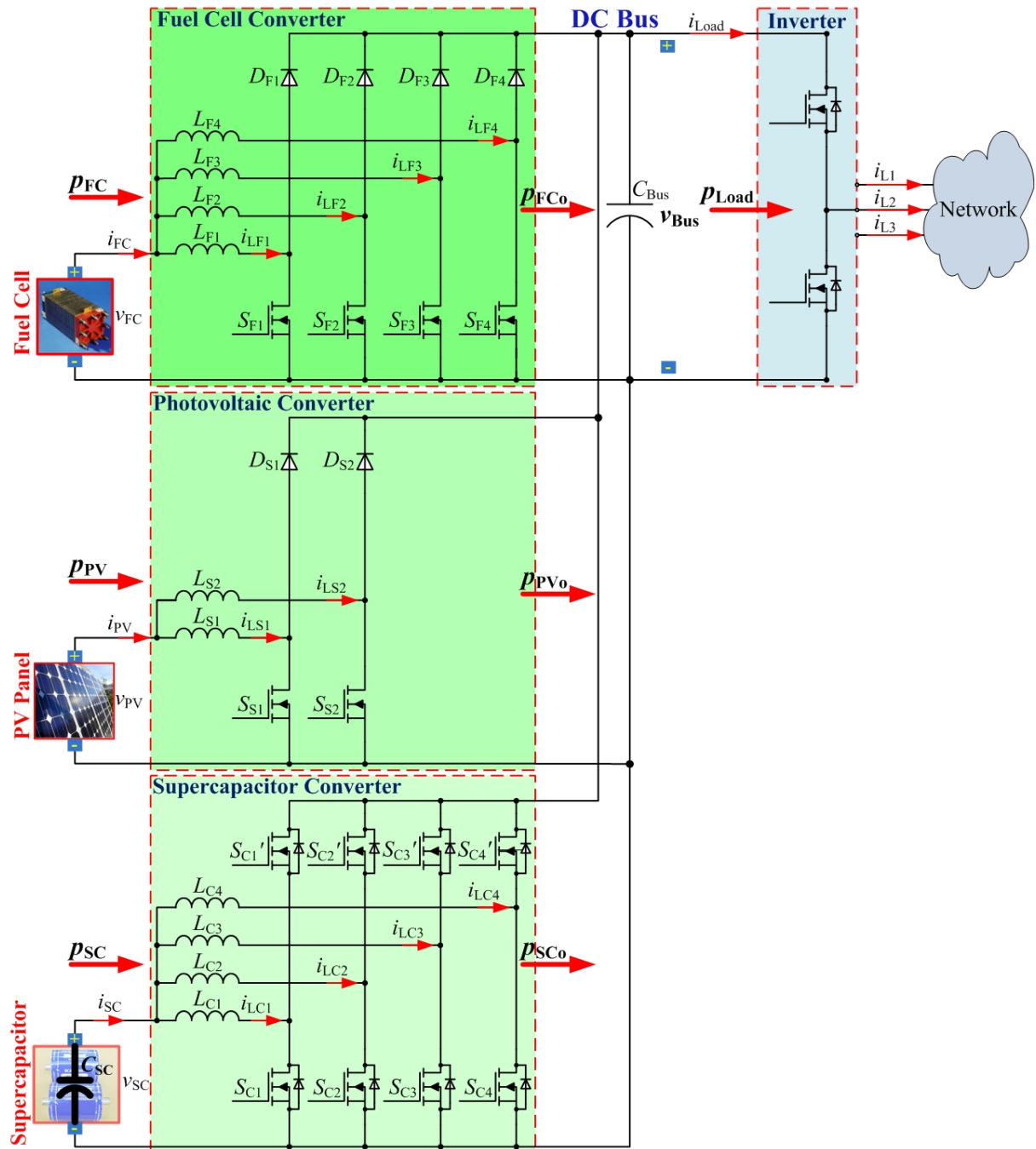
$$i_{FC} = i_{FCREF} = \frac{P_{FC}}{v_{FC}} = \frac{P_{FCREF}}{v_{FC}} \quad (2-25)$$

$$i_{PV} = i_{PVREF} = \frac{P_{PV}}{v_{PV}} = \frac{P_{PVREF}}{v_{PV}} \quad (2-26)$$

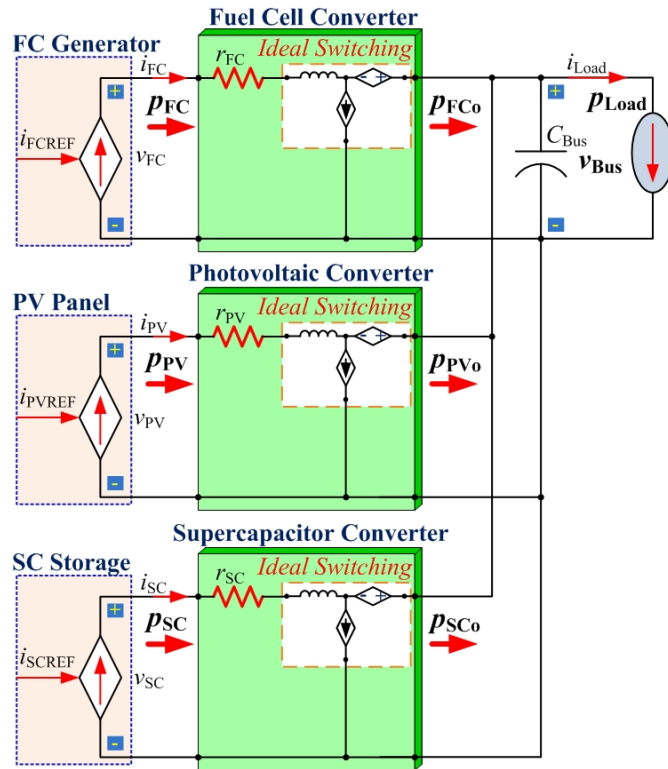
$$i_{SC} = i_{SCREF} = \frac{P_{SC}}{v_{SC}} = \frac{P_{SCREF}}{v_{SC}} \quad (2-27)$$

เป็นผลทำให้เซลล์เชื้อเพลิง เซลล์แสงอาทิตย์และกระแสของซูปเปอร์คาปาซิเตอร์ทำงานเป็นแหล่งจ่ายกระแสที่ควบคุมได้ (Controlled current sources) แสดงได้ดังภาพที่ 2-25 เราพิจารณาให้มีค่าสูญเสียในตัวแปลงไฟแต่ละตัวเป็นตัวต้านทานที่มีค่าสูญเสียคงที่คือ r_{FC} , r_{PV} และ r_{SC} ของตัวแปลงไฟของเซลล์เชื้อเพลิง ของตัวแปลงไฟของเซลล์แสงอาทิตย์และของตัวแปลงไฟของซูปเปอร์คาปาซิเตอร์ตามลำดับ

พลังงานไฟฟ้าที่คาปาซิเตอร์ในบัสไฟตรง (E_{Bus}) และพลังงานไฟฟ้าที่ซูปเปอร์คาปาซิเตอร์ (E_{SC}) สามารถเขียนได้ดังนี้



ภาพที่ 2-24 ไดอะแกรมของระบบจ่ายไฟด้วยเซลล์เชื้อเพลิง เซลล์แสงอาทิตย์และซูเปอร์คาปาซิเตอร์ ซึ่ง p_{Load} ($= v_{Bus} \times i_{Load}$), v_{Bus} , และ i_{Load} คือกำลังของโหลด แรงดันที่บัสไฟตรงและกระแสที่บัสไฟตรง ตามลำดับ p_{FC} ($= v_{FC} \times i_{FC}$), v_{FC} , และ i_{FC} คือกำลัง แรงดันและกระแสของเซลล์เชื้อเพลิง ตามลำดับ p_{PV} ($= v_{PV} \times i_{PV}$), v_{PV} , และ i_{PV} คือกำลัง แรงดันและกระแสของเซลล์แสงอาทิตย์ ตามลำดับ p_{SC} ($= v_{SC} \times i_{SC}$), v_{SC} , และ i_{SC} คือกำลัง แรงดันและกระแสของซูเปอร์คาปาซิเตอร์ ตามลำดับ p_{FC0} , p_{PV0} และ p_{SC0} คือกำลังเอาต์พุตที่ส่งไปยังบัสไฟตรงของเซลล์เชื้อเพลิง เซลล์แสงอาทิตย์และซูเปอร์คาปาซิเตอร์ ตามลำดับ



ภาพที่ 2-25 วงจรเทียบเคียงของแหล่งจ่ายไฟแบบผสมที่น่าเสนอ

$$E_{Bus} = \frac{1}{2} C_{Bus} v_{Bus}^2 \quad (2-28)$$

$$E_{SC} = \frac{1}{2} C_{SC} v_{SC}^2 \quad (2-29)$$

ขณะที่พลังงานสะสมรวม (E_T) ที่เก็บอยู่ในคาปาซิเตอร์ที่บัสไปตรง (C_{Bus}) และในซูเปอร์คาปาซิเตอร์ (C_{SC}) สามารถเขียนได้ดังนี้

$$E_T = \frac{1}{2} C_{Bus} v_{Bus}^2 + \frac{1}{2} C_{SC} v_{SC}^2 \quad (2-30)$$

ดังแสดงในภาพที่ 2-25 สามารถเขียนเป็นสมการอนุพันธ์ของพลังงานไฟฟ้าที่คาปาซิเตอร์ในบัสไปตรง (E_{Bus}) กับ p_{FCo} , p_{PVo} , p_{SCo} , และ p_{Load} ได้ดังนี้

$$\dot{E}_{Bus} = p_{FCo} + p_{PVo} + p_{SCo} - p_{Load} \quad (2-31)$$

ซึ่ง

$$p_{FCo} = p_{FC} - r_{FC} \left(\frac{p_{FC}}{v_{FC}} \right)^2 \quad (2-32)$$

$$PPV_o = PPV - r_{PV} \left(\frac{PPV}{v_{PV}} \right)^2 \quad (2-33)$$

$$PSC_o = PSC - r_{SC} \left(\frac{PSC}{v_{SC}} \right)^2 \quad (2-34)$$

$$P_{Load} = v_{Bus} \cdot i_{Load} = \sqrt{\frac{2E_{Bus}}{C_{Bus}}} \cdot i_{Load} \quad (2-35)$$

$$P_{SC} = v_{SC} \cdot i_{SC} = \sqrt{\frac{2E_{SC}}{C_{SC}}} \cdot i_{SC} \quad (2-36)$$

2.4.3 การควบคุมแบบไม่เชิงเส้นสำหรับแหล่งจ่ายไฟแบบผสม

2.4.3.1 พลังงานสมดุลย์

วัตถุประสงค์ของการควบคุมคือความมีเสถียรภาพ (stability) ความแข็งแกร่ง (robustness) ประสิทธิภาพ (high overall efficiency) และการทำงานที่เหมาะสมที่สุด (optimization) เพื่อจ่ายพลังงานให้กับโหลดและชาร์จซูเปอร์คาปาซิเตอร์ ระบบควบคุมแบบหลายตัวแปรนี้จึงต้องมีคำสั่งอ้างอิงของแรงดันที่บัสไฟตรง (v_{BusREF}) (แทนพลังงานที่บัสไฟตรง (E_{Bus}) ที่เราเรียกว่า “การมีเสถียรภาพที่บัสไฟตรง *DC link stabilization*”) และคำสั่งอ้างอิงของแรงดันที่ซูเปอร์คาปาซิเตอร์ (v_{SCREF}) (แทนพลังงานที่ซูเปอร์คาปาซิเตอร์ (E_{SC}) ที่เราเรียกว่า “*supercapacitor state-of-charge SOC*”)

จากแนวความคิดงานวิจัยก่อนหน้านี้ [26], [27] เซลล์แสงอาทิตย์จะถูกควบคุมเป็นแหล่งจ่ายหลัก เซลล์เชื้อเพลิงทำงานเป็นแหล่งจ่ายจ่ายไฟเมื่อพลังงานในสภาวะอยู่ตัวไม่พอกจากเซลล์แสงอาทิตย์ ขณะที่ซูเปอร์คาปาซิเตอร์เป็นแหล่งพลังงานที่มีความเร็วสูงมากๆ จะช่วยจ่ายไฟช่วงไดนามิกที่สูงๆ ดังนั้นหลักการบริหารจัดการพลังงานในระบบคือให้ซูเปอร์คาปาซิเตอร์จ่ายไฟเพื่อรักษาระดับแรงดันที่บัสไฟตรง ส่วนเซลล์แสงอาทิตย์และเซลล์เชื้อเพลิง (เป็นเครื่องกำเนิดพลังงานที่ช้ากว่าซูเปอร์คาปาซิเตอร์) ทำหน้าที่รักษาระดับแรงดันที่บัสไฟตรงและที่ซูเปอร์คาปาซิเตอร์

2.4.3.2 พิสัยการมีคุณสมบัติแบบ flatness ของแหล่งจ่ายแบบผสม

เพื่อยืนยันการมีคุณสมบัติแบบ flatness ดังได้อธิบายไปแล้วในหัวข้อ 1.6 จะถูกพิสูจน์ดังต่อไปนี้ เพื่อรักษาระดับแรงดันไฟที่บัสไฟตรงและที่ซูเปอร์คาปาซิเตอร์ บนพื้นฐานของทฤษฎีการควบคุมแบบ flatness ตัวแปรเอาต์พุต ($\mathbf{y}$) ตัวแปรควบคุมอินพุต ($\mathbf{u}$) และตัวแปรสเตท ($\mathbf{x}$) ถูกกำหนดดังนี้

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} E_{Bus} \\ E_T \end{bmatrix} \quad (2-37)$$

$$\mathbf{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} P_{SCREF} \\ P_{TREF} \end{bmatrix} \quad (2-38)$$

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} v_{Bus} \\ v_{SC} \end{bmatrix} \quad (2-39)$$

ซึ่ง p_{TREF} คือกำลังไฟฟ้ารวมจากเซลล์แสงอาทิตย์และเซลล์เชื้อเพลิง จากสมการที่ (1-32) (1-33) และ (1-34) ตัวแปรสเททสามารถเขียนได้ดังนี้

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2y_1}{C_{Bus}}} \\ \sqrt{\frac{2(y_2 - y_1)}{C_{SC}}} \end{bmatrix} = \begin{bmatrix} \varphi_1(y_1) \\ \varphi_2(y_1, y_2) \end{bmatrix} \quad (2-40)$$

จากสมการที่ (2-31) ตัวแปรอินพุต (u) สามารถคำนวณได้จากตัวแปรเอาต์พุตตัว (y) และอนุพันธ์เทียบกับเวลาคือ

$$u_1 = 2p_{SCLim} \cdot \left[1 - \sqrt{1 - \frac{\dot{y}_1 + \sqrt{\frac{2y_1}{C_{Bus}}} \cdot i_{Load} - P_{FCo} - P_{PVo}}{p_{SCLim}}} \right] \quad (2-41)$$

$$= \psi_1(y_1, \dot{y}_1) = p_{SCREF}$$

$$u_2 = 2p_{TMax} \cdot \left[1 - \sqrt{1 - \frac{\dot{y}_2 + \sqrt{\frac{2y_1}{C_{Bus}}} \cdot i_{Load}}{p_{TMax}}} \right] \quad (2-42)$$

$$= \psi_2(y_1, \dot{y}_2) = p_{TREF}$$

ซึ่ง

$$p_{SCLim} = \frac{v_{SC}^2}{4r_{SC}}, \quad p_{TMax} = \frac{v_T^2}{4r_T} \quad (2-43)$$

ขณะที่ p_{SCLim} คือกำลังไฟฟ้าสูงสุดที่ถูกจำกัดจากตัวแปลงไฟของซูปเปอร์คาปาซิเตอร์ p_{TMax} คือเทียบเคียงกำลังไฟฟ้าสูงสุดที่ถูกจำกัดจากตัวแปลงไฟของเซลล์แสงอาทิตย์และเซลล์เชื้อเพลิง v_T คือแรงดันไฟฟ้าเทียบเคียงจากแหล่งจ่ายไฟจากเซลล์แสงอาทิตย์และเซลล์เชื้อเพลิงและ r_T คือค่าตัวต้านทานเทียบเคียงในตัวแปลงไฟของเซลล์แสงอาทิตย์และเซลล์เชื้อเพลิง

อันที่จริงแล้ว

$$p_{TMax} = p_{FCMax} + p_{PVMax} \quad (2-44)$$

ซึ่ง p_{FCMax} คือกำลังไฟฟ้าสูงสุดจากเซลล์เชื้อเพลิงและ p_{PVMax} คือกำลังไฟฟ้าสูงสุดจากเซลล์แสงอาทิตย์

2.4.3.3 กฎการควบคุมและเสถียรภาพ (Control Law and Stability)

จากสมการที่ (1.35) กฎการควบคุมพลังงานแสดงได้ดังนี้ [28], [29]

$$v_1 = \dot{y}_1 = \dot{y}_{1REF} + K_{11}(y_{1REF} - y_1) + K_{12} \int_0^t (y_{1REF} - y_1) d\tau \quad (2-45)$$

$$v_2 = \dot{y}_2 = \dot{y}_{2REF} + K_{21}(y_{2REF} - y_2) \quad (2-46)$$

ซึ่ง y_{1REF} คือคำสั่งอ้างอิงของตัวแปรเอาต์พุตตัวที่ 1 (พลังงานที่คาปาซิเตอร์ที่บัสไฟตรง) และ y_{2REF} คือคำสั่งอ้างอิงของตัวแปรเอาต์พุตตัวที่ 2 (พลังงานรวมที่คาปาซิเตอร์ที่บัสไฟตรงกับที่ชูปเปอร์คาปาซิเตอร์)

จากสมการที่ (2-45) ถ้ากำหนดให้ $e_1 = y_1 - y_{1REF}$, $K_{11} = 2\zeta\omega_n$ และ $K_{12} = \omega_n^2$ จะได้

$$\ddot{e}_1 + 2\zeta\omega_n \cdot \dot{e}_1 + \omega_n^2 \cdot e_1 = 0 \quad (2-47)$$

แทน $\dot{y}_1$ ลงในสมการที่ (2-41) จะได้สมการในเทอมของการควบคุมแบบป้อนกลับ เราอาจจะเรียกว่า “inverse dynamics”

$$u_1 = 2P_{SCLim} \cdot \left[1 - \sqrt{1 - \left(\frac{equ.(2-45) + P_{Load} - P_{FCo} - P_{PVo}}{P_{SCLim}} \right)} \right] \quad (2-48)$$

เพื่อการคำนวณที่ง่ายลง เราอาจจะประมาณว่า $r_{SC} = 0$ ทำให้ $p_{SC} = P_{SCo}$ โดยการกำหนดให้ $P_{SCMax} \leq P_{SCLim}$ เราอาจจะเขียนสมการ inverse dynamics ได้ง่ายขึ้นคือ

$$u_1 = \left(\overbrace{\dot{y}_1 = \dot{E}_{Bus}}^{\dot{y}_1 = \dot{E}_{Bus}} \right) + P_{Load} - P_{FCo} - P_{PVo} \quad (2-49)$$

$$= P_{SCREF}$$

เช่นเดียวกันจากสมการที่ (2-46) ถ้ากำหนดให้ $e_2 = y_2 - y_{2REF}$, $K_{21} = 1/\tau_S$ จะได้

$$\tau_S \cdot \dot{e}_2 + e_2 = 0 \quad (2-50)$$

แทน $\dot{y}_2$ ลงในสมการที่ (2-42) จะได้สมการในเทอมของการควบคุมแบบป้อนกลับ ที่เรียกว่า “inverse dynamics”

$$\begin{aligned}
 \dot{y}_2 &= \dot{E}_T \\
 u_2 &= \overbrace{(\dot{y}_{2\text{REF}} - (1/\tau_S)e_2)} + p_{\text{Load}} \\
 &= p_{\text{TREF}} \\
 &= p_{\text{PVREF}} + p_{\text{FCREF}}
 \end{aligned} \tag{2-51}$$

จากสมการที่ (2-49) และ (2-51) เห็นได้ชัดว่าระบบควบคุมจะมีเสถียรภาพแน่นอนสำหรับค่า K_{11} , $K_{12} > 0$ และ $K_{21} > 0$ อย่างไรก็ตาม บนพื้นฐานของระบบควบคุมเป็นชั้นๆ (cascade control structure) และความถี่ของการสวิตช์อิเล็กทรอนิกส์กำลัง (ω_s) วงควบคุมชั้นนอก (ในที่นี้คือการควบคุมพลังงานที่บัสไฟตรง) จะต้องทำงานที่ cut-off frequency $\omega_E \ll \omega_C$ ซึ่ง ω_C คือ cut-off frequency ของระบบควบคุมของวงควบคุมกำลังจากซูเปอร์คาปาซิเตอร์ซึ่งเป็นวงชั้นในนั่นเองและ $\omega_C \ll \omega_s$ เมื่อตัวแปรเอาต์พุตมีเสถียรภาพ ระบบควบคุมทั้งหมดก็จะมีเสถียรภาพไปด้วยเพราะตัวแปรทั้งหมดสามารถแสดงในเทอมของ differential flatness

ภาพที่ 2-26 ได้อธิบายถึงแนวคิดระบบควบคุมที่ได้นำเสนอสำหรับแหล่งจ่ายไฟจากพลังงานทดแทนที่ได้อธิบายข้างบน กฎการควบคุมพลังงานที่บัสไฟตรงสร้างกำลังไฟฟ้าอ้างอิงสำหรับซูเปอร์คาปาซิเตอร์ p_{SCREF} (อ้างอิงสมการที่ (2-41)) สัญญาณ p_{SCREF} นี้จะถูกหารด้วยแรงดันที่วัดมาจากซูเปอร์คาปาซิเตอร์ v_{SC} และจะจำกัดแรงดันของซูเปอร์คาปาซิเตอร์ให้อยู่ในช่วงต่ำสุดและสูงสุด $[V_{\text{SCMin}}, V_{\text{SCMax}}]$ โดยการจำกัดกระแสชาร์จหรือกระแสคายประจุ (ไม่ได้อธิบายในเอกสารนี้ สามารถหาอ่านเพิ่มเติมได้จาก [19], [30]) ผลลัพธ์ก็คือได้กระแสอ้างอิงสำหรับซูเปอร์คาปาซิเตอร์ i_{SCREF}

กฎการควบคุมพลังงานรวมหรือกฎการควบคุมพลังงานสำหรับซูเปอร์คาปาซิเตอร์กำเนิดกำลังไฟฟ้าอ้างอิงรวม p_{TREF} (อ้างอิงสมการที่ (2-42)) อย่างแรก สัญญาณ p_{TREF} นี้จะถูกพิจารณาให้เป็นกำลังอ้างอิงสำหรับโซล่าเซลล์ p_{PVREF} สัญญาณนี้จะถูกจำกัดไม่ให้เกินกำลังไฟฟ้าสูงสุด p_{PVMax} ด้วยตัวติดตามกำลังไฟฟ้า (maximum power point tracking MPPT) ซึ่งไม่ได้อธิบายในงานวิจัยนี้ อย่างไรก็ตาม ความแตกต่างระหว่างกำลังไฟฟ้าอ้างอิงรวม p_{TREF} กับกำลังอ้างอิงสำหรับโซล่าเซลล์ p_{PVREF} คือกำลังไฟฟ้าอ้างอิงสำหรับเซลล์เชื้อเพลิง p_{FCREF} สัญญาณนี้จะถูกจำกัดไม่ให้เกินกำลังไฟฟ้าสูงสุด p_{FCMax} และจะจำกัดไดนามิกส์ของเซลล์เชื้อเพลิง [31], [32] ในที่นี้ ตัวหน่วงลำดับที่ 2 ($D_{\text{FC}}(s)$) ถูกเลือกสำหรับการจำกัดไดนามิกส์ของเซลล์เชื้อเพลิง (FC power dynamic limitation) แสดงได้ดังนี้

$$D_{\text{FC}}(s) = \frac{1}{\left(\frac{s}{\omega_{n1}}\right)^2 + \frac{2\zeta_1}{\omega_{n1}}s + 1} \tag{2-52}$$

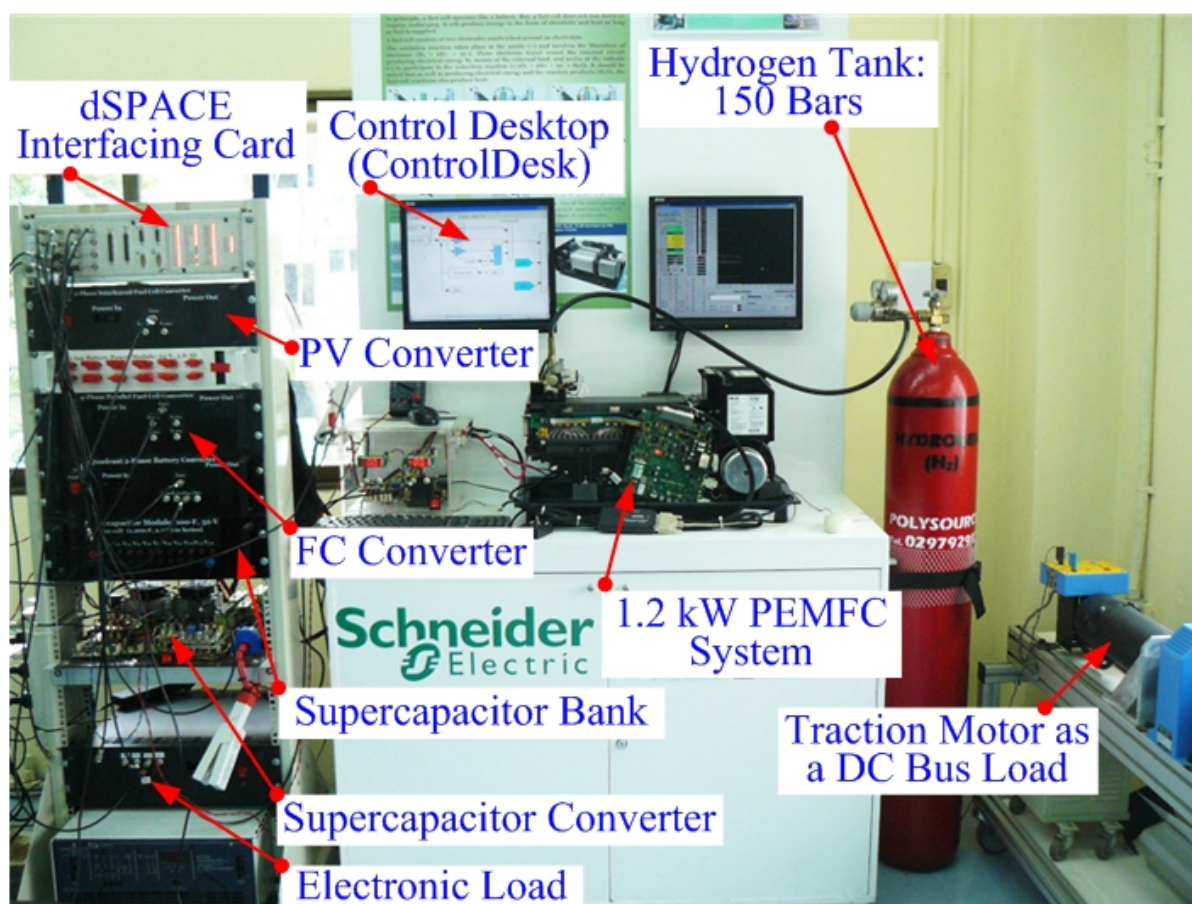
ซึ่ง ω_{n1} และ ζ_1 คือตัวแปรการควบคุม

วิธีการทดลอง ผลการทดลองและวิจารณ์ผลการทดลอง

จากขั้นตอนการออกแบบและดำเนินงานตามที่ได้กล่าวไปแล้วในบทที่ 2 เมื่อนำวงจรต่าง ๆ มาประกอบรวมกันเป็นชิ้นงานที่สมบูรณ์เรียบร้อยแล้ว ในบทนี้จะกล่าวถึงผลการดำเนินงานของวงจรที่ได้ออกแบบไว้และผลการทดสอบการทำงานของวงจรต่าง ๆ ดังนี้

3.1 รายละเอียดชุดทดลอง

ชุดทดลองระบบจ่ายไฟแบบผสมต้นแบบขนาดเล็กแสดงดังภาพที่ 3-1 ระบบเซลล์เชื้อเพลิง (Ballard Nexa fuel cell system) แผงโซลาร์เซลล์ (ติดตั้งบนดาดฟ้าสถาบันนวัตกรรมเทคโนโลยี ไทย-ฝรั่งเศส) และโมดูลซูเปอร์คาปาซิเตอร์แสดงดังภาพที่ 3-1 ถึงภาพที่ 3-3 ตามลำดับ รายละเอียดแหล่งจ่ายแต่ละตัวแสดงในตารางที่ 3-1



ภาพที่ 3-1 ชุดทดลองระบบจ่ายไฟแบบผสมต้นแบบขนาดเล็ก



ภาพที่ 3-2 แผงโซลาร์เซลล์ (ติดตั้งบนดาดฟ้าสถาบันนวัตกรรมเทคโนโลยี ไทย-ฝรั่งเศส)

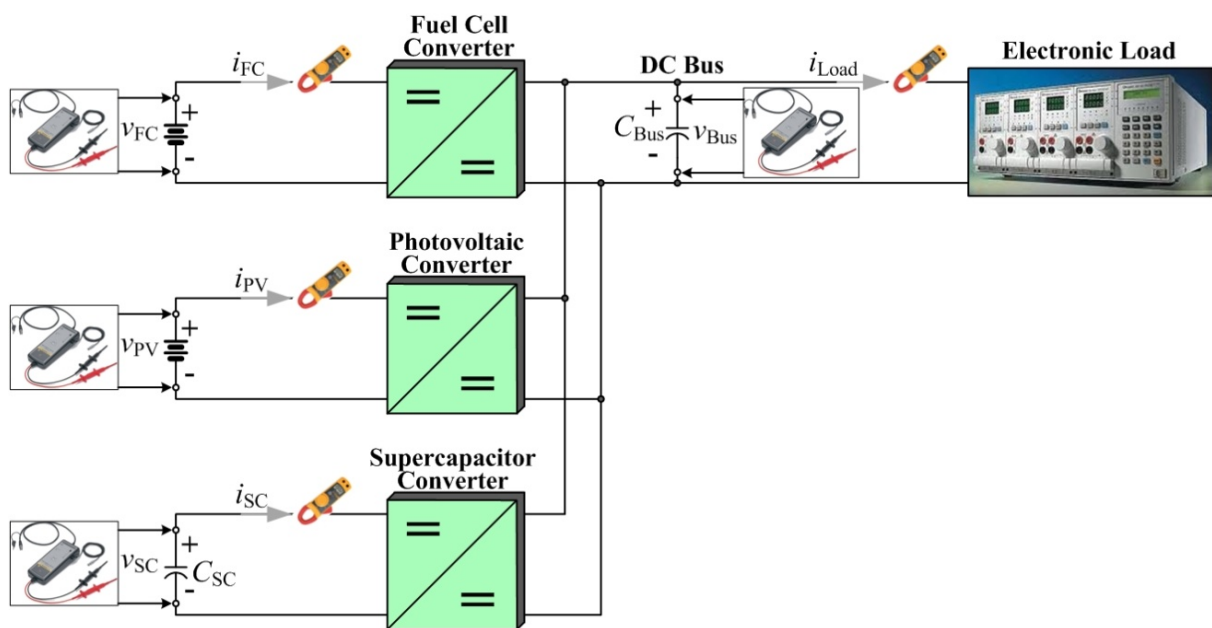


ภาพที่ 3-3 โมดูลซูเปอร์คาปาซิเตอร์

ตารางที่ 3-1 รายละเอียดแหล่งจ่ายไฟแต่ละตัว

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

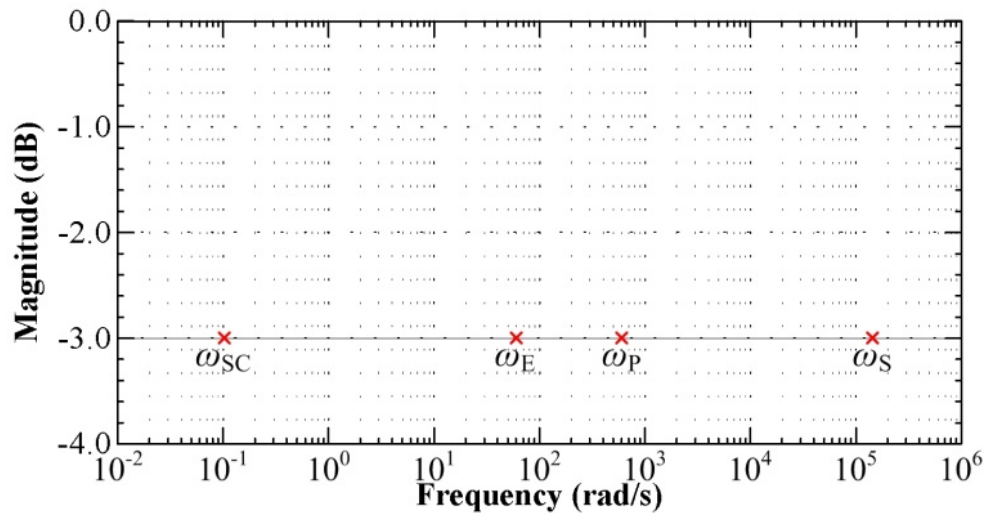
แรงดันที่บัสไฟตรงจะถูกควบคุมที่ 60 V และบัสไฟตรงจะถูกต่อเข้ากับโหลดอิเล็กทรอนิกส์เพื่อจำลองสถานะต่างๆ ของบัสไฟตรง การวัดค่ากระแสของเซลล์เชื้อเพลิง (i_{FC}) กระแสของโซลาร์เซลล์ (i_{PV}) กระแสของซูเปอร์คาปาซิเตอร์ (i_{SC}) กระแสของโหลด (i_{Load}) แรงดันที่บัสไฟตรง (V_{Bus}) แรงดันของเซลล์เชื้อเพลิง (V_{FC}) แรงดันของโซลาร์เซลล์ (V_{PV}) และแรงดันของซูเปอร์คาปาซิเตอร์ (V_{SC}) จะถูกวัดด้วย zero-flux Hall effect sensors ตำแหน่งจุดวัดต่างๆ แสดงดังภาพที่ 3-4 ระบบควบคุมพลังงานทั้งระบบถูกสร้างในตัวควบคุมแบบ real time ในการ์ด dSPACE DS1104 (ดังภาพที่ 3-1) ผ่านตัวคำนวณใน Matlab-Simulink ที่มีความถี่สุ่ม (sampling frequency) ที่ 25 kHz



ภาพที่ 3-4 จุดวัดแรงดันและกระแสของชุดทดลอง

3.2 รายละเอียดระบบควบคุม

อัตราขยายของตัวควบคุม $K_{11} = 450 \text{ rad}\cdot\text{s}^{-1}$ และ $K_{12} = 22,500 \text{ rad}^2\cdot\text{s}^{-2}$ เพื่อให้ระบบมีอัตราหน่วง (damping ratio) เท่ากับ 1.5 และมีความถี่ธรรมชาติ (natural frequency) เท่ากับ $150 \text{ rad}\cdot\text{s}^{-1}$ ซึ่งจะทำให้ cutoff frequency (ω_E) ของวงปิดของระบบควบคุมพลังงานที่บัสไฟตรงมีค่าเท่ากับ $60 \text{ rad}\cdot\text{s}^{-1}$ ซึ่งมีค่าต่ำกว่า cutoff frequency (ω_P) ของวงปิดของระบบควบคุมกำลังของซูเปอร์คาปาซิเตอร์ (ω_P) มีค่าเท่ากับ $600 \text{ rad}\cdot\text{s}^{-1}$ (ซึ่งวงปิดของระบบควบคุมกำลังของซูเปอร์คาปาซิเตอร์จะถูกประมาณเป็นตัวหน่วงลำดับที่ 1 มีค่าคงที่ของเวลา (time constant) เท่ากับ 2.2 ms ที่ได้จากการทดลอง identification) ดังนั้นระบบควบคุมมีเสถียรภาพ อัตราขยายของตัวควบคุมของวงปิดระบบควบคุมพลังงานรวม (หรือพลังงานของซูเปอร์คาปาซิเตอร์) $K_{21} = 0.1 \text{ W}\cdot\text{J}^{-1}$ ทำให้ cutoff frequency (ω_{sc}) ของวงปิดระบบควบคุมพลังงานรวมเท่ากับ $0.1 \text{ rad}\cdot\text{s}^{-1}$ ที่ซึ่ง $\omega_{sc} \ll \omega_E$ เพื่อเป็นการการันตีสำหรับการมีเสถียรภาพของทั้งระบบควบคุม ดังนั้น cutoff frequency ของทุกวงปิดแสดงได้ดังภาพที่ 3-5 ดังนั้นพารามิเตอร์ของระบบควบคุมทั้งสองวงแสดงดังตารางที่ 3-2 และ 3-3



ภาพที่ 3-5 การกำหนดค่าของตัวควบคุมโดยเลือกกำหนดค่า cutoff frequency ที่ซึ่ง ω_s คือความถี่สวิตช์ของตัวแปลงไฟของซูปเปอร์คาปาซิเตอร์ที่ 25 kHz ($157,080 \text{ rad}\cdot\text{s}^{-1}$) ω_p คือ cutoff frequency ของวงปิดของระบบควบคุมกำลังของซูปเปอร์คาปาซิเตอร์มีค่าเท่ากับ $600 \text{ rad}\cdot\text{s}^{-1}$ ω_E คือ cutoff frequency ของวงปิดของระบบควบคุมพลังงานที่บัสไฟตรงมีค่าเท่ากับ $60 \text{ rad}\cdot\text{s}^{-1}$ ω_{sc} และ คือ cutoff frequency ของวงปิดของระบบควบคุมพลังงานรวม (หรือพลังงานของซูปเปอร์คาปาซิเตอร์)

ตารางที่ 3-2 พารามิเตอร์ของระบบควบคุมพลังงานที่บัสไฟตรง

V_{BusREF}	60	V
C_{Bus}	12200	μF
K_{11}	450	$\text{rad}\cdot\text{s}^{-1}$
K_{12}	22,500	$\text{rad}^2\cdot\text{s}^{-2}$
r_{FC}	0.13	Ω
r_{SO}	0.10	Ω
r_{SC}	0.08	Ω
V_{SCMax}	32	V
V_{SCMin}	15	V
I_{SCRated}	150	A

ตารางที่ 3-3 พารามิเตอร์ของระบบควบคุมพลังงานรวม (หรือพลังงานของซูปเปอร์คาปาซิเตอร์)

V_{SCREF}	25	V
C_{SC}	100	F
K_{21}	0.1	$\text{W}\cdot\text{J}^{-1}$
p_{FCMin}	0	W
$I_{\text{FCMax}} (\text{Rated})$	46	A
I_{FCMin}	0	A
ζ_1	1	
ω_{n1}	0.4	$\text{rad}\cdot\text{s}^{-1}$

3.3 ผลการทดลอง

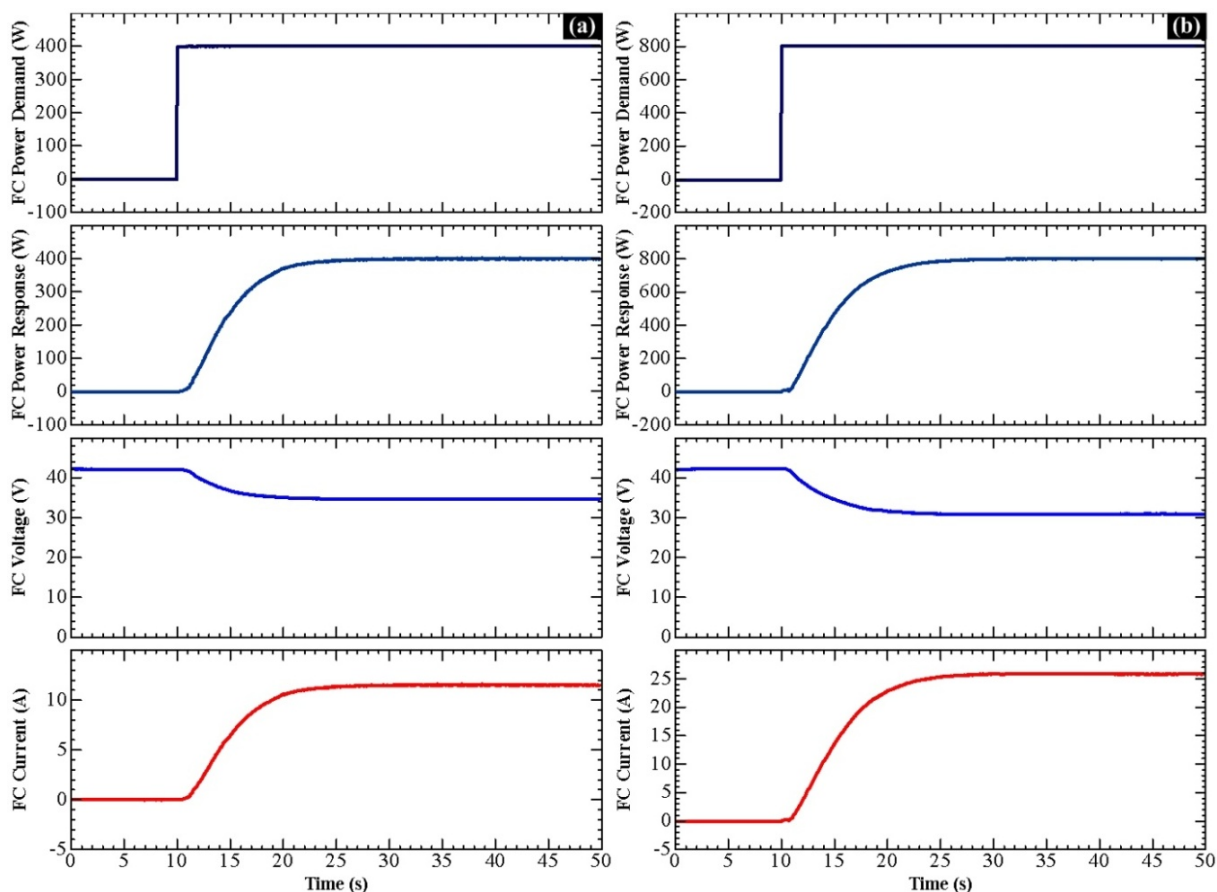
3.3.1 ไดนามิกส์ของระบบควบคุมกำลังของแต่ละแหล่งจ่าย (Power Loop Identification)

เพื่อเป็นการยืนยันถึงไดนามิกส์ของระบบควบคุมกำลัง (หรือกระแส) ของแหล่งจ่ายแต่ละตัว ภาพที่ 3-6 ถึงภาพที่ 3-8 แสดงผลการทดลองที่ทดสอบความเร็วในการตอบสนองต่อสัญญาณคำสั่งของกำลังของแต่ละแหล่งจ่าย ภาพที่ 3-6 แสดงการตอบสนองต่อสัญญาณคำสั่งของกำลังของเซลล์เชื้อเพลิง ในภาพนำเสนอคำสั่งอ้างอิงของกำลังของเซลล์เชื้อเพลิง (FC Power Demand) กำลังของเซลล์เชื้อเพลิง (FC Power Response) แรงดันของเซลล์เชื้อเพลิง (FC Voltage) และกระแสของเซลล์เชื้อเพลิง (FC Current) ชัดเจนที่การตอบสนองของกำลังของเซลล์เชื้อเพลิงเป็นตัวหน่วงลำดับที่ 2 (second order characteristics) เป็นไปตามสมการที่ (2-52) และเห็นได้ชัดที่ไม่มีปรากฏการณ์การหิวเชื้อเพลิง (fuel starvation phenomenon) เกิดขึ้นในเซลล์ เนื่องจากระบบมีการหน่วงการทำงานของกำลังจากเซลล์เชื้อเพลิงไม่ให้งานเร็วเกินไปนั่นเอง ส่วนในภาพที่ 3-7 แสดงการตอบสนองต่อสัญญาณคำสั่งของกำลังของโซลาร์เซลล์ ในภาพนำเสนอคำสั่งอ้างอิงของกำลังของโซลาร์เซลล์ (PV Power Demand) กำลังของโซลาร์เซลล์ (PV Power Response) แรงดันของโซลาร์เซลล์ (PV Voltage) และกระแสของโซลาร์เซลล์ (PV Current) สุดท้ายภาพที่ 3-8 แสดงการตอบสนองต่อสัญญาณคำสั่งของกำลังของซูเปอร์คาปาซิเตอร์ ในภาพนำเสนอคำสั่งอ้างอิงของกำลังของซูเปอร์คาปาซิเตอร์ (PV Power Demand) กำลังของซูเปอร์คาปาซิเตอร์ (PV Power Response) แรงดันของซูเปอร์คาปาซิเตอร์ (PV Voltage) และกระแสของซูเปอร์คาปาซิเตอร์ (PV Current) เห็นได้ชัดว่าการตอบสนองของกำลังจากซูเปอร์คาปาซิเตอร์เป็นไปอย่างรวดเร็วมาก มันสามารถจ่ายกำลังไปสู่บัสไฟตรงจาก 0 W ถึง 400 W ใช้เวลาแค่ประมาณ 50 ms เท่านั้น ซึ่งนี่คือจุดเด่นของแบตเตอรี่ชนิดซูเปอร์คาปาซิเตอร์ที่เหนือกว่าแบตเตอรี่ชนิดอื่นๆ ในด้านไดนามิกส์และ Power Densities

3.3.2 ไดนามิกส์ของการควบคุมบัสไฟตรง

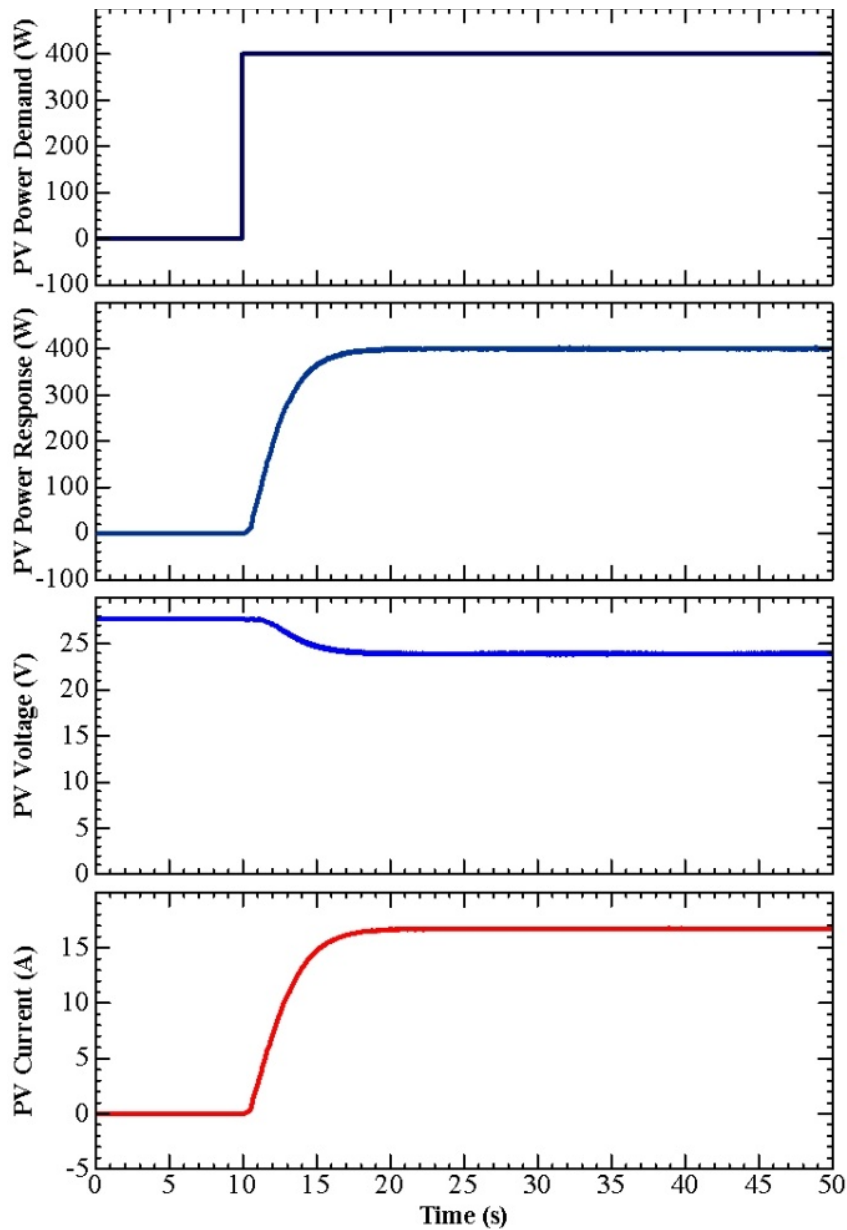
ภาพที่ 3-9 แสดงสัญญาณขณะมีการสลับโหลดขนาดใหญ่ แสดงแรงดันบัสไฟตรง (dc bus voltage) (ซึ่งคือตัวแปรสถานะ x_1 นำเสนอแทนตัวแปรเอาต์พุต y_1) โหลด (load power) (หรือก็คือสัญญาณรบกวน) กำลังของซูเปอร์คาปาซิเตอร์ (supercapacitor power) (ซึ่งคือตัวแปรควบคุมที่เป็นอินพุตตัวที่ 1 u_1) และกำลังของโซลาร์เซลล์ (PV power) เริ่มต้นขณะที่ไม่มีโหลด ซูเปอร์คาปาซิเตอร์ถูกชาร์จเต็มแล้ว (นั่นคือ $V_{SCREF} = 25$ V) และบัสไฟตรงถูกควบคุมให้คงที่ที่ 60 V ($V_{BusREF} = 60$ V) เป็นผลทำให้กำลังของเซลล์เชื้อเพลิง โซลาร์เซลล์และซูเปอร์คาปาซิเตอร์มีค่าเท่ากับศูนย์ ขณะทดลองกำลังสูงสุดจากโซลาร์เซลล์ถูกจำกัดอยู่ที่ประมาณ 400 W โดยตัวติดตามกำลังสูงสุด (MPPT) ผลการทดลองแสดงให้เห็นการตอบสนองทางไดนามิกส์ต่อการสลับโหลดขนาดใหญ่เป็นไปตามสมการที่ (2-47) ซึ่งเป็นไปตามลักษณะสมบัติของสมการหน่วงลำดับที่ 2 การแกว่งเล็กน้อยของบัสไฟตรงเพราะว่าอัตราขยาย K_{12} มีค่าสูงและโหลดมีค่าสูงมาก ค่าอัตราขยาย K_{12} สามารถลดลงได้เพื่อลดการแกว่ง อย่างไรก็ตาม มันจะทำให้การตอบสนองช้าลง กฎการควบคุม (control law) แสดงให้เห็นว่าระบบมีเสถียรภาพและมีการตอบสนองที่ดีที่สุดเพื่อควบคุมแรงดันที่บัสไฟตรงที่ 60 V ถึงแม้ว่าไดนามิกส์ของระบบควบคุมสามารถทำให้ดีขึ้นได้แต่ระบบอาจจะเข้าไปใกล้ขอบของการไม่มีเสถียรภาพได้ (reduced

stability margin) ข้อสังเกต ในทางปฏิบัติการสร้างโหลดที่เป็นสเตปจะทำได้ยากดังแสดงในภาพ และเนื่องจากกำลังของเซลล์เชื้อเพลิงถูกจำกัดด้านไดนามิกส์ ดังนั้นไดนามิกส์ของโหลดจะจ่ายโดยซูเปอร์คาปาซิเตอร์และโซล่าเซลล์

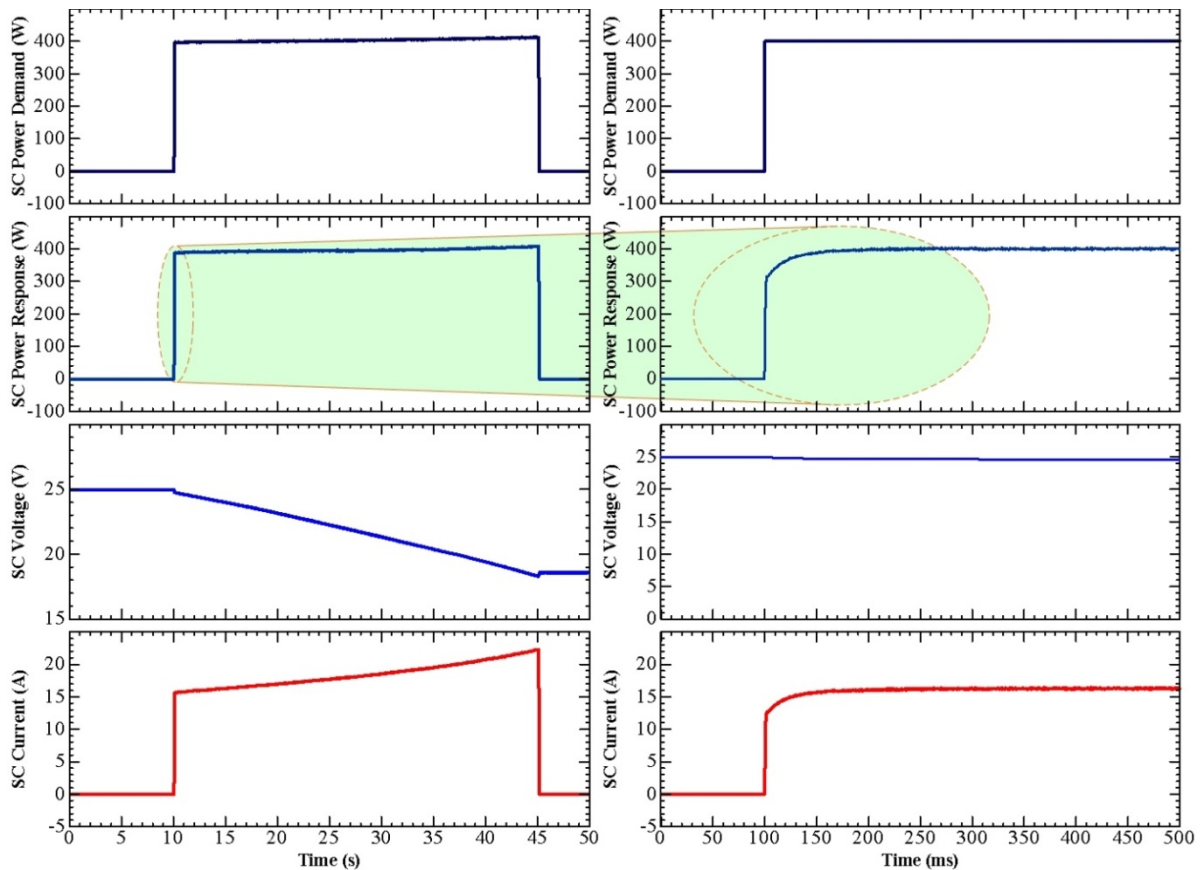


ภาพที่ 3-6 ไดนามิกส์ของระบบควบคุมกำลังของเซลล์เชื้อเพลิง นำเสนอคำสั่งอ้างอิงของกำลังของเซลล์เชื้อเพลิง (FC Power Demand) กำลังของเซลล์เชื้อเพลิง (FC Power Response) แรงดันของเซลล์เชื้อเพลิง (FC Voltage) และกระแสของเซลล์เชื้อเพลิง (FC Current)

- คำสั่งอ้างอิงของกำลังของเซลล์เชื้อเพลิงสเตปจาก 0 W ไปยัง 400 W ที่เวลา 10 s
- คำสั่งอ้างอิงของกำลังของเซลล์เชื้อเพลิงสเตปจาก 0 W ไปยัง 800 W ที่เวลา 10 s

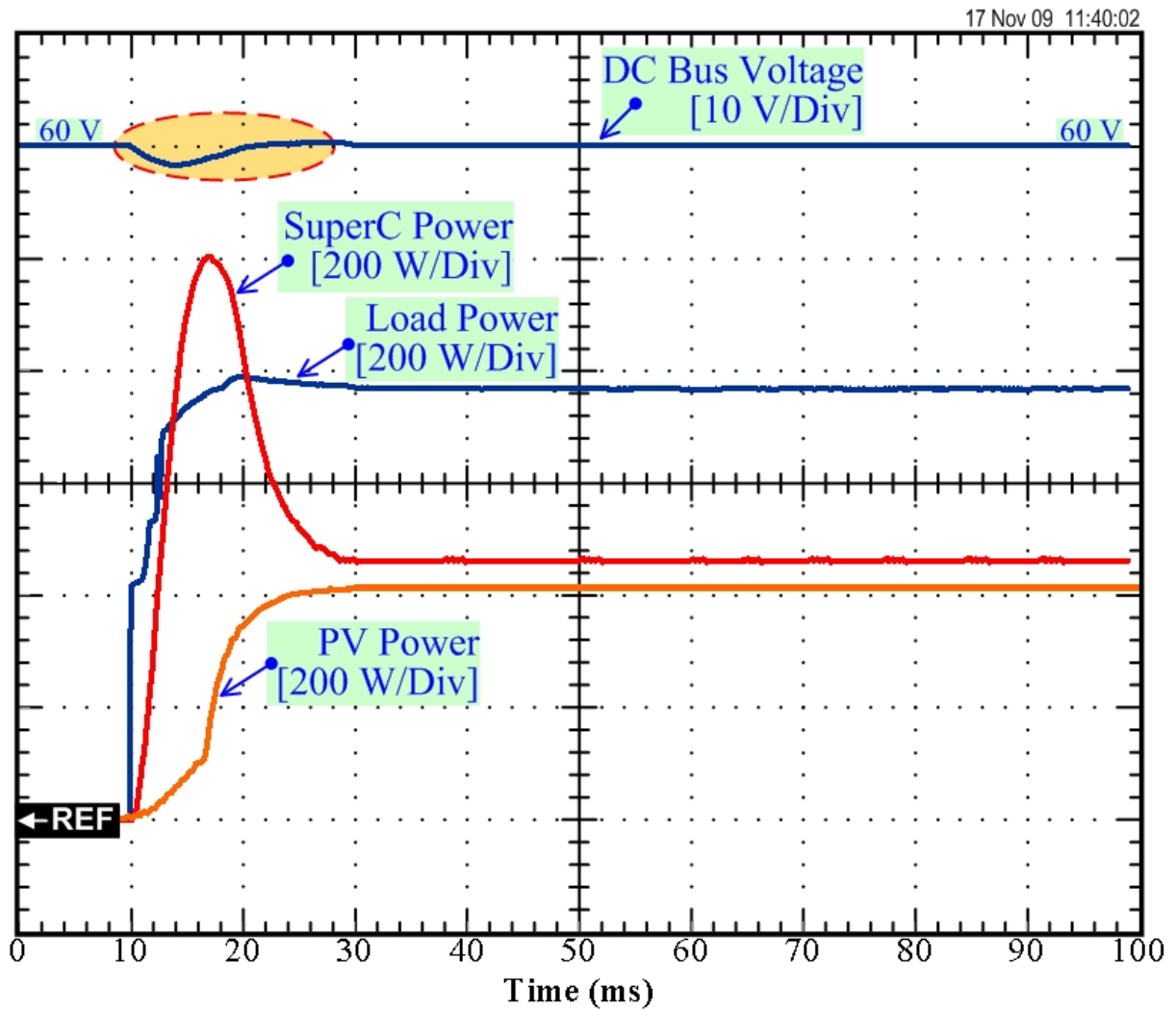


ภาพที่ 3-7 ไดนามิกส์ของระบบควบคุมกำลังของโซลาร์เซลล์ นำเสนอคำสั่งอ้างอิงของกำลังของโซลาร์เซลล์ (PV Power Demand) กำลังของโซลาร์เซลล์ (PV Power Response) แรงดันของโซลาร์เซลล์ (PV Voltage) และกระแสของโซลาร์เซลล์ (PV Current)

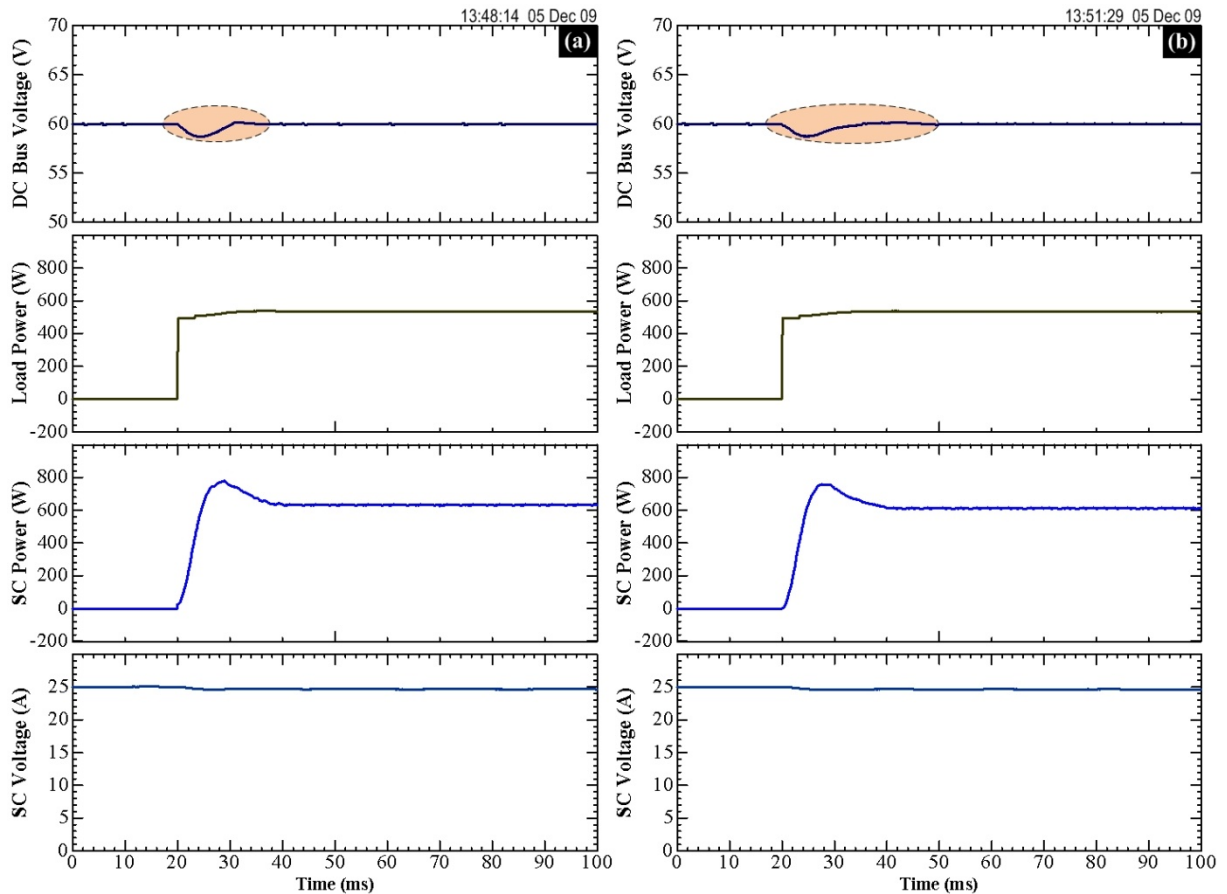


ภาพที่ 3-8 ไดนามิกส์ของระบบควบคุมกำลังของซูเปอร์คาปาซิเตอร์ นำเสนอคำสั่งอ้างอิงของกำลังของซูเปอร์คาปาซิเตอร์ (SC Power Demand) กำลังของซูเปอร์คาปาซิเตอร์ (SC Power Response) แรงดันของซูเปอร์คาปาซิเตอร์ (SC Voltage) และกระแสของซูเปอร์คาปาซิเตอร์ (SC Current)

เนื่องจากระบบควบคุมโดยวิธีการคำนวณแบบ flatness จะต้องมีการพารามิเตอร์ของระบบเข้ามาคำนวณด้วย ซึ่งระบบอาจจะไม่มีการเปลี่ยนแปลงของพารามิเตอร์เหล่านี้ เพื่อยืนยันว่าวิธีการควบคุมแบบนี้ไม่มีผลกระทบต่อการเปลี่ยนแปลงพารามิเตอร์ในระบบ (robustness) ระบบควบคุมถูกทดลองเปรียบเทียบกับไดนามิกส์ของระบบที่ต้องการ ($r_{FC} = 0.14 \, \Omega$, $r_{PV} = 0.12 \, \Omega$, $r_{SC} = 0.10 \, \Omega$) และพารามิเตอร์คลาดเคลื่อน ($r_{FC} = 0 \, \Omega$, $r_{PV} = 0 \, \Omega$, $r_{SC} = 0 \, \Omega$) ผลการทดลองเพื่อเปรียบเทียบโมเดลที่ต้องการและโมเดลคลาดเคลื่อนแสดงดังภาพที่ 3-10 เป็นการทดลองขณะที่มีการสลับของโหลดขนาดใหญ่จาก 0 W ถึง 500 W แสดงสัญญาณแรงดันที่บัสไฟตรง (DC bus voltage) กำลังของโหลด (Load power) กำลังของซูเปอร์คาปาซิเตอร์ (SC power) และแรงดันของซูเปอร์คาปาซิเตอร์ (SC voltage) เพราะว่ากำลังจากเซลล์เชื้อเพลิงและโซลาร์เซลล์ช้ากว่ากำลังจากซูเปอร์คาปาซิเตอร์มาก ดังนั้นซูเปอร์คาปาซิเตอร์จะจ่ายกำลังไดนามิกส์ที่โหลดต้องการทั้งหมด เห็นได้ชัดว่าสัญญาณในภาพที่ 3-10(a) และ (b) จะไม่แตกต่างกันมากนัก แรงดันที่บัสไฟตรงจะมีผลกระทบมาจากการสลับของโหลดขนาดใหญ่ แต่ระบบควบคุมไม่มีผลกระทบมากนักจากที่พารามิเตอร์ในโมเดลคลาดเคลื่อน ดังนั้นทำให้สรุปได้ว่าระบบควบคุมแบบ flatness มีความทนทานต่อการเปลี่ยนแปลงพารามิเตอร์ (robustness)



ภาพที่ 3-9 การตอบสนองต่อการสลับโหลดจาก 0 W ถึง 760 W ที่เวลา $t = 10$ ms หมายถึง $p_{\text{Load}} \approx p_{\text{SC}} + p_{\text{PV}}$ ($p_{\text{FC}} \approx 0$ ช่วงไดนามิกส์)



ภาพที่ 3-10 เปรียบเทียบไดนามิกการควบคุมแรงดันที่บัสไฟตรงของแหล่งจ่ายไฟแบบผสมขณะที่มีการสลับของโหลดค่าสูง

- a). โมเดลถูกต้อง ($r_{FC} = 0.14 \, \Omega$, $r_{PV} = 0.12 \, \Omega$, $r_{SC} = 0.10 \, \Omega$)
 b). โมเดลคลาดเคลื่อน ($r_{FC} = 0 \, \Omega$, $r_{PV} = 0 \, \Omega$, $r_{SC} = 0 \, \Omega$)

3.3.3 รอบของโหลด (Load Cycle)

ภาพที่ 3-11 แสดงสัญญาณขณะจ่ายไฟให้กับโหลดรอบเดียว แสดงแรงดันที่บัสไฟตรง (dc bus voltage) (ซึ่งคือตัวแปรสแตตัสที่ 1 x_1 , นำเสนอแทนตัวแปรเอาต์พุต y_1) แรงดันของเซลล์เชื้อเพลิง (FC voltage) แรงดันของโซล่าเซลล์ (PV voltage) กำลังของโหลด (load power) กำลังของซูเปอร์คาปาซิเตอร์ (supercapacitor power) (หรือตัวแปรอินพุต u_1) กำลังของเซลล์เชื้อเพลิง (FC power) กำลังของโซล่าเซลล์ (PV power) กระแสของซูเปอร์คาปาซิเตอร์ (supercapacitor current) กระแสของเซลล์เชื้อเพลิง (FC current) กระแสของโซล่าเซลล์ (PV current) และแรงดันของซูเปอร์คาปาซิเตอร์ (supercapacitor voltage) (ซึ่งคือตัวแปรสแตตัสที่ 2 x_2 หรือนำเสนอสถานะการชาร์จของซูเปอร์คาปาซิเตอร์ (supercapacitor state-of-charge)) สถานะเริ่มต้นอยู่ในสถานะที่ไม่มีโหลดและซูเปอร์คาปาซิเตอร์ถูกชาร์จเต็มแล้ว ($v_{SC} = 25 \, V$) เป็นผลให้กำลังของเซลล์เชื้อเพลิง โซล่าเซลล์และซูเปอร์คาปาซิเตอร์เท่ากับศูนย์ ที่เวลา $t = 20 \, s$ โหลดขนาดใหญ่สลับจาก $0 \, W$ ไปยัง $840 \, W$ ขณะทำการทดลอง กำลังสูงสุดของโซล่าเซลล์ (ซึ่งขึ้นอยู่กับมุมรับแสง สภาพอากาศและอุณหภูมิ) มีค่าเท่ากับประมาณ $200 \, W$ ถูกคำนวณโดยตัว MPPT และกำลังสูงสุดของเซลล์เชื้อเพลิงถูกจำกัดไว้ที่ $360 \, W$ ดังนั้น กำลังของ

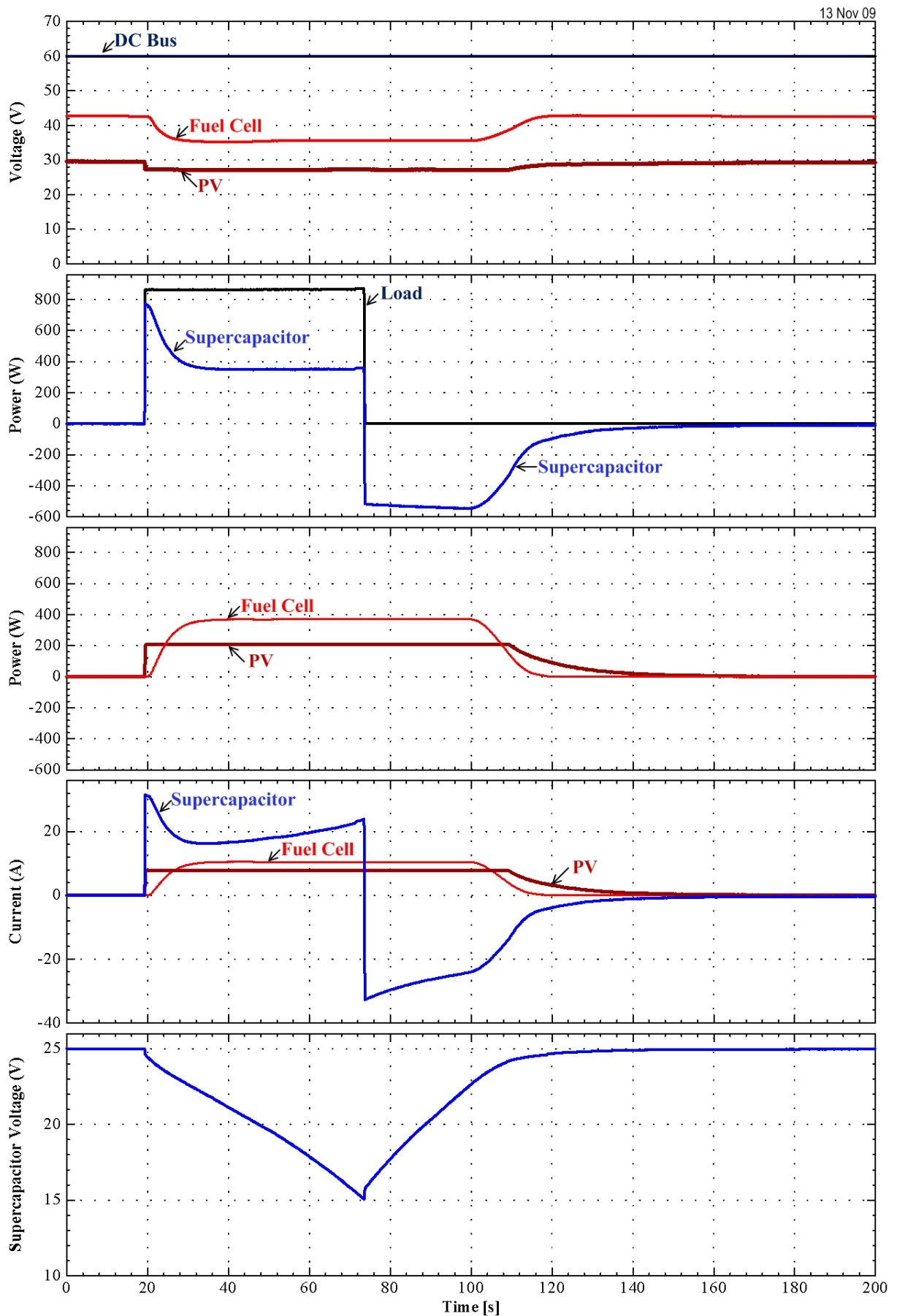
เซลล์เชื้อเพลิงไหลเพิ่มขึ้นพร้อมๆ กับการจำกัดความชันในลักษณะของตัวหน่วงลำดับที่ 2 (second order dynamics) ไปจนถึงกำลังสูงสุดที่จำกัดที่ 360 W ชูปเปอร์คาปาซิเตอร์และโซล่าเซลล์จ่ายไฟทั้งหมดช่วงไดนามิกส์ขณะโหลดกระชาก ชูปเปอร์คาปาซิเตอร์ยังคงอยู่ในสถานะคายประจุหลังจากโหลดสเทปเพราะโหลดที่สภาวะอยู่ตัว (840 W) มีค่าสูงกว่ากำลังสูงสุดรวมกันจากเซลล์เชื้อเพลิงและโซล่าเซลล์

หลังจากนั้นที่เวลา $t = 72$ s โหลดสเทปจาก 840 W ไปยัง 0 เป็นผลให้ชูปเปอร์คาปาซิเตอร์เปลี่ยนสถานะจากคายประจุเป็นชาร์จประจุ มีปรากฏการณ์ 4 อย่างเกิดขึ้น

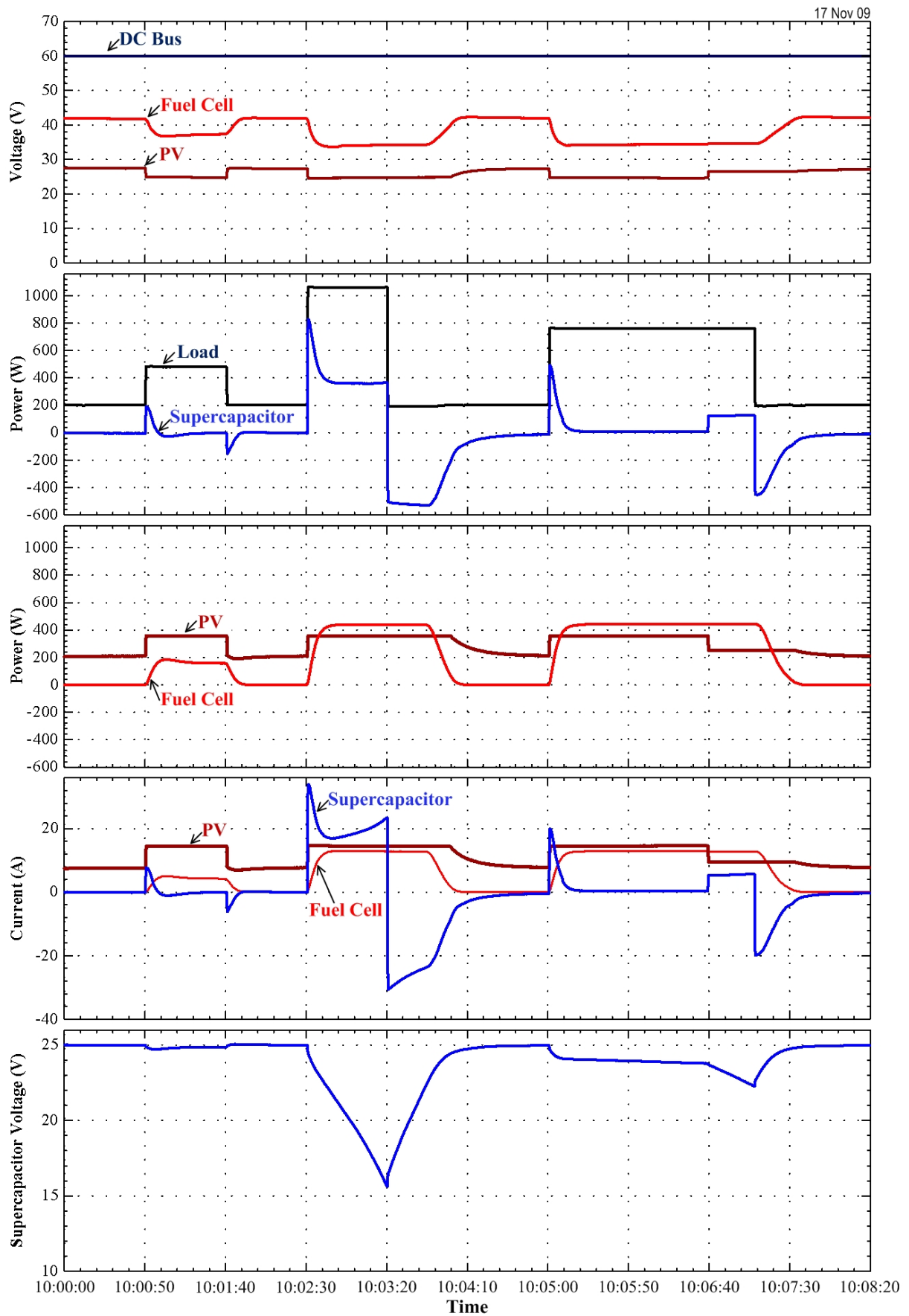
- ปรากฏการณ์แรก เซลล์เชื้อเพลิงและโซล่าเซลล์ยังคงจ่ายไฟที่กำลังสูงสุด เพื่อขับโหลดและชาร์จชูปเปอร์คาปาซิเตอร์
- ปรากฏการณ์ที่สอง ที่เวลา $t = 100$ s ($v_{sc} = 23$ V) ชูปเปอร์คาปาซิเตอร์ถูกชาร์จเก็บประจุเกือบเต็ม ทำให้ชูปเปอร์คาปาซิเตอร์ลดกำลังในการชาร์จประจุลง เป็นผลให้กำลังจากเซลล์เชื้อเพลิงลดลง
- ปรากฏการณ์ที่สาม ที่เวลา $t = 108$ s ($v_{sc} = 24.5$ V) ชูปเปอร์คาปาซิเตอร์ถูกชาร์จเก็บประจุเกือบเต็มที่แล้ว เป็นผลให้กำลังจากเซลล์เชื้อเพลิงและโซล่าเซลล์ลดลง
- ปรากฏการณ์ที่สี่ ที่เวลา $t = 160$ s ชูปเปอร์คาปาซิเตอร์ถูกชาร์จเต็ม เป็นผลให้กำลังของเซลล์เชื้อเพลิง โซล่าเซลล์และชูปเปอร์คาปาซิเตอร์มีค่าเท่ากับศูนย์

เห็นได้ชัดว่าสัญญาณแรงดันที่บัสไฟตรงมีเสถียรภาพตลอดรอบของโหลดขนาดใหญ่ ซึ่งเป็นจุดเด่นที่สำคัญที่มีชูปเปอร์คาปาซิเตอร์ช่วยทำให้สมรรถนะด้านไดนามิกส์ของทั้งระบบดีขึ้น

สุดท้าย ภาพที่ 3-12 แสดงสัญญาณขณะทดลองมีรอบของโหลดหลายรอบ สัญญาณก็จะคล้ายๆ กับภาพที่ 3-11 ขณะทำการทดลอง กำลังสูงสุดจากเซลล์เชื้อเพลิงถูกจำกัดที่ 440 W และกำลังจากโซล่าเซลล์ถูกจำกัดโดย MPPT ตัวอย่างเช่นที่เวลา 10:00:50 กำลังสูงสุดจากโซล่าเซลล์มีค่าประมาณ 360 W ที่เวลา 10:03:20 กำลังสูงสุดจากโซล่าเซลล์มีค่าประมาณ 360 W ที่เวลา 10:05:50 กำลังสูงสุดจากโซล่าเซลล์มีค่าประมาณ 360 W ที่เวลา 10:06:40 กำลังสูงสุดจากโซล่าเซลล์มีค่าลดลงจาก 360 W ไปยัง 240 W ชัดเจนมากที่แหล่งจ่ายไฟแบบผสมนี้มีการทำงานที่สมดุลย์ตลอดเวลา ($p_{Load}(t) \approx p_{FC}(t) + p_{PV}(t) + p_{sc}(t)$) ด้วยวิธีการควบคุมที่นำเสนอ



ภาพที่ 3-11 การตอบสนองของแหล่งจ่ายไฟแบบผสมต่อโหลดรอบเดียว



ภาพที่ 3-12 การตอบสนองของแหล่งจ่ายไฟแบบผสมต่อโหลดหลายรอบ

จุดเด่นหลักของงานวิจัยนี้คือนำเสนอการหาโมเดลและการควบคุมโรงไฟฟ้าแบบผสมที่จ่ายไฟโดยเซลล์เชื้อเพลิง โซลาร์เซลล์และแบตเตอรี่ชนิดซูเปอร์คาปาซิเตอร์ โรงไฟฟ้าต้นแบบที่ทำการศึกษารวบรวมด้วยระบบเซลล์เชื้อเพลิงชนิด PEMFC (ขนาด 1200 W เรียกว่า Nexa Ballard FC power system) แผงโซลาร์เซลล์ (ขนาด 800 W ของบริษัท เอกรัฐโซลาร์ จำกัด) และโมดูลของซูเปอร์คาปาซิเตอร์ (100 F, 32 V ของบริษัท Maxwell Technologies) วงจรแปลงไฟแบบทบทแรงดันขนานกันสี่ตัวสำหรับเซลล์เชื้อเพลิง วงจรแปลงไฟแบบทบทแรงดันขนานกันสองตัวสำหรับโซลาร์เซลล์และวงจรแปลงไฟแบบสองทิศทางขนานกันสี่ตัวสำหรับซูเปอร์คาปาซิเตอร์ ซึ่งเป็นต้นแบบสำหรับงานกำลังสูง หลักการทำงาน การวิเคราะห์และการออกแบบแต่ละขั้นตอนได้ถูกนำเสนอ

โซลาร์เซลล์จะทำงานเป็นแหล่งจ่ายไฟหลัก ขณะที่เซลล์เชื้อเพลิงจะช่วยจ่ายไฟเพื่อชดเชยบางสถานการณ์ที่โซลาร์เซลล์ไม่สามารถจ่ายไฟได้ในสถานะอยู่ตัว ซูเปอร์คาปาซิเตอร์ทำหน้าที่เป็นแหล่งพลังงานสำรองหรือแหล่งจ่ายไฟสำรอง ช่วยจ่ายไฟเมื่อเซลล์เชื้อเพลิงและโซลาร์เซลล์ไม่สามารถจ่ายไฟทั้งในสถานะอยู่ตัวและไดนามิกส์

ด้วยวิธีการควบคุมแบบไม่เชิงเส้นแบบ flatness งานวิจัยนี้นำเสนอวิธีการแก้ปัญหาอย่างง่ายสำหรับปัญหาด้านไดนามิกส์ เสถียรภาพและความทนทานต่อการเปลี่ยนแปลงของพารามิเตอร์ในระบบอิเล็กทรอนิกส์กำลังซึ่งเป็นระบบไม่เป็นเชิงเส้น ซึ่งเป็นแนวคิดต้นแบบสำหรับการประยุกต์ใช้งานในลักษณะนี้

ชุดทดลองด้านฮาร์ดแวร์ได้ถูกออกแบบและสร้างขึ้นจริงในห้องทดลอง เพื่อพิสูจน์ยืนยันวิธีการควบคุมและกฎการควบคุม ผลการทดลองพิสูจน์ให้เห็นว่าระบบทำงานได้เป็นอย่างดี

อย่างไรก็ตาม กฎการควบคุมที่นำเสนอมีความจำเป็นต้องวัดกระแสของโหลด เพื่อคำนวณกำลังของโหลด งานในอนาคต ระบบจะต้องมีตัวสังเกตการณ์ของโหลด (load observer) เพื่อหลีกเลี่ยงการวัดกระแสของโหลดนี้



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Output จากโครงการวิจัยที่ได้รับทุนจาก สกว.

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Comparative Study of Fuel-Cell Vehicle Hybridization with Battery or Supercapacitor Storage Device

Phatiphat Thounthong, *Member, IEEE*, Viboon Chunkag, Panarit Sethakul, Bernard Davat, *Member, IEEE*, and Melika Hinaje

Abstract—This paper studies the impact of fuel-cell (FC) performance and control strategies on the benefits of hybridization. One of the main weak points of the FC is slow dynamics dominated by a temperature and fuel-delivery system (pumps, valves, and, in some cases, a hydrogen reformer). As a result, fast load demand will cause a high voltage drop in a short time, which is recognized as a fuel-starvation phenomenon. Therefore, to employ an FC in vehicle applications, the electrical system must have at least an auxiliary power source to improve system performance when electrical loads demand high energy in a short time. The possibilities of using a supercapacitor or a battery bank as an auxiliary source with an FC main source are presented in detail. The studies of two hybrid power systems for vehicle applications, i.e., FC/battery and FC/supercapacitor hybrid power sources, are explained. Experimental results with small-scale devices (a polymer electrolyte membrane FC of 500 W, 40 A, and 13 V; a lead-acid battery module of 33 Ah and 48 V; and a supercapacitor module of 292 F, 500 A, and 30 V) in a laboratory authenticate that energy-storage devices can assist the FC to meet the vehicle power demand and help achieve better performance, as well as to substantiate the excellent control schemes during motor-drive cycles.

Index Terms—Battery, converters, current control, electric vehicles, fuel cells (FCs), power supplies, supercapacitor, voltage regulation.

I. INTRODUCTION

FUEL CELLS (FCs) are able to generate electrical power with high efficiency, low operation noise, and no emissions

from hydrogen gaze and air. Byproducts are exhaust gases, water, and waste heat. The supplied electrical power can be used in vehicles for propulsion as well as for the operation of electrically powered accessories. Polymer electrolyte membrane (or proton exchange membrane) FCs (PEMFCs) utilize a solid polymer electrolyte membrane, operate at lower temperature, and are considered by many to be the most suitable for vehicle applications (such as cars, buses, tramways, trains, or aircraft) [1], [2].

Although recent literature portrays FCs as a newly emerging energy source, the technology was actually invented in the 19th century. In 1839, Sir William Grove, a Welsh judge and scientist, assembled the first FC. Since then, FCs have been primarily used in research settings. The National Aeronautics and Space Administration selected PEMFCs for the space program in the 1960s, rejecting both nuclear power, which had a higher safety risk, and solar power, which had a higher cost [1]. FCs provided power for the Gemini and Apollo missions and, at present, provide water and electricity to the space shuttle. Despite their high-profile use in the space program, the commercialization of FC technology was not explored until the early 1980s.

Many factors have limited the marketable development of FCs, including manufacturing cost, fuel generation and distribution, and system complexity. The high manufacturing cost is caused by a number of factors: expensive raw materials used as catalysts, expensive membrane materials, and expensive fabrication processes for collector plates.

In addition to manufacturing cost, fuel generation and distribution have also prevented widespread commercialization. Most FCs consume pure hydrogen or hydrogen-rich gas as the primary fuel. So far, experimental results and real-world applications of PEMFCs revealed that they perform best on pure hydrogen (H_2) as anode input gas. However, for many applications, particularly mobile, due to a lack of availability of refueling infrastructure and impractical storage techniques, pure hydrogen is not yet a viable option. Pure hydrogen as an anode gas source for PEMFCs, at this time, has a number of formidable limitations. One of the major limitations is onboard hydrogen storage. As a viable alternative for carrying pure hydrogen, onboard hydrogen generation by reforming hydrocarbons such as natural gas, gasoline, or alcohol fuels would be an obvious choice. However, gas produced from a reformer contains about 70%–75% hydrogen, 20%–25% carbon dioxide (CO_2 poisoning), and 10–100 ppm carbon monoxide

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(CO poisoning) [3]; furthermore, these reformers are large and expensive, and they operate at high temperatures.

Since most advanced vehicles like FC electric vehicles have one energy storage (buffer) device as part of the propulsion system, it is possible and necessary to apply advanced control technologies to significantly optimize the vehicle's fuel economy, emissions, and/or drivability [4], [5].

Nonetheless, the recent studies of Corrêa *et al.* [6], who worked with a 0.5-kW PEMFC (BCS Technology Company) and a 0.5-kW PEMFC (Avista Company), Thounthong *et al.* [5], [7], who worked with a 0.5-kW PEMFC [Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW) Company, Germany] and a 1.2-kW Nexa PEMFC (Ballard Power System Company, Canada), Adzakpa *et al.* [8], who worked with a 0.6-kW PEMFC (H Power Company), Wang *et al.* [9], who worked with a 0.5-kW PEMFC (Avista Company), and Gaynor *et al.* [10], who worked with a 350-kW Solid Oxide FC, have demonstrated the fact that the FC time constants are dominated by a temperature and fuel-delivery system (pumps, valves, and, in some cases, a hydrogen reformer). As a result, fast energy demand will cause a high voltage drop in a short time, which is recognized as a fuel-starvation phenomenon [11].

When starved from fuel or oxygen, the FC performance degrades, and the cell voltage drops. This condition of operation is evidently hazardous for the FC stack [11], [12]. Fuel starvation can result in generation of hydrogen in the cathode or oxygen in the anode. For instance, in the event of hydrogen starvation, the cell current cannot be maintained, causing a high anode potential. Therefore, the water, which is present at the anode, may split into hydrogen and oxygen, producing oxygen in the anode. In the same way, during oxygen starvation, the reaction at the cathode will produce hydrogen. The presence of oxygen at the anode and hydrogen at the cathode will lead to the reversal of the cell potential, which is a negative potential difference between the anode and the cathode. Cell reversal accelerates the corrosion of carbon components such as backing layers with ensuing electrocatalyst corrosion and eventually leads to damaged components. During hydrogen starvation, oxygen at the anode can react with the carbon present in the gas diffusion and backing layers to form carbon dioxide (CO₂ poisoning).

Thus, to utilize an FC in dynamic applications, its current or power slope must be limited to circumvent the fuel-starvation problem, e.g., 4 A · s⁻¹ for a 0.5-kW 12.5-V PEMFC [13] and 5, 10, and 50 A · s⁻¹ for a 20-kW 48-V PEMFC [14]. As a result, the vehicle electrical system must have at least an auxiliary power source (an energy storage device), such as a battery, supercapacitor, or flywheel, to improve the system performance when electrical loads at a dc bus demand high power in a short time (e.g., vehicle acceleration and deceleration) [15], [16]. Therefore, an FC vehicle can benefit from being hybridized with an energy-storage device [17]–[19], which assumes some of the roles that the FC would normally handle.

This paper deals with the conception and the achievement of a hybrid power source that is supplied by a PEMFC as the main energy source and a battery or a supercapacitor as an auxiliary power source, particularly for future vehicle

applications. Its interest is focused on control algorithms. It enables the management of transient power demand, power peaks, and regenerative braking with regard to FC, battery, and supercapacitor constraints. The general structures of the studied systems, the control principles of the hybrid sources, the realization of the experimental bench, and the experimental validation will be presented in the following sections.

II. BATTERY VERSUS SUPERCAPACITOR AS AN ENERGY-STORAGE DEVICE

Currently, the battery is still the most extensive energy-storage device for providing and deliver electricity. There are many kinds of battery technology, such as lead-acid, NiCd, NiMH, or Li-ion. For a lead-acid cell, the terminal voltage of battery V_b and the internal resistance R_b are strong functions of the state of charge (SOC). The battery actual voltage curve is not constant. This is because the internal resistance is almost linear during the discharge, but the losses are substantially below 25% SOC due to the increase in the internal resistance. Therefore, the battery SOC estimation is defined here again as [20], [21]

$$\text{SOC}(t) = \frac{1}{Q_{\text{Bat}}} \int_{t_0}^t i_{\text{Bat}}(t) \cdot dt + \text{SOC}_0(t_0) \quad (1)$$

where SOC_0 is the known battery SOC (in percentage) at time t_0 , Q_{Bat} is the rated capacity (in ampere-hours), and $i_{\text{Bat}}(t)$ is the charging battery current (in amperes).

Supercapacitors (or ultracapacitors) are an emerging technology in the field of energy storage systems. Current breakthroughs in material design and fabrication methods that are aimed at maximizing rated capacitance have provided tremendous increases in the energy-storage capabilities of supercapacitors [22], [23]. The terminal voltage of supercapacitors is limited, however, due to the dissociation of the electrolyte. This limits the maximum voltage to 2.5–3 V.

When comparing the power characteristics of supercapacitors and batteries, the comparisons should be made for the same charge/discharge efficiency. The relative performance of supercapacitors and power batteries can be directly assessed from the pulse power tests since both types of devices are capable of high-power pulses, although batteries are not intended to be charged/discharged for long periods at these high power levels. The pulse testing of a battery is usually done at a specified partial SOC, as only a small fraction of the energy stored in the battery is used in the cycle tests. Of particular interest in the pulse tests is the round-trip efficiency of the devices. This is determined from the ratio of the energy out of the devices to the energy into the devices during the test cycle. This efficiency primarily depends on the internal equivalent series resistance (ESR) of the device. For supercapacitors, their charge/discharge efficiency is high, and the energy lost to heat during each cycle is relatively small and readily removed. The energy lost to heat in batteries is a much larger amount, making heat removal more crucial and its extraction costs much higher. This is to say that the cycle efficiency of batteries is around 80%, and the cycle efficiency of supercapacitors is around 95% [24], [25]. For a

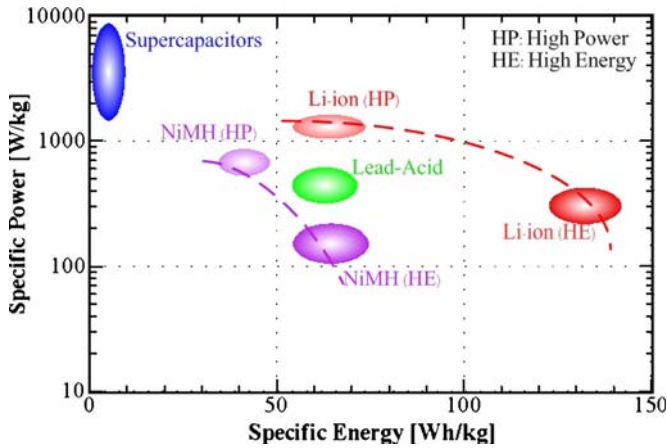


Fig. 1. Specific power versus specific energy of modern storage devices: supercapacitor, lead-acid, NiMH, and Li-ion battery technology. Note that the supercapacitors, NiMH, and Li-ion batteries are based on SAFT Company (France) technology.

corresponding high-efficiency discharge, batteries would have a much lower power capability.

Furthermore, the main drawback of batteries is a slow charging time, limited by a charging current [25], [26]; in contrast, supercapacitors may be charged over a short time, depending on a high charging current (power) that is available from the main source. Capacitor voltage v_C can then be found using the following classical equation:

$$v_C(t) = \frac{1}{C} \int_{t_0}^t i_C(t) \cdot dt + v_C(t_0) \quad (2)$$

where $i_C(t)$ is the charging capacitor current.

Moreover, Fig. 1 compares the advanced technologies of batteries and supercapacitors in terms of specific power and energy. Although it is true that a battery has the largest energy density (i.e., more energy is stored per weight than other technologies), it is important to consider the availability of that energy. This is the traditional advantage of capacitors. With a time constant of less than 0.1 s, energy can be taken from a capacitor at a very high rate [27], [28]. On the contrary, a battery of the same size will not be able to supply the necessary energy in the same time period. Unlike batteries, more advantageous for the case of supercapacitors is the fact that they can withstand a very large number of charge/discharge cycles without degradation (or virtually infinite cycles) [24], [25].

III. FC/BATTERY AND FC/SUPERCAPACITOR HYBRID POWER SOURCES

A. Structure of the Hybrid Power Sources

Different power converter topologies can be used for the power electronic interface between the FC and the utility dc bus. For the dc link voltage level, it depends on its applications. Basically, low-voltage high-current structures are needed because of FC electrical characteristics. A classical boost converter is often selected as an “FC converter” [29]–[31] because it can be operated in the current control mode in a continuous

condition mode. Then, one does not need a blocking diode and a passive filter between an FC and a converter. Based on the load conditions, the boost converter can be commanded to draw a specific amount of current from the FC with a ripple that is well defined by the frequency, the size of the inductor, and the duty ratio. However, a classical boost converter will be limited when the power increases or for higher step-up ratios.

In many applications, the use of an isolation transformer can provide an increased output/input voltage conversion ratio, as required, and full-bridge topologies can be used [7]. However, there are applications where transformer-less energy converter systems could potentially offer significant advantages, including simplicity, cost, and converter size reduction, particularly in high-power applications. That way, the use of paralleling power converters with an interleaved technique may offer some better performances [7].

One may summarize here again that the constraints to operate an FC are as follows.

- 1) The FC power or current must be kept within an interval (a rated value, a minimum value, or zero).
- 2) The FC current must be controlled as a unidirectional current.
- 3) The FC current slope must be limited to the maximum absolute value (e.g., $4 \text{ A} \cdot \text{s}^{-1}$ [13], [32]) to prevent an FC stack from the fuel starvation phenomenon.
- 4) The switching frequency of the FC current must be greater than 1.25 kHz and the FC ripple current must be lower than around 5% of the rated value to ensure minor impact to the FC conditions [7].

Proposed hybrid power sources are depicted in Figs. 2 and 3. The battery actual voltage curve is not constant. It is linear over most of its operating range. The battery voltage variation is at least 25%. Nonetheless, at the end of discharge, the battery voltage decreases very rapidly toward zero. This is because the internal resistance of a lead-acid battery is almost linear during discharge, but the losses are largely below 25% SOC due to the increase in the internal resistance of the battery. As depicted in Fig. 2, we propose the FC/battery hybrid source by directly connecting the battery module to a dc bus [33], [34]. For this reason, there is no battery converter in this structure to improve system efficiency and converter cost. Then, this system will be operated based on unregulated dc bus voltage, in which the dc bus voltage is equal to the battery voltage.

For the FC/supercapacitor hybrid source (see Fig. 3), a supercapacitor module is frequently connected to the dc bus by means of a classical two-quadrant (bidirectional) dc/dc converter [35]–[38]. Supercapacitor current i_{SuperC} , which flows across the storage device, can be positive or negative, allowing energy to be transferred in both directions.

B. Energy Management of the Hybrid Power Sources

When an FC operates, its fuel (hydrogen and oxygen) flows are controlled by an “FC controller,” which receives current demand. This current demand is the FC current reference i_{FCREF} coming from the hybrid control algorithms detailed hereafter. The fuel flows must be adjusted to match the reactant delivery

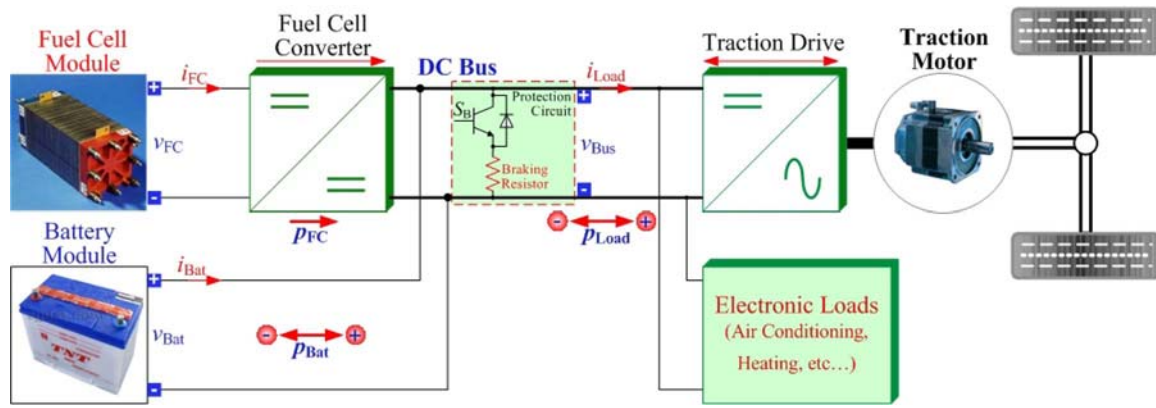


Fig. 2. Proposed structure of the FC/battery hybrid power source, where $p_{FC} (= v_{FC} \times i_{FC})$, v_{FC} , and i_{FC} are the FC power, voltage, and current, respectively. $p_{Bat} (= v_{Bat} \times i_{Bat})$, v_{Bat} , and i_{Bat} are the battery power, voltage, and current, respectively. $p_{Load} (= v_{Bus} \times i_{Load})$, v_{Bus} , and i_{Load} are the load power, the dc bus voltage, and the load current, respectively. Note that it has been assumed that there are no losses in the FC converter, and here, v_{Bus} is v_{Bat} .

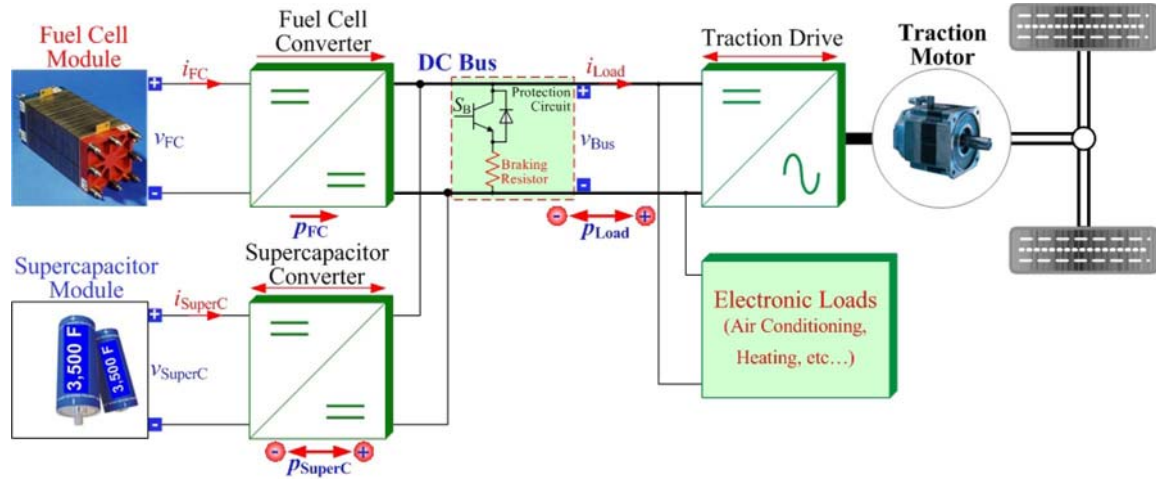


Fig. 3. Proposed structure of the FC/supercapacitor hybrid power source, where $p_{FC} (= v_{FC} \times i_{FC})$, v_{FC} , and i_{FC} are the FC power, voltage, and current, respectively. $p_{SuperC} (= v_{SuperC} \times i_{SuperC})$, v_{SuperC} , and i_{SuperC} are the supercapacitor power, voltage, and current, respectively. $p_{Load} (= v_{Bus} \times i_{Load})$, v_{Bus} , and i_{Load} are the load power, the dc bus voltage, and the load current, respectively. Note that it has been assumed that there are no losses in the FC and supercapacitor converters.

rate to the usage rate by the FC controller [39]. For this reason, the inner FC current control loop is obligatory, and the hybrid control algorithms demand energy from the FC to the dc link by generating i_{FCREF} [1], which is synchronously sent to the FC system. One can take advantage of the safety and high dynamic characteristics of this loop as well. Note that the definitions of current direction are also illustrated in Figs. 2 and 3, and the dynamics of the current regulation loops are also supposed to be much faster than those of the outer control loops, which are detailed hereafter.

The energy management of hybrid power sources has already been studied recently, for example, by Jiang and Dougal [40], who worked on an unregulated voltage FC/battery hybrid source; by Ayad *et al.* [41], who studied the control of an unregulated voltage battery/supercapacitor hybrid source; and by Thounthong *et al.* [42], whose work concerned a regulated voltage FC/supercapacitor hybrid source. The problem of such a control strategy is well known: The definition of system states (state-machine-used) implies control algorithm permutations that may lead to a phenomenon of chattering when the system is operating near a border between two states. Of course, solutions

exist to avoid such a phenomenon—hard filtering, hysteretic transition, and transition defined by a continuous function.

The control algorithm presented here is not based on the state definition; therefore, naturally, it does not present the problem of chattering near state borders. Its basic principle lies in using the storage device, which is the fastest energy source of the system, to supply the energy that is required to the load, as if this device were a standard power supply. Therefore, the FC, although obviously the main energy source of the system, functions as the source that supplies energy to storage devices to keep them charged.

1) *FC/Battery Hybrid Power Source*: One takes advantage of a battery bank, which is directly connected to a dc bus to supply transient energy demand and peak loads that are required during traction motor acceleration and deceleration, as if this device is a standard power supply [43]–[45]. The proposed control strategy is a cascade control structure composed of three loops, as portrayed in Fig. 4. The outer loop is the battery SOC control that links the battery SOC to the battery charging current reference i_{BatREF} . The middle loop controls the battery-charging current and links i_{BatREF} to the FC current

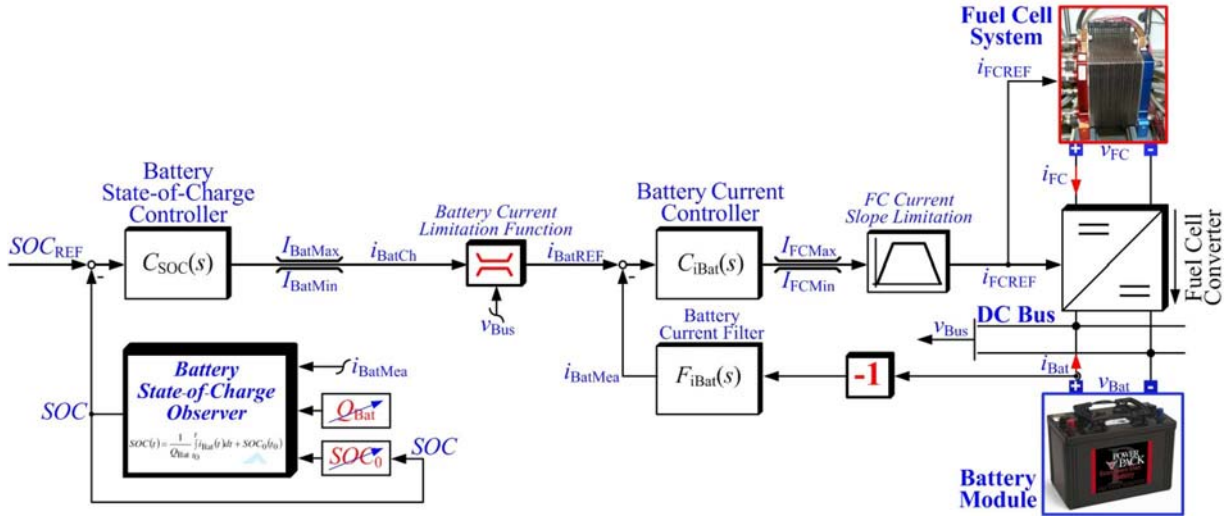


Fig. 4. Proposed energy management of the FC/battery hybrid power source.

reference i_{FCREF} . The inner loop is the FC current control, which is not presented in Fig. 4.

A simple method to charge the battery is with constant current (maximum charging current I_{BatMax} is set around $Q_{Bat}/10$; for a modern Li-ion battery, it can be set at $I_{BatMax} = Q_{Bat}$) when the SOC is far from the SOC reference SOC_{REF} , with reduced current when the SOC is near SOC_{REF} , or with no current when the SOC is equal to SOC_{REF} . For the battery SOC, it is estimated from (1), as depicted in “Battery State-of-Charge Observer” in Fig. 4.

More importantly, in vehicle applications, to replace aged batteries, battery monitoring is compulsory. In particular, the potential capacity Q_{Bat} is dependent on the depth of the discharge, the discharge rate, the cell temperature, the charging regime, the dwell time at low and high SOC, battery maintenance procedures, the current ripple, and the amount and frequency of overcharge [21].

It is beyond the scope of this paper to observe the potential capacity of the battery. It is assumed that Q_{Bat} is constant. Additionally, in a real system of applications, SOC_0 can be retained in a storage device.

According to this SOC control algorithm, the “Battery State-of-Charge Controller” generates a battery-charging current i_{BatCh} for the battery current control loop. The battery current command i_{BatCh} must be limited within an interval [maximum charging current I_{BatMax} , maximum discharging current I_{BatMin}].

To avoid overvoltage at the dc bus in case of an erroneous SOC estimation or high regenerative braking, the dc bus voltage (the battery voltage) must be monitored to limit the charging current. The “Battery Current Limitation Function” consists of limiting the battery current reference i_{BatREF} versus the dc bus voltage as

$$i_{BatREF}(t) = i_{BatCh}(t) \cdot \min \left(1, \frac{V_{BusMax} - v_{Bus}(t)}{\Delta v_{Bus}} \right) \quad (3)$$

where V_{BusMax} is the defined maximum dc bus voltage, and Δv_{Bus} is the defined voltage band.

The battery-current control loop receives i_{BatREF} from an SOC regulation loop. The measured battery current must be reversed because the definition of the battery current is negative for the charging current. The battery current controller generates the FC current reference i_{FCREF} . It must be limited in level, within the interval maximum I_{FCMax} (corresponding to a rated current of the FC) and minimum I_{FCMin} (set to 0 A) and limited in slope to the maximum absolute value (in amperes per second), which enables the safe operation of the FC with respect to the constraints that are associated with the FC.

One may summarize that the control principle of the whole system is based on the battery SOC, whatever the load power is.

- If the SOC is lower than SOC_{REF} , the battery-charging current reference is a negative value, and an FC current is necessary to charge the battery.
- If the SOC is higher than SOC_{REF} , the battery-charging current reference is a positive value or equal to zero, and the FC current reference is reduced to zero.

As a consequence, a transient in the load modifies the FC current when the battery SOC becomes lower than SOC_{REF} . In any case, if the SOC is higher than SOC_{REF} , the FC current reference is equal to zero. For transient conditions, as FC current dynamics have been intentionally reduced, the battery supplies all load variations.

It must be noted here that, in this system, the PEMFC is the main source, and the battery module is the secondary source. The battery functions to compensate the FC dynamic performance to avoid the FC starvation problem, supply the overenergy demand, and absorb the regenerative braking energy. There are two possibilities to connect a battery module with a dc bus. First, a battery bank is directly connected to the dc bus as proposed in our system. Second, a battery bank may be connected to the dc bus by a bidirectional converter, but it will increase system losses and cost. Nevertheless, the battery will be cycled whenever there is a load. Because, as mentioned earlier, the battery lifetime is usually limited by the number of cycles, its longevity might suffer. There are no solutions to improve the battery lifetime in the FC/battery hybrid source,

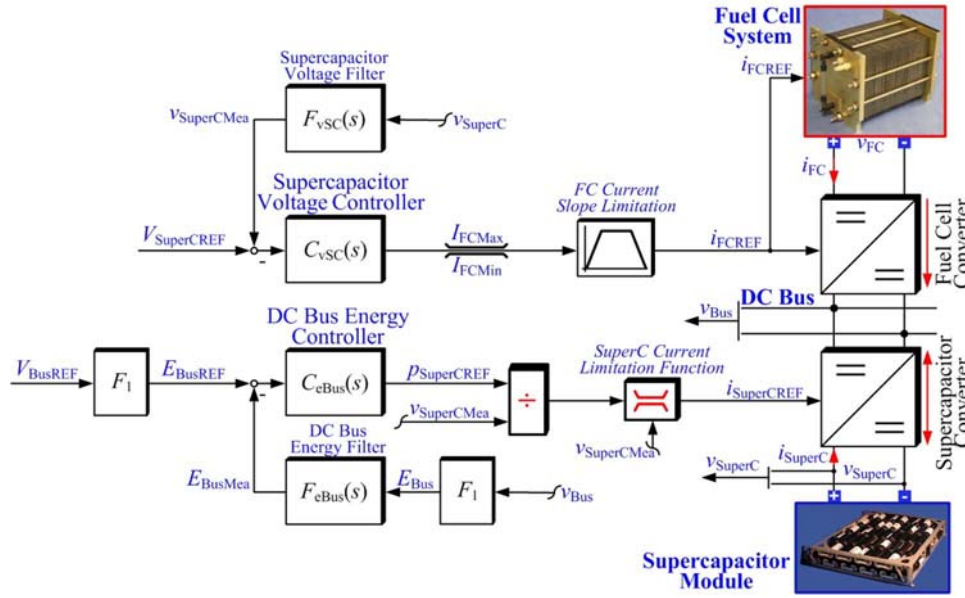


Fig. 5. Proposed energy management of the FC/supercapacitor hybrid power source.

even if a battery bank is directly connected to the dc bus or to the dc bus by a bidirectional converter. The battery will be always cycled whenever there is a load because the FC power dynamics are compensated by the battery power. To improve the battery lifetime, an FC/battery/supercapacitor hybrid source is proposed. We want the supercapacitor to supply or to absorb the load transient power and not the battery. Nonetheless, this system is under study [18].

2) *FC/Supercapacitor Hybrid Power Source*: To manage energy change in the system, its basic principle lies in using the supercapacitor, which is the fastest energy source of the system, to supply the energy that is required to achieve the dc bus voltage regulation, as if this device were a standard power supply. Therefore, the FC, although obviously the main energy source of the system, is equivalent to a load working only in regenerative braking and may be seen as a device that supplies energy to supercapacitors to keep them charged [44].

Consequently, the supercapacitor converter is driven to realize a classical dc bus voltage regulation, and the FC converter is driven to maintain the supercapacitor module at a given SOC. Therefore, the dynamics of the current regulation loops are also supposed to be much faster than those of the outer control loops. Thus, the currents i_{SuperC} and i_{FC} are considered to perfectly follow their references $i_{SuperCREF}$ and i_{FCREF} , respectively. The supercapacitor and FC current control loops are supplied by two reference signals, i.e., $i_{SuperCREF}$ and i_{FCREF} , which are generated by the dc bus voltage regulation loop and the supercapacitor voltage regulation loop, as shown in Fig. 5.

For the dc bus voltage control loop, it uses the dc bus capacitive energy E_{Bus} as the state variable and the supercapacitor delivered power $p_{SuperCREF}$ as the command variable to obtain a natural linear transfer function for the system. If the losses in both the FC and supercapacitor converters are neglected, the dc link capacitive energy E_{Bus} is given versus supercapacitor

power p_{SuperC} , FC power p_{FC} , and load power p_{Load} by the following differential equation:

$$\frac{dE_{Bus}(t)}{dt} = p_{SuperC}(t) + p_{FC}(t) - p_{Load}(t). \quad (4)$$

Function “ F_1 ” presented in Fig. 5 is a voltage-to-energy transformation, which is proportional for the total dc bus capacitance C_{Bus} to the square function

$$E_{Bus}(t) = \frac{1}{2} \cdot C_{Bus} \cdot v_{Bus}^2(t). \quad (5)$$

It enables the generation of both dc bus energy reference E_{BusREF} and dc bus energy measurement E_{BusMea} through dc bus voltage reference V_{BusREF} and dc bus voltage measurement v_{Bus} , respectively. The “DC Bus Energy Controller” generates a supercapacitor power reference $p_{SuperCREF}$. This signal is then divided by the measured supercapacitor voltage $v_{SuperCMea}$ and limited to maintain the supercapacitor voltage within an interval $[V_{SuperCMin}, V_{SuperCMax}]$. The upper value of this interval corresponds to the rated voltage of the storage device, and the lower value, which is traditionally equal to $V_{SuperCMax}/2$, corresponds to a level under which the supercapacitor discharge becomes ineffective. This results in supercapacitor current reference $i_{SuperCREF}$.

The “SuperC Current Limitation Function” consists of limiting reference $i_{SuperCREF}$ to the interval $[I_{SuperCMin}, I_{SuperCMax}]$, which is defined, versus measured supercapacitor voltage $v_{SuperCMea}$, as follows:

$$\left. \begin{aligned} I_{SuperCMin} &= -I_{SuperCRated} \\ &\quad \times \min \left(1, \frac{V_{SuperCMax} - v_{SuperCMea}(t)}{\Delta v_{SuperC}} \right) \\ I_{SuperCMax} &= +I_{SuperCRated} \\ &\quad \times \min \left(1, \frac{v_{SuperCMea}(t) - V_{SuperCMin}}{\Delta v_{SuperC}} \right) \end{aligned} \right\}. \quad (6)$$

$I_{SuperCRated}$ and Δv_{SuperC} are the regulation parameters.

For the supercapacitor voltage regulation loop, the “Supercapacitor Voltage Controller” generates an FC current reference i_{FCREF} limited in level and slope with respect to the constraints associated with the FC. The i_{FCREF} that drives the FC converter through the FC current loop is then kept within an interval $[I_{FCMin}, I_{FCMax}]$. The upper value of this interval corresponds to the rated current of the FC, and the lower value should be zero. Slope limitation to the maximum absolute value of some amperes per second enables safe operation of the FC, even during the transient power demand.

One may summarize that, using this form of control principle, the state of the supercapacitor module is naturally defined, through the dc bus voltage regulation, by the load power level, and by its SOC. In narrow steady-state conditions, we have the following.

- 1) If load power is negative, the dc link voltage regulation generates a negative supercapacitor current reference $i_{SuperCREF}$.
- 2) If load power is greater than the approximate FC rated power, the dc bus voltage regulation generates a positive supercapacitor current reference $i_{SuperCREF}$.
- 3) Otherwise, the state of the supercapacitor module depends on its SOC: the supercapacitor current will, therefore, be positive if $v_{SuperC} > V_{SuperCREF}$ and negative if $v_{SuperC} < V_{SuperCREF}$.

In all cases, the FC state depends only on the supercapacitor voltage; the FC current will be strictly positive and less than $I_{FCRated}$ if $v_{SuperC} < V_{SuperCREF}$. Otherwise, it will be zero. In transient conditions, as FC current dynamics have been intentionally reduced, the supercapacitor supplies load variations. In effect, the dc bus voltage regulation transforms a sudden increase in load power into a sudden increase in the supercapacitor current and, on the contrary, a sudden decrease in load power into a sudden decrease in the supercapacitor current.

3) *Conclusion of Proposed Energy-Management Algorithms:* The main important point in hybrid systems presented here is to balance the energy between the FC main source, the auxiliary source, and the load. The FC power (or current) dynamics have been intentionally reduced; the auxiliary source supplies all load variations.

Finally, Figs. 6 and 7 present simulation results during a high constant stepped load power. They show the load, auxiliary, and FC powers in per unit [p.u.]. In simulations, the FC minimum and maximum powers are set at 0 p.u. (corresponding to the FC minimum current) and 1.0 p.u. (corresponding to the FC maximum current), respectively. The power dynamics of the FC are set at $0.6 \text{ p.u.} \cdot \text{s}^{-1}$. As illustrated in Fig. 6, initially, the storage device is full of charge, and the load power is 0.2 p.u. As a result, the storage device power is zero, and the FC supplies 0.2 p.u. for the constant load power. At $t = 1 \text{ s}$, the constant load power steps to 3.0 p.u. One can observe the following.

- The auxiliary source supplies most of the transient power required.
- The FC power increases to the limited power 1.0 p.u. with a slope of $0.6 \text{ p.u.} \cdot \text{s}^{-1}$.

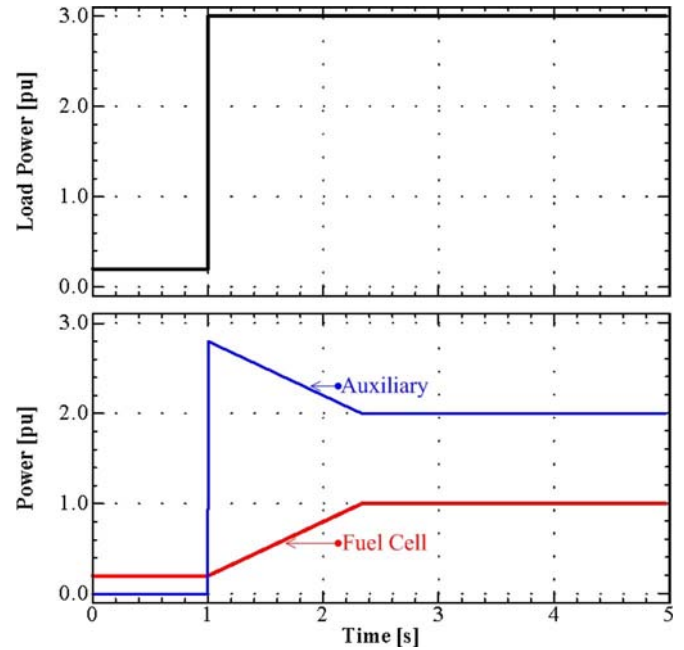


Fig. 6. Simulation result: hybrid source response during a high positive load step. Note that the power unit is per unit (p.u.).

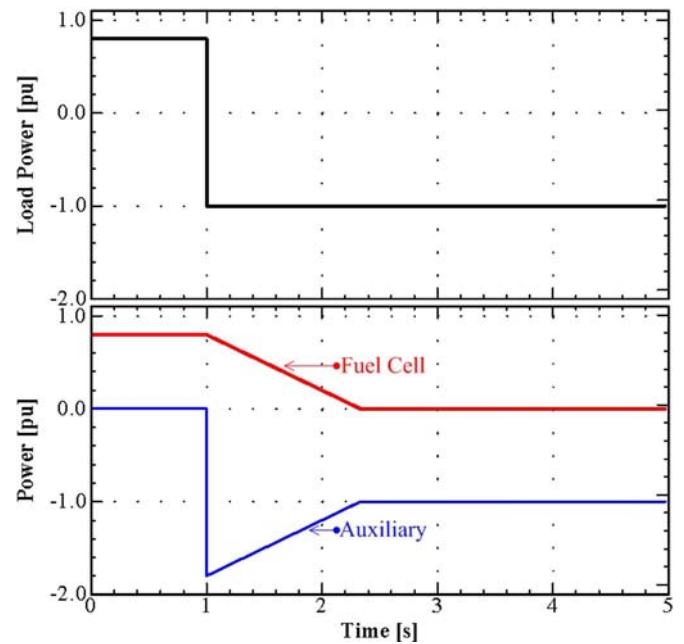


Fig. 7. Simulation result. Hybrid source response during a high negative load step (imitated regenerative braking).

- Synchronously, the auxiliary power, after a sharp increase (discharging), slowly decreases to a constant discharge of 2.0 p.u.

At a steady state, the constant load power of 3.0 p.u. is entirely supplied by the FC of 1.0 p.u. and the storage device of 2.0 p.u. (the discharging state).

As a final simulation illustrated in Fig. 7, initially, the auxiliary energy source is full of charge, and the load power is 0.8 p.u. As a result, the storage device power is zero, and the FC supplies 0.8 p.u. for the constant load power. At $t = 1 \text{ s}$, the

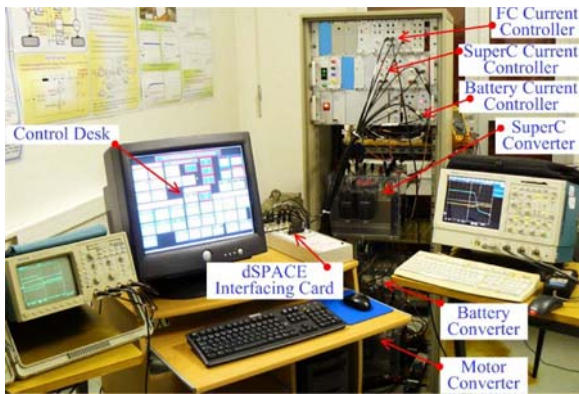


Fig. 8. Hybrid source test bench.



Fig. 9. PEMFC stack and storage devices.

constant load power steps to -1.0 p.u. (imitated regenerative braking). One can see, again, the following.

- The auxiliary source absorbs most of the transient negative power.
- The FC power reduces to zero with a slope of $0.6 \text{ p.u.} \cdot \text{s}^{-1}$ because the FC power source is a unidirectional power flow.
- Simultaneously, the auxiliary source, after a sharp decrease (charging), slowly increases to a constant charge at -1.0 p.u.

IV. EXPERIMENTAL VERIFICATION

A. Test Bench Explanation

The small-scale test bench of the hybrid systems in our laboratory is presented in Fig. 8. As illustrated in Fig. 9, the PEMFC system (500 W, 40 A, 13 V) was achieved by the ZSW Company. It is composed of 23 cells of 100 cm^2 in series. It is supplied using pure hydrogen from bottles under pressure and with clean and dry air from a compressor. The battery module is obtained by means of four aged lead-acid batteries [7.78 Ah (33 Ah at the nameplate), 12 V] connected in series. The supercapacitor module is obtained by means of 12 SAFT supercapacitors SC3500 (capacitance: 3500 F; rated voltage: 2.5 V; rated current: 500 A; low-frequency ESR: $0.8 \text{ m}\Omega$) connected in series.

The FC converter is a classical boost converter and is selected to adapt the low dc voltage delivered by the FC, which is approximately 12.5 V at rated power, to the 42-V dc bus. Thus, the FC converter is composed of a high-frequency input inductor ($72 \text{ }\mu\text{H}$), an output filtering capacitor (Panasonic aluminum electrolytic capacitors: $30\,000 \text{ }\mu\text{F}$), a diode (Schottky diode STPS80H100TV: 100 V, 40 A), and a main power switch (power metal-oxide-semiconductor field-effect

transistor STE180NE10: 100 V, 180 A). The frequency of the pulsewidth modulation that drives the FC converter is 25 kHz.

The supercapacitor converter is a classical two-quadrant dc/dc converter (a bidirectional converter). Thus, the supercapacitor converter is composed of a high-frequency input inductor ($54 \text{ }\mu\text{H}$), an output filtering capacitor (Panasonic aluminum electrolytic capacitors: 330 mF), and two power switches (power insulated-gate bipolar transistors SKM200GB123D: 1200 V, 200 A). The supercapacitor current, which flows across the storage device, can either be positive or negative, allowing energy to be transferred in both directions. The converter is driven by means of complementary pulses, which are generated by a hysteresis comparator, and applied on the gates of the power switches.

In the case of the FC/battery hybrid power source test bench, the total dc bus capacitance is 360 mF (30 mF of the output capacitance of the FC converter and 330 mF of the output capacitance of the load converter). In the case of the FC/supercapacitor hybrid power source test bench, the total dc bus capacitance is 690 mF (30 mF of the output capacitance of the FC converter, 330 mF of the output capacitance of the load converter, and 330 mF of the output capacitance of the supercapacitor converter).

The dc bus is connected to only a traction motor drive (10 kW) coupled with a small-inertia flywheel. The supercapacitor and FC current control loops, on the other hand, have been realized by analog circuits to function at a high bandwidth. The proposed energy-control algorithms have been implemented in the real-time card dSPACE DS1104 through the mathematical environment of MATLAB-Simulink, with a sampling frequency of 25 kHz. The ControlDesk software enables changes in the parameters of the control loops. Two digital oscilloscopes (Tektronix Com.), as shown in Fig. 8, are used as data acquisition to store signal waveforms, which are presented hereafter.

The control parameters of the PEMFC are set as follows.

- $I_{\text{FCMax}} = 40 \text{ A}$ (rated FC current, corresponding to the rated FC power).
- $I_{\text{FCMin}} = 0 \text{ A}$ (minimum FC current, corresponding to the minimum FC power).
- The FC current absolute slope limitation is set to $4 \text{ A} \cdot \text{s}^{-1}$ (corresponding to the FC power slope of around $50 \text{ W} \cdot \text{s}^{-1}$). This value has been experimentally determined as the highest current slope of our FC system, where no fuel starvation occurs [13].

B. Test Results of the FC/Battery Hybrid Power Source

The controlled parameters of this system are set as follows:

- $\text{SOC}_{\text{REF}} = 100\%$ (equal to 7.78 Ah);
- $I_{\text{BatMax}} = +6 \text{ A}$ (the maximum battery charging current);
- $I_{\text{BatMin}} = -50 \text{ A}$ (the maximum battery discharging current);
- $V_{\text{BusMax}} = 61 \text{ V}$;
- $\Delta v_{\text{Bus}} = 2 \text{ V}$.

Figs. 10 and 11 present waveforms that are obtained during the motor-drive cycle. They show the dc bus voltage (the battery voltage), the FC voltage, the load power, the battery power, the

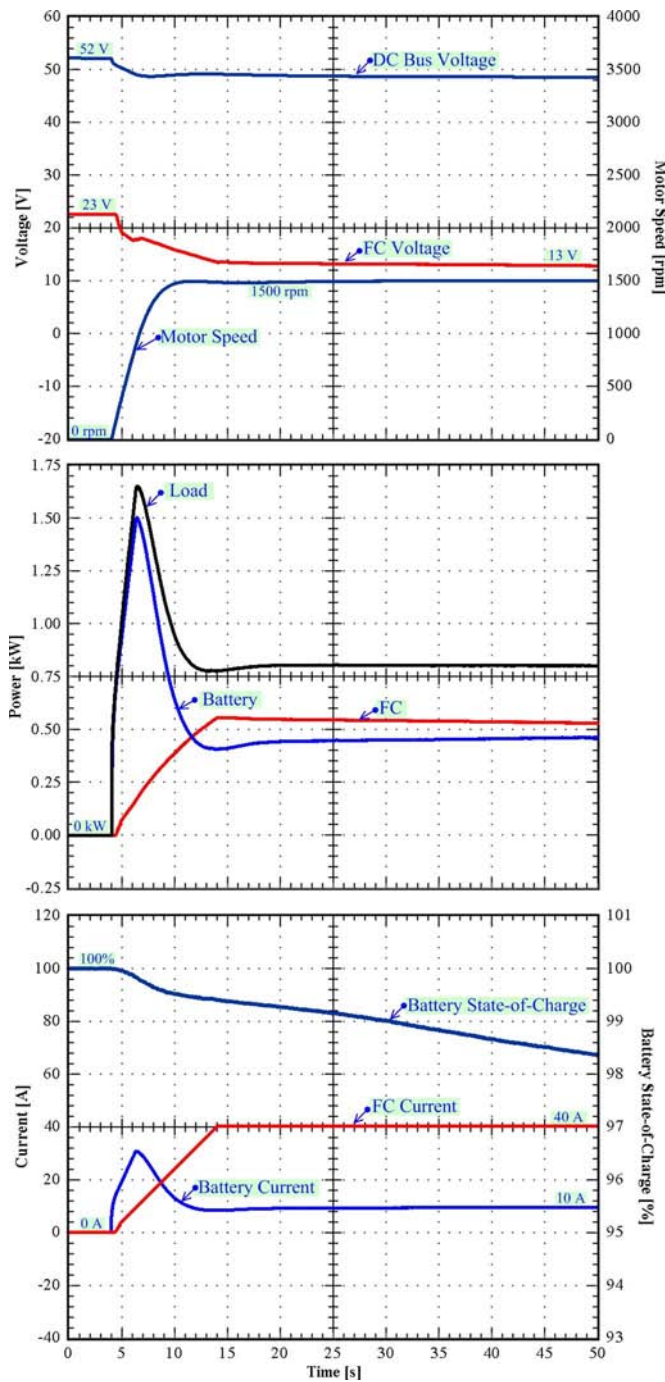


Fig. 10. FC/battery hybrid source response during motor starting to 1500 r/min.

FC power, the motor speed, the battery current, the FC current, and the battery SOC. The battery SOC is calculated from (1) by MATLAB-Simulink and is then sent through a digital-to-analog-converter card of dSPACE to an oscilloscope.

The initial state is zero for both the FC and battery powers and 100% for the battery SOC. At $t = 4$ s, the motor reaches the final speed of 1500 r/min such that the final FC current is $I_{FC\text{Rated}}$. One can observe the following.

- The battery supplies most of the power of 1600 W that is required during motor acceleration.

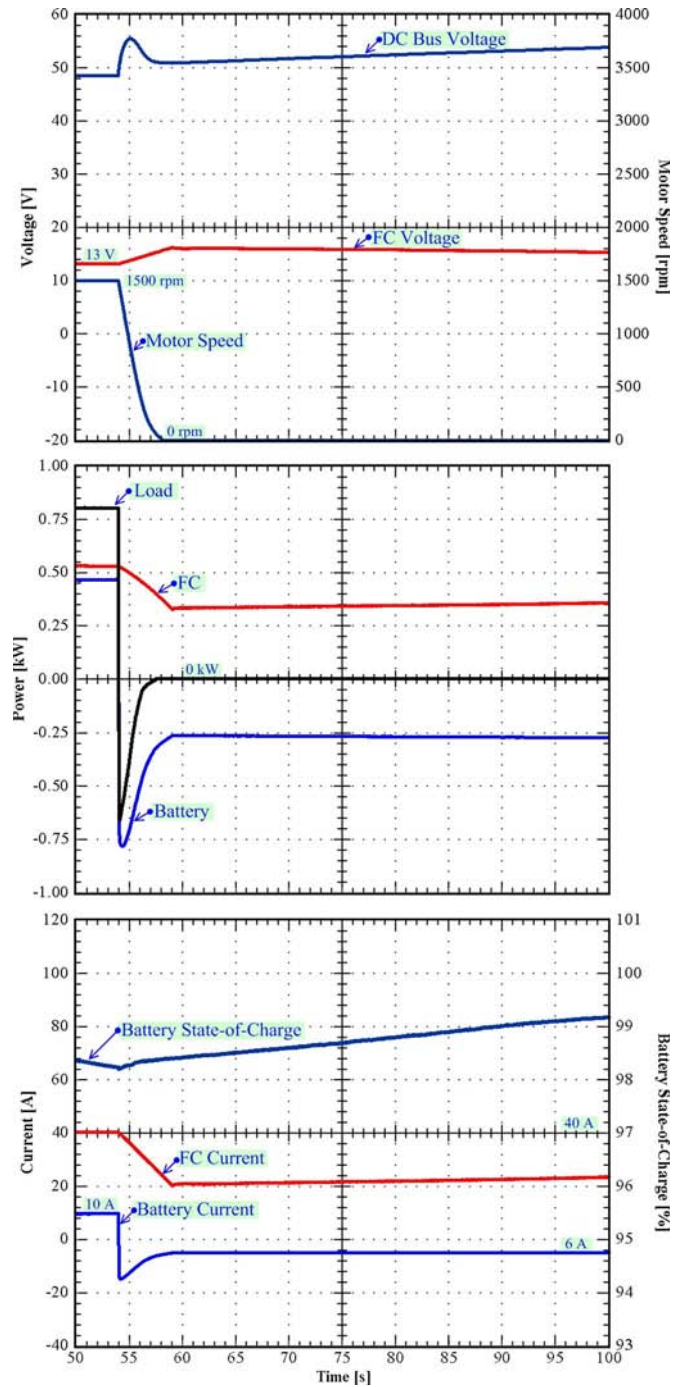


Fig. 11. FC/battery hybrid source response during motor braking from 1500 r/min.

- The FC power increases with a limited slope up to a level of the rated power of 500 W.
- Concurrently, the battery power, after a sharp increase during motor acceleration, slowly decreases to a constant discharging power of 400 W.
- The steady-state load power at the constant speed of 1500 r/min is about 800 W, which is entirely supplied by the FC and the battery.

Therefore, this characteristic can be comparable with the simulation results in Figs. 6 and 7. After that, at $t = 54$ s, the motor reduces speed and then stops. It can be scrutinized that

there are three phases. First, the battery recovers the power that is supplied to the dc link by the FC and the motor (known as the regenerative braking energy). Second, the battery recovers the reduced power that is supplied to the dc bus by only the FC. Third, the battery is charged at a constant current of 6 A by the FC. During the first and second phases, the FC power reduces from a rated power of 500 W with a constant slope of $50 \text{ W} \cdot \text{s}^{-1}$. In the third phase, the FC power is nearly constant at around 300 W to charge the battery. After that, both the FC and the battery power will reduce to zero when the SOC reaches SOC_{REF} .

C. Test Results of the FC/Supercapacitor Hybrid Power Source

The control parameters of this system are set as follows:

- $V_{\text{BusREF}} = 42 \text{ V}$ (a new standard dc bus voltage in the automotive electrical system called “PowerNet” [17]);
- $V_{\text{SuperCREF}} = 25 \text{ V}$;
- $V_{\text{SuperCMax}} = 30 \text{ V}$;
- $V_{\text{SuperCMin}} = 15 \text{ V}$;
- $I_{\text{SuperCRated}} = 200 \text{ A}$;
- $\Delta v_{\text{SuperC}} = 0.5 \text{ V}$.

Figs. 12 and 13 present waveforms that are obtained during the motor-drive cycle. They show the dc bus voltage, the FC voltage, the load power, the supercapacitor power, the FC power, the motor speed, the supercapacitor current, the FC current, and the supercapacitor voltage (or the supercapacitor SOC).

The initial state is in no-load power, and the storage device is full of charge, i.e., $V_{\text{SuperC}} = 25 \text{ V}$; as a result, both the FC and supercapacitor powers are zero. At $t = 20 \text{ s}$, the motor speed accelerates to the final speed of 1000 r/min; synchronously, the final FC power increases with a limited slope of $50 \text{ W} \cdot \text{s}^{-1}$ to a rated power of 500 W. Thus, the supercapacitor, which supplies most of the power that is required during motor acceleration, remains in a discharge state after the motor start because the steady-state load power (approximately 600 W) is greater than the FC rated power (500 W), and the peak load power is about 1000 W, which is about two times that of the FC rated power.

After that, at $t = 50.5 \text{ s}$, the motor speed decelerates and stops with a peak load power of about -500 W . The supercapacitor is deeply charged, demonstrating the three phases. First, the supercapacitor recovers the energy that is supplied to the dc bus by the FC (500 W) and the traction motor. Second, the supercapacitor is charged only by the FC. Third, the supercapacitor is nearly fully charged, which then reduces the charging current. After that, both the FC and supercapacitor powers reduce to zero when V_{SuperC} reaches $V_{\text{SuperCREF}}$ of 25 V.

Only small perturbations on the dc bus voltage waveform can be seen, which is of major importance when using supercapacitors to improve the dynamic performance of the whole system. These characteristics can be, again, comparable with the simulation results in Figs. 6 and 7.

The proposed energy-management algorithms of FC/battery and FC/supercapacitor hybrid sources are used to balance powers in the system with respect to dynamic constraints. During motor acceleration or deceleration (a high stepped load), as can

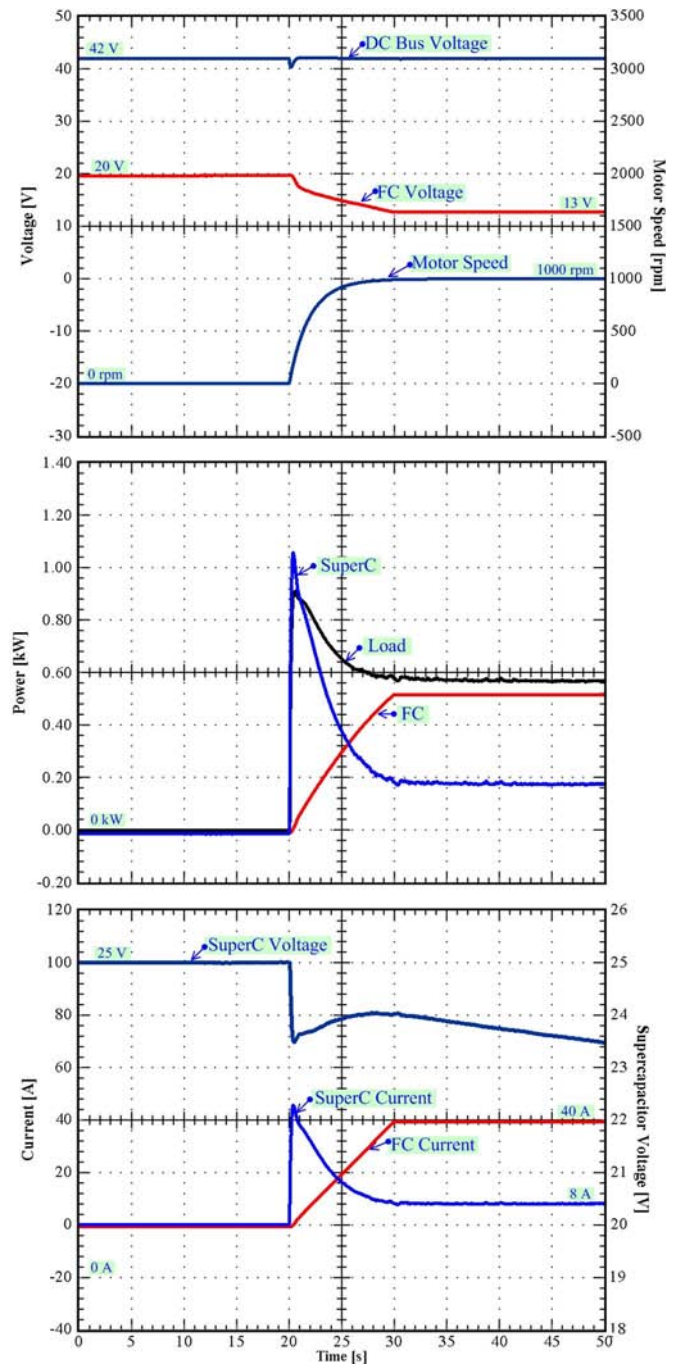


Fig. 12. FC/supercapacitor hybrid source response during motor startup to 1000 r/min.

be seen in Figs. 6 and 7 in simulation results (in per unit) and in Figs. 10–13 in experimental results, the powers are always balanced during dynamic and transient states. Importantly, the high dynamics during load steps are compensated by storage devices. For the FC/battery hybrid source, the stepped energy is naturally supplied or absorbed by the battery because the battery bank is directly connected to the dc bus based on the control algorithm of the unregulated dc bus voltage. In the case of the FC/supercapacitor hybrid source, the stepped energy is automatically supplied or absorbed by the supercapacitor because the proposed control algorithm is based on the regulated dc bus voltage. Then, the supercapacitor module functions as

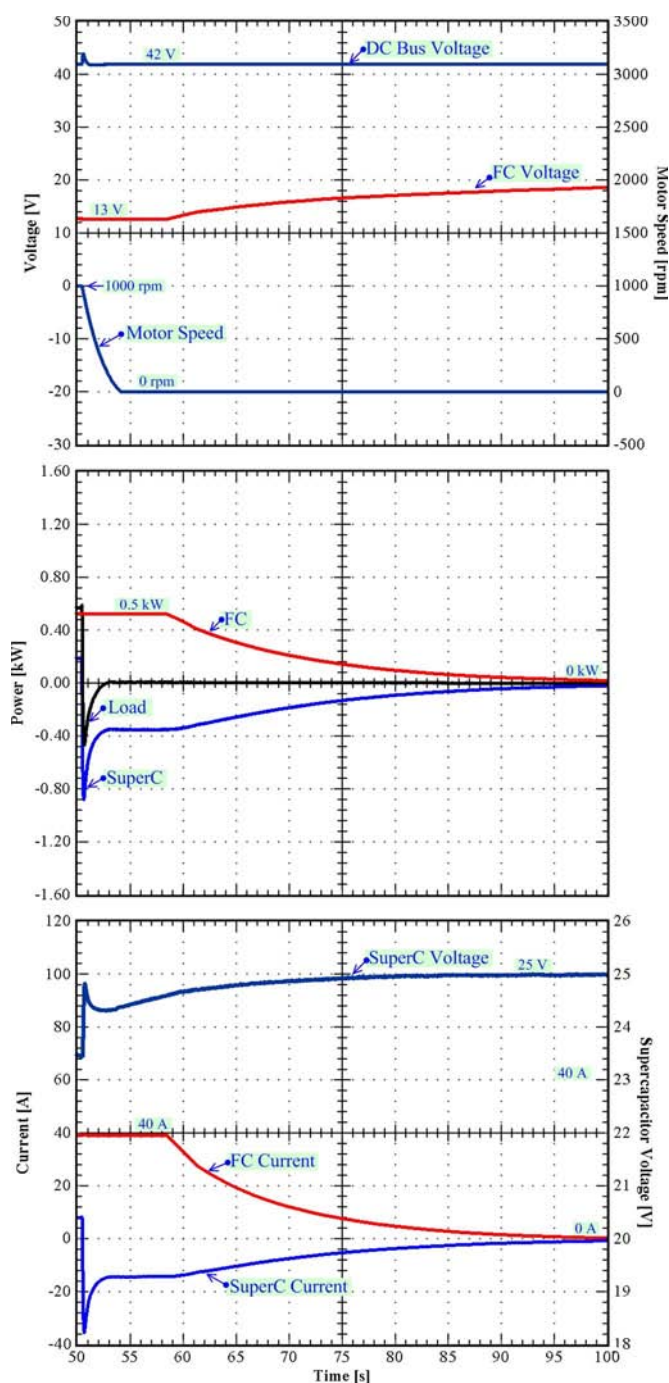


Fig. 13. FC/supercapacitor hybrid source response during motor braking from 1000 r/min.

the one supplying or absorbing the energy that is required to achieve the dc bus voltage.

V. CONCLUSION

The advantages of an FC hybrid vehicle could include improved vehicle performance and fuel economy and lower system cost. The degree of hybridization benefits from 1) FC efficiency characteristics; 2) FC downsizing; 3) displacing FC tasks with the secondary source functionality; or 4) energy recovery through regenerative braking. This paper has studied

the role of the energy-storage device in FC hybrid vehicles to understand their potential impact on dynamic performances.

Experimental verifications with a small-scale hybrid test bench in the laboratory have evidently shown the possibility of improving the performance of the whole system and validated the proposed control algorithms: the FC/battery hybrid source and the FC/supercapacitor hybrid source.

In general, the FC/supercapacitor hybrid has better performance because the supercapacitor can more effectively assist the FC to meet the transient power demand (the supercapacitor can be charged or discharged at a high current, in which the battery cannot function), and high-current charges and discharges from the battery will reduce its lifetime as well.

Nonetheless, an FC hybrid vehicle with supercapacitors as the only energy storage will be deficient or even malfunction during the vehicle startup because of the startup time of a PEMFC of around 5–10 min, in which the battery has higher specific energy than the supercapacitor. Consequently, a more practical answer will be an FC/battery/supercapacitor hybrid power source [45] to increase the battery lifetime due to the reduction of high-current charges and discharges.

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Energy management of fuel cell/solar cell/supercapacitor hybrid power source

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ABSTRACT

This study presents an original control algorithm for a hybrid energy system with a renewable energy source, namely, a polymer electrolyte membrane fuel cell (PEMFC) and a photovoltaic (PV) array. A single storage device, i.e., a supercapacitor (ultracapacitor) module, is in the proposed structure. The main weak point of fuel cells (FCs) is slow dynamics because the power slope is limited to prevent fuel starvation problems, improve performance and increase lifetime. The very fast power response and high specific power of a supercapacitor complements the slower power output of the main source to produce the compatibility and performance characteristics needed in a load. The energy in the system is balanced by d.c.-bus energy regulation (or indirect voltage regulation). A supercapacitor module functions by supplying energy to regulate the d.c.-bus energy. The fuel cell, as a slow dynamic source in this system, supplies energy to the supercapacitor module in order to keep it charged. The photovoltaic array assists the fuel cell during daytime. To verify the proposed principle, a hardware system is realized with analog circuits for the fuel cell, solar cell and supercapacitor current control loops, and with numerical calculation (dSPACE) for the energy control loops. Experimental results with small-scale devices, namely, a PEMFC (1200 W, 46 A) manufactured by the Ballard Power System Company, a photovoltaic array (800 W, 31 A) manufactured by the Ekarat Solar Company and a supercapacitor module (100 F, 32 V) manufactured by the Maxwell Technologies Company, illustrate the excellent energy-management scheme during load cycles.

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1. Introduction

Currently, most of the energy demand in the world is met by fossil and nuclear power plants. A small part is drawn from renewable energy technologies such as wind, solar, fuel cell, biomass and geothermal energy [1,2]. Wind energy, solar energy and fuel cells have experienced a remarkably rapid growth in the past ten years [3–5] because they are pollution-free sources of power. Additionally, they generate power near the load centres, which eliminates the need to run high-voltage transmission lines through rural and urban landscapes.

The cost of solar photovoltaic and fuel cell electricity is still high [6–8]. Nevertheless, with ongoing research, development and utilization of these technologies around the world, the costs of solar cells and fuel cell energy are expected to fall in the next few years. As for solar cell and fuel cell electricity producers, they now sell power

freely to end-users through truly open access to the transmission lines. For this reason, they are likely to benefit as much as other producers of electricity. Another benefit in their favour is that the cost of renewable energy falls as technology advances, whereas the cost of electricity from conventional power plants rises with inflation. The difference in their trends indicates that hydrogen and solar power will be more advantageous in future.

In the near future, the utility power system at a large scale will be supplied by renewable energy sources and storage device(s), i.e., *hybrid energy systems*, in order to increase their reliability and make them more effective. The specific properties of fuel cells and solar cells are as follows:

- The amount of power the fuel cell system delivers is controlled by the amount of current drawn from the system if the proper conditions for cell operation are maintained. When a large load is applied to the cells, the sudden increase in the current can cause the system to stall if the depleted oxygen or hydrogen cannot be replenished immediately and sufficiently. Cell starvation can lead to a system stall, permanent cell damage or

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Nomenclature

a.c.	alternating current
d.c.	direct current
FC	fuel cell
PV	photovoltaic
SC	supercapacitor
C_{Bus}	total capacitance at d.c.-bus (F)
C_{SC}	total capacitance of supercapacitor module (F)
i_{Load}	d.c.-bus load current (A)
i_{FC}	fuel cell current (A)
i_{FCREF}	fuel cell current reference (set-point) (A)
i_{Sol}	solar cell (photovoltaic) current (A)
i_{SolREF}	solar cell current reference (set-point) (A)
i_{SC}	supercapacitor current (A)
i_{SCREF}	supercapacitor current reference (set-point) (A)
P_{Load}	load power (W)
P_{FC}	fuel cell power (W)
P_{FCa}	fuel cell output power to d.c.-bus (W)
P_{FCREF}	fuel cell power reference (set-point) (W)
P_{FCMax}	maximum fuel cell power (W)
P_{Sol}	solar cell (photovoltaic) power (W)
P_{Sola}	solar cell output power to d.c.-bus (W)
P_{SolREF}	solar cell power reference (set-point) (W)
P_{SolMax}	maximum solar cell power (W)
P_{SC}	supercapacitor power (W)
P_{SCa}	supercapacitor output power to d.c.-bus (W)
P_{SCREF}	supercapacitor power reference (set-point) (W)
P_{SCMax}	maximum supercapacitor power (W)
V_{Bus}	d.c.-bus voltage (V)
V_{FC}	fuel cell voltage (V)
V_{Sol}	solar cell (photovoltaic) voltage (V)
V_{SC}	supercapacitor voltage (V)
Y_{Bus}	d.c.-bus energy (J)
Y_{BusREF}	d.c.-bus energy reference (set-point) (J)
Y_{SC}	supercapacitor energy (J)
Y_{SCREF}	supercapacitor energy reference (set-point) (J)
Y_{T}	total energy at d.c.-bus and supercapacitor (J)
r_{FC}	equivalent series resistance in fuel cell converter (Ω)
r_{Sol}	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
$\varphi(\cdot), \psi(\cdot), \phi(\cdot)$	smooth mapping functions

reduced cell lifetime. To protect the fuel cells from overloading and starvation, especially during transient conditions, excessive oxygen and hydrogen can be supplied to the cells during the steady-state operation, which increases the reserve of available power in anticipation of a load increase. This strategy, however, is conservative and leads to increased parasitic losses, decreased air utilization and thereby compromised system performance. Therefore, the fuel cell power or current slope must be limited to prevent a fuel cell stack from experiencing the fuel starvation phenomenon and to optimize the system, for example, 4 A s^{-1} for a 0.5 kW, 12.5-V PEMFC [9], and 5, 10 and 50 A s^{-1} for a 20 kW, 48-V PEMFC [10].

- The output power of solar cells fluctuates considerably depending on solar radiation, weather conditions and temperature [11,12].

Therefore, in order to supply electric power to fluctuating loads with a hybrid system composed of the above-mentioned fuel cell and solar cell, an electric energy-storage system is needed to compensate for the gap between the output from the renewable energy sources and the load, in addition to the collaborative load sharing among those energies [13–15].

Moreover, hydrogen as an energy storage media has the potential to address both daily and seasonal buffering requirements. Systems that employ an electrolyzer to convert excess electricity to hydrogen coupled with hydrogen storage and regeneration using a fuel cell can, in principle, provide power with zero (or near zero) emissions. Hydrogen production by solar energy is a ‘renewable-regenerative system’ [4], and this process is known as the electrolysis process. The basic principle is the following: when the photovoltaic input power exceeds the load power demand, the system controller determines that the energy should be directed to hydrogen production. In this kind of operation, i.e., a solar-based renewable-regenerative system, almost half of the solar input energy is directed to hydrogen production and converted with 60% energy efficiency [4].

Based on present storage device technology, battery design has to supply the trade-off between specific energy, specific power and cycle life. The difficulty in obtaining high values of these three parameters has led to some suggestions that the energy-storage system of distributed generation systems should be a hybridization of an energy source and a power source [16,17]. The energy source, mainly fuel cells and solar cells in this study, has high specific energy, whereas the power source has high specific power. The power sources can be recharged from the main energy source(s) when there is less demand. The power source that has received wide attention is the supercapacitor (or ‘ultracapacitor’, or ‘electrochemical double-layer capacitor’) [18–20].

The enhancements in the performance of renewable energy source power systems that are gained by adding energy storage are all derived from the ability to shift the system output. Firming-up the renewable system is accomplished by ensuring that energy is available when there is a demand for it rather than being limited by the availability of the renewable resource. As a result, the system output may need to be shifted to periods when the hydrogen and/or the sun, for example, are not available [21]. Depending on the size and type of the energy-storage system and the load, it may be possible to provide all of the power needed to support the load. A much more common scenario is for the energy storage to simply provide enough power for applications, like peak shaving, without having full load support capability. The energy-storage system may also provide sufficient energy to ride out electric service interruptions that range from a few seconds to a few hours. This is especially important for service disruptions that occur when the renewable resource is not available.

In this study, a fuel cell/photovoltaic/supercapacitor hybrid power source is proposed. A power electronic converter structure, energy management and innovative energy control law are presented. To authenticate the proposed principle, the hardware system is realized by analog circuits and digital estimation with a dSPACE controller. Experimental results obtained with small-scale devices illustrate the system performance.

2. Renewable energy hybrid system

2.1. System configuration

The power converter structure of the system is shown in Fig. 1. Fuel cell and solar cell power-generating systems may provide direct or alternating current (d.c. or a.c.) to satisfy application-specific power needs (Fig. 1). The current, voltage and power quality

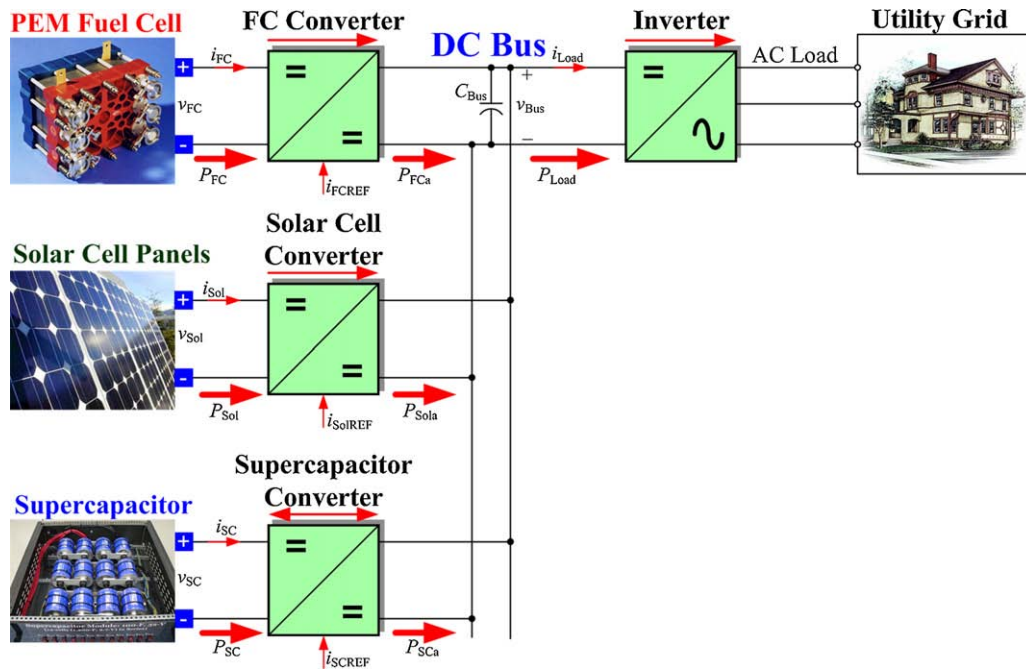


Fig. 1. Proposed hybrid energy system supplied by fuel cell, solar cell and supercapacitor, where $p_{Load} (= v_{Bus} \times i_{Load})$, v_{Bus} and i_{Load} are load power, d.c.-bus voltage and d.c.-bus load current, respectively. $p_{FC} (= v_{FC} \times i_{FC})$, v_{FC} and i_{FC} are fuel cell power, voltage and current, respectively. $p_{Sol} (= v_{Sol} \times i_{Sol})$, v_{Sol} and i_{Sol} are solar cell power, voltage and current, respectively. $p_{SC} (= v_{SC} \times i_{SC})$, v_{SC} and i_{SC} are supercapacitor power, voltage, and current, respectively. p_{FCa} , p_{Sola} and p_{SCa} are the output powers to d.c. link from converters of fuel cell, solar cell and supercapacitor, respectively. i_{FCREF} , i_{SolREF} , i_{SCREF} are the current references of the fuel cell, solar cell and supercapacitor converters, respectively.

are controlled by electronic power-conditioning systems. Generally, voltage regulators and d.c.–d.c. converters (chopper circuits) are used to control and adjust the fuel cell and photovoltaic d.c. output voltages to useful values [22,23].

The voltages of the fuel cell and solar cell vary with the current drawn by the load and decrease significantly at high load currents [24]. Therefore, a power-electronics system is needed to process the raw output power from the stack or panel and provide power to the load at a constant d.c. or a.c. voltage. Typically, the power-electronics systems include multiple interconnected power converters: for example, a d.c.–d.c. converter is often followed by a d.c.–a.c. converter for stationary applications [25]. The switching scheme in such power converters can be based on pulse-width modulation (PWM), resonant, quasi-resonant, soft-switched, or line-commutated switching [26–28]. Furthermore, the topological structures of these converters can vary dramatically [29].

The supercapacitor bank is always connected to the d.c.-bus by means of a two-quadrant d.c.–d.c. converter (bidirectional converter), a ‘supercapacitor converter’. The supercapacitor power can be positive or negative, which allows energy to be transferred in both directions [30].

An inverter is used to convert the d.c. voltage to a useful a.c. voltage. It may operate as grid-independent or with grid-synchronization. Then, the solar cell supplies all its output power to the d.c.-bus, and the fuel cell supplies a slowly fluctuating power difference between the load power p_{Load} demand and the solar cell output power. A supercapacitor storage device can compensate for both a sudden change in the load demand and rapidly fluctuating solar cell output power caused by solar radiation; therefore, the load is supplied with stable power.

As depicted in Fig. 1, the proposed system has a multi-source structure (or cascade scheme). The cascaded structure can lead to interactions between converters that cause the system to be unstable, if they are designed separately. This problem has been studied during the past decade. In this case, to study interactions between the converters, impedance criteria are often used to determine the

stability of the cascaded system. Nonetheless, the technique only proves the asymptotic stability around a given operating point. The large signal stability properties or the behaviour of the system in the case of outsized disturbances are not considered in this model. In this paper, a non-linear control algorithm based on the differential flatness principle of the renewable power plant is proposed. Design controller parameters are independent of the operating point. Interactions between the converters are taken into account by the controllers, and high dynamics in perturbation rejection are accomplished.

2.2. Energy management

For reasons of safety and dynamics, the fuel cell, solar cell and supercapacitor converters are usually controlled primarily by inner current-regulation loops [17]. The dynamics of current-regulation loops are much faster than those of outer control loops, which are described later. Therefore, the fuel cell current i_{FC} , the solar cell current i_{Sol} and the supercapacitor current i_{SC} are considered to follow their references i_{FCREF} , i_{SolREF} and i_{SCREF} perfectly.

Energy management of multi-power sources has already been studied recently, for example, Feroldi et al. [31] studied control (based on efficiency map) of a fuel cell/supercapacitor hybrid power source for vehicle applications, Payman et al. [32] studied control of a regulated d.c. voltage supplied by a fuel cell and supercapacitor storage device based on a differential flatness system, and Thounthong et al. addressed a regulated d.c.-bus voltage fuel cell/supercapacitor hybrid source [33], a regulated d.c.-bus voltage fuel cell/battery/supercapacitor hybrid source [34] and an unregulated d.c.-bus voltage fuel cell/battery hybrid source [14].

Thus, in the proposed system depicted in Fig. 1, there are two-voltage variables, or two-energy variables, to be regulated. The d.c.-bus energy y_{Bus} is the most important variable, and the supercapacitor storage energy y_{SC} is the next most important. Therefore, based on the previous work described above, it is proposed to utilize supercapacitors, which are the fastest energy source in the pro-

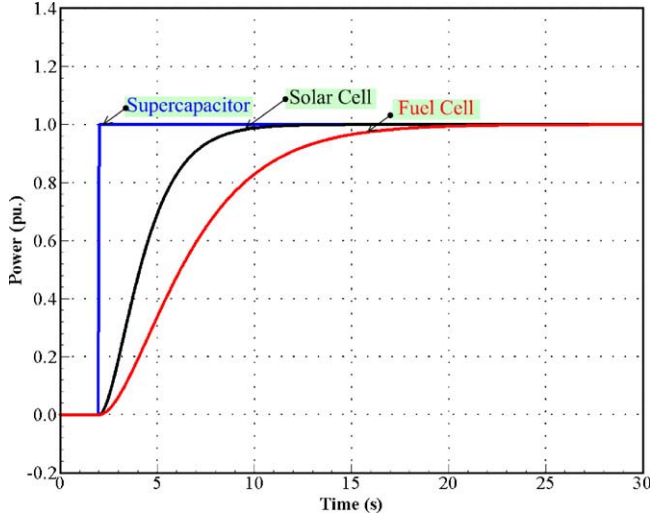


Fig. 2. Dynamic classification for proposed hybrid power source.

posed system, to supply the energy for the d.c.-bus [33,34]. Thus, the fuel cell (as the slowest dynamic device) and solar cell supply energy for both the d.c.-bus capacitor C_{Bus} and the supercapacitors C_{SC} to keep them charged.

At the d.c. link, there are three sources that supply energy at the same time. Therefore, the dynamics of the three sources must be classified in order to guarantee system stability [34], as illustrated in Fig. 2. Note that the power unit in Fig. 2 is the normalized unit (or per-unit [pu]). Thus, the defined dynamic classification depicted in Fig. 2 is obtained from the simulation result using Matlab–Simulink, and the experimental results of the power source dynamics are presented after the performance validation section. The supercapacitor is operated as the highest dynamic power source to provide the micro-cycles and the fast dynamic power supply. It can withstand a very large number of charge–discharge cycles without degradation (or virtually infinite cycles) [33,35]. The fuel cell generator is operated as the lowest dynamic power source. The fuel cell current or power slope must be limited to avoid the fuel starvation phenomenon. The fuel cell limited current or power slope has been experimentally determined to be the highest slope of an operating fuel cell system, where no fuel starvation occurs in order to improve its lifetime [33,34]. The photovoltaic generator is between the fuel cell and supercapacitor in the dynamic classification.

2.2.1. Principle of differential flatness theory

A non-linear control algorithm based on the flatness properties [36–38] of the system is proposed. According to the flatness-control law, the tuning controller parameters are independent of the operating point [32]. According to Fliess et al. [39,40], an independent dynamic system is considered to be differentially flat if an output y is given by:

$$y = \phi(x, u, \dot{u}, \dots, u^{(\alpha)}), \quad y \in \mathbb{R}^m \quad (1)$$

such that the state x and controls u (or inputs) can be written as:

$$x = \varphi(y, \dot{y}, \dots, y^{(\beta)}), \quad x \in \mathbb{R}^n \quad (2)$$

$$u = \psi(y, \dot{y}, \dots, y^{(\beta+1)}), \quad u \in \mathbb{R}^m \quad (3)$$

where $\varphi(\cdot)$, $\psi(\cdot)$, $\phi(\cdot)$ are the smooth mapping functions, α and β are a finite number of their time derivatives, and $(n, m) \in \mathbb{N}$. Moreover, it is assumed that $m \leq n$.

The output y is called a *flat output*. Thus, a dynamic system is, in nature, differentially flat if it is equivalent to a system without dynamics, i.e., a static system. In other words, there are no differential constraints in output space. The apparent advantage of a

differentially flat system is that every trajectory in the output space is feasible; therefore, trajectory generation is theoretically simpler in terms of the flat outputs. For this reason, by using the flatness estimation in power electronic applications, interactions between the converters are taken into account by the flatness-control law and high dynamics in perturbation elimination are achieved.

2.2.2. d.c.-Bus energy control

Based on the flatness-control, the electrostatic energy y_{Bus} stored in the total d.c.-bus capacitor C_{Bus} is considered as the flat output variable (Eq. (1)), i.e.:

$$y_{Bus} = \frac{1}{2} C_{Bus} v_{Bus}^2 \quad (4)$$

It is assumed that the supercapacitor current follows its reference value perfectly. Thus:

$$i_{SC} = i_{SCREF} = \frac{p_{SC}}{v_{SC}} = \frac{p_{SCREF}}{v_{SC}} \quad (5)$$

where p_{SCREF} is the control variable of the reduced system described in Eq. (3).

Therefore, the state variable v_{Bus} may be put into a form similar to that in Eq. (2):

$$v_{Bus} = \sqrt{\frac{2y_{Bus}}{C_{Bus}}} = \varphi_1(y) \quad (6)$$

To obtain a relationship between the control variable p_{SC} and the flat output variable y_{Bus} , the differential equation verified by the reduced model from Fig. 1 is written as:

$$\dot{y}_{Bus} = p_{FCa} + p_{Sola} + p_{SCa} - p_{Load} \quad (7)$$

where

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

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

$$p_{SCa} = p_{SC} - r_{SC} \left(\frac{p_{SC}}{v_{SC}} \right)^2 \quad (10)$$

r_{FC} is the total equivalent series resistance in the fuel cell converter. Here, only static resistance loss is considered [32]. r_{Sol} is the total equivalent series resistance in the solar cell converter. r_{SC} is the total equivalent series resistance in the supercapacitor converter.

It follows that:

$$p_{SCREF} = 2p_{SCMax} \left[1 - \sqrt{1 - \left(\frac{\dot{y}_{Bus} + p_{Load} - p_{FCa} - p_{Sola}}{p_{SCMax}} \right)} \right] = \psi_1(y, \dot{y}) \quad (11)$$

where

$$p_{SCMax} = \frac{v_{SC}^2}{4r_{SC}} \quad (12)$$

$$p_{Load} = v_{Bus} i_{Load} = \sqrt{\frac{2y_{Bus}}{C_{Bus}}} i_{Load} \quad (13)$$

p_{SCMax} is the limited maximum power from the supercapacitor module.

Thus, it is apparent that $p_{SC} = \psi_1(y, \dot{y})$, which corresponds with Eq. (3), and the proposed reduced system with the control variable p_{SC} can be considered to be a flat system associated with y_{Bus} as the flat output variable.

To ensure the control of the flat output variable y_{Bus} to its reference trajectory y_{BusREF} , the following control law is based on the

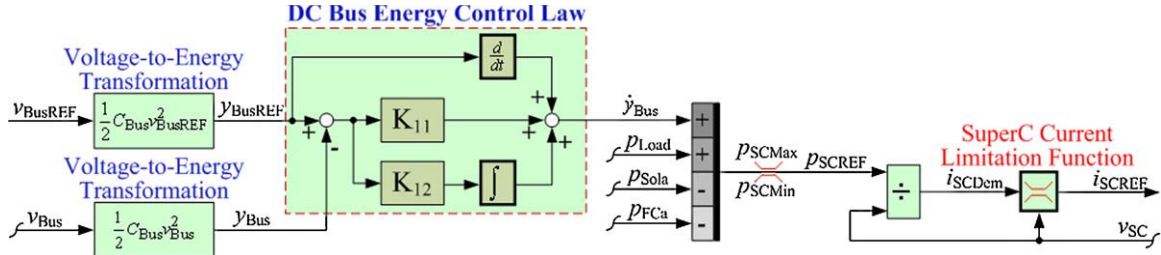


Fig. 3. Proposed d.c.-bus energy control loop for fuel cell/solar cell/supercapacitor hybrid source.

well-known second-order control law:

$$(\dot{y}_{Bus} - \dot{y}_{BusREF}) + K_{11}(y_{Bus} - y_{BusREF}) + K_{12} \int_0^t (y_{Bus} - y_{BusREF}) d\tau = 0 \quad (14)$$

where K_{11} , and K_{12} are the controller parameters. Defining $e_{yBus} = y_{Bus} - y_{BusREF}$, $K_{11} = 2\zeta\omega_n$, and $K_{12} = \omega_n^2$ gives:

$$\ddot{e}_{yBus} + 2\zeta\omega_n\dot{e}_{yBus} + \omega_n^2 e_{yBus} = 0 \quad (15)$$

It is obvious that the control system is stable for $K_{11}, K_{12} > 0$. Based on the power electronic constant switching frequency f_s and a cascade control structure, the outer control loop (here the d.c.-bus energy control) must operate at a cut-off frequency $f_e \ll f_c$ (a cut-off frequency of the supercapacitor current loop or power loop) $\ll f_s$ [41]. The d.c.-bus energy control loop detailed above is portrayed in Fig. 3.

The d.c.-bus energy control law generates a supercapacitor power reference p_{SCREF} . This signal is then divided by the measured supercapacitor voltage v_{SC} and limited to maintain the supercapacitor voltage within an interval $[V_{SCMin}, V_{SCMax}]$ by limiting the supercapacitor charging current or discharging current, as presented in the block "SuperC Current Limitation Function" [33]. The higher voltage value V_{SCMax} of this interval corresponds to the maximum voltage of the storage device. Generally, the lower voltage value V_{SCMin} is chosen as $V_{SCMax}/2$, which causes only 25% of the energy in the supercapacitor bank to remain [33]; as a result, the supercapacitor discharge becomes ineffective. This results in the supercapacitor current reference i_{SCREF} .

2.2.3. Supercapacitor energy control

The classical electrostatic energy storage y_{SC} in the supercapacitor is expressed by:

$$y_{SC} = \frac{1}{2} C_{SC} v_{SC}^2 \quad (16)$$

where C_{SC} is the supercapacitor capacitance (refer to Fig. 1), and v_{SC} is the supercapacitor voltage.

Again, based on the flatness-control, the total electrostatic energy y_T stored in the total d.c.-bus capacitor C_{Bus} and the supercapacitor C_{SC} is taken as the flat output variable (Eq. (1)), i.e.:

$$y_T = y_{Bus} + y_{SC} = \frac{1}{2} C_{Bus} v_{Bus}^2 + \frac{1}{2} C_{SC} v_{SC}^2 \quad (17)$$

It is again assumed that the fuel cell and photovoltaic currents follow their reference values perfectly. Thus:

$$i_{FC} = i_{FCREF} = \frac{p_{FC}}{v_{FC}} = \frac{p_{FCREF}}{v_{FC}} \quad (18)$$

$$i_{Sol} = i_{SolREF} = \frac{p_{Sol}}{v_{Sol}} = \frac{p_{SolREF}}{v_{Sol}} \quad (19)$$

where p_{FCREF} and p_{SolREF} are the control variables of the reduced system (Eq. (3)).

Thus, the state variable v_{SC} may be put into a form similar to that of Eq. (2):

$$v_{SC} = \sqrt{\frac{2(y_T - y_{Bus})}{C_{SC}}} = \varphi_2(y) \quad (20)$$

The differential equation verified by the reduced model from Fig. 1 is:

$$\dot{y}_T = p_{Ta} - p_{Load} \quad (21)$$

where

$$p_{Ta} = p_{FCa} + p_{Sola} = p_T - r_T \left(\frac{p_T}{v_T} \right)^2 \quad (22)$$

For a fuel cell and a solar cell that are combined as an energy source to supply energy to a d.c.-bus and supercapacitor, v_T is defined as presented in Eq. (22) and r_T represents the total losses in the fuel cell and photovoltaic converters.

Therefore:

$$p_{TREF} = 2p_{TMax} \left[1 - \sqrt{1 - \left(\frac{\dot{y}_T + p_{Load}}{p_{TMax}} \right)} \right] = \psi_2(y, \dot{y}) \quad (23)$$

where

$$p_{TMax} = \frac{v_T^2}{4r_T} \quad (24)$$

In fact:

$$p_{TMax} = p_{FCMax} + p_{FCMax} \quad (25)$$

p_{FCMax} is the maximum fuel cell power. p_{SolMax} is the maximum photovoltaic power.

Photovoltaic power systems require some specific estimation algorithms to deliver the maximum power point (MPP) because the output features of a solar cell vary with environmental changes in irradiance and temperature. Many previous investigations have presented different techniques for maximum power point tracking (MPPT) of photovoltaic arrays [42–44]. It is beyond the scope of this study to present the MPPT algorithm here, though it is similar to Eq. (14). Because the supercapacitor energy storage has a large capacity and the supercapacitor energy is defined as a slower dynamic variable than the d.c.-bus energy variable, the total (supercapacitor) energy control law is defined as:

$$(\dot{y}_T - \dot{y}_{TREF}) + K_{21}(y_T - y_{TREF}) = 0 \quad (26)$$

The supercapacitor energy control loop is shown in Fig. 4. The total energy control law generates a total power reference p_{TREF} . First, p_{TREF} is considered to be the photovoltaic power reference $p_{SolarREF}$. It must be limited in level, within an interval maximum $p_{SolarMax}$ (MPP) and minimum $p_{SolarMin}$ (set to 0 W), and have limited dynamics to respect constraints in the dynamic classification (Fig. 2). Here, the second-order delay [34] is selected as a photovoltaic power dynamic limitation, as illustrated in Fig. 4. Second, the difference between the total power reference p_{TREF} and the

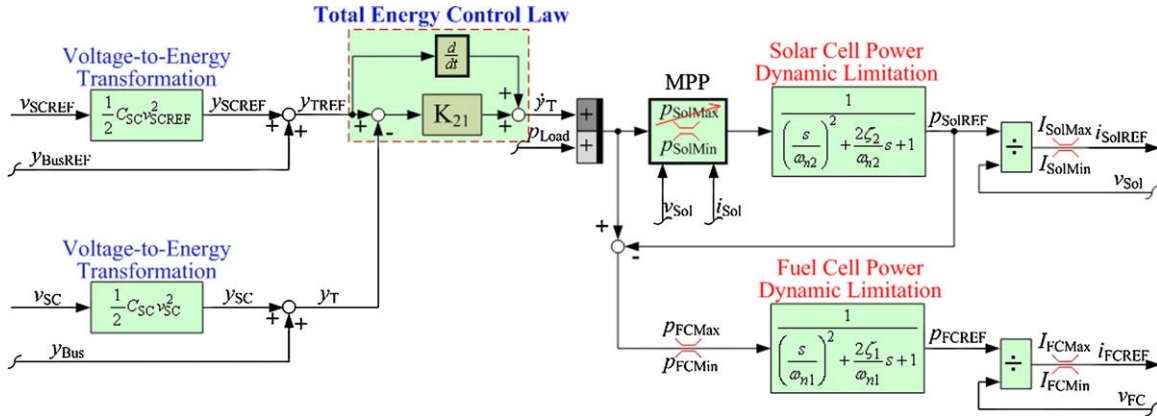


Fig. 4. Proposed supercapacitor energy control loop for fuel cell/solar cell/supercapacitor hybrid source.

photovoltaic power reference p_{SolarREF} is the fuel cell power reference p_{FCREF} . It must be limited in level, within an interval maximum p_{FCMax} and minimum p_{FCMin} (set to 0 W), and be limited in dynamics to respect the dynamic classification constraints in Fig. 2. Again, second-order delay is selected as a fuel cell power dynamic limitation.

3. Performance validation

3.1. Test bench description

In order to authenticate the proposed original hybrid energy management, a small-scale test bench has been implemented, as presented in Fig. 5. The fuel cell system used in this effort is a Ballard Nexa fuel cell system (1.2 kW, 46 A). It is supplied using pure hydrogen with a regulated pressure of 10 bar from bottles under a pressure of 150 bar and with clean dry air from a compressor. The photovoltaic array (800 W, 31 A) was obtained by connecting four panels (200 W, 7.78 A) in series. The solar cell panels were developed and manufactured by the Ekarat Solar Company. They were installed on the roof of the laboratory building, as illustrated in Fig. 5. The supercapacitor module (100 F, 32 V, based on Maxwell Technologies Company) was obtained by connecting 12 cells BCAP1200 (capacitance: 1200 F; maximum voltage: 2.7 V) in series, as shown in Fig. 5.

The fuel cell converter (1200 W) is composed of four-phase boost converters connected in parallel using the interleaving technique [45] and is selected to adapt the low d.c. voltage delivered

by the fuel cell, which is approximately 26 V at rated power, to the 60 V d.c.-bus. Thus, each boost converter is composed of a high-frequency input inductor (420 μH), four output filtering capacitors connected in parallel (each capacitor is an aluminum electrolytic capacitor (470 μF), thus the total capacitance is 1880 μF), a diode (Schottky diode RURG3020: 200 V, 30 A), and a main power switch (power metal–oxide–semiconductor field-effect transistor IRFP264N MOSFET: 250 V, 38 A). The frequency of the pulse-width modulation (PWM) that drives each boost converter is 25 kHz.

The solar cell converter (800 W) is composed of two-phase boost converters connected in parallel by the interleaving technique and is selected to adapt the low d.c. voltage delivered by the solar panels, which is approximately 25 V at rated power, to the 60 V d.c.-bus. Thus, each boost converter is composed of a high-frequency input inductor (140 μH), four output filtering capacitors connected in parallel (total capacitance: 4400 μF), a diode (Schottky diode RURG3020: 200 V, 30 A), and a main power switch (power metal–oxide–semiconductor field-effect transistor IRFP264N MOSFET: 250 V, 38 A). The frequency of the PWM that drives each boost converter is 25 kHz.

The supercapacitor converter is composed of four-phase bidirectional converters connected in parallel by the interleaving technique. Thus, each two-quadrant converter is composed of a high-frequency input inductor (290 μH), an output filtering capacitor (aluminum electrolytic capacitors: 680 μF), two power switches (power metal–oxide–semiconductor field-effect transistor IRFP264N MOSFET: 250 V, 38 A), and two diodes (Schottky diode RURG3020: 200 V, 30 A). The frequency of the PWM that drives

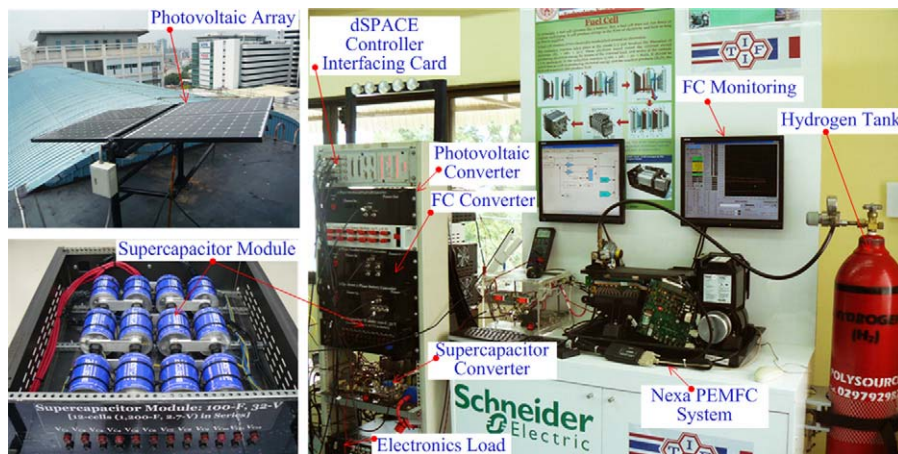


Fig. 5. Hybrid power source test bench.

Table 1
d.c.-bus energy control loop parameters.

Parameter	Value	
V_{BusREF}	60	V
C_{Bus}	12,200	μF
K_{11}	450	rad s^{-1}
K_{12}	22,500	rad s^{-2}
r_{FC}	0.14	Ω
r_{Sol}	0.12	Ω
r_{SC}	0.10	Ω
V_{SCMax}	32	V
V_{SCMin}	15	V
I_{SCRated}	150	A

each bidirectional converter is 25 kHz. The supercapacitor current, which flows across the storage device, can either be positive or negative, which allows energy to be transferred in both directions.

3.2. Control description

Measurements of the fuel cell current i_{FC} , the solar cell current i_{Sol} , the supercapacitor current i_{SC} , the load current i_{Load} , the d.c. link voltage v_{Bus} , the fuel cell voltage v_{FC} , the solar cell voltage v_{Sol} , and the supercapacitor voltage v_{SC} are collected with zero-flux Hall effect sensors.

The fuel cell, the solar cell and the supercapacitor current-regulation loops were realized by analog circuits to function at a high bandwidth. Parameters associated with the d.c.-bus energy regulation loop and the supercapacitor energy regulation loop can be seen in Tables 1 and 2, respectively. The fuel cell power dynamic delay is shown in Table 2; this value was experimentally determined as the highest power slope of the FC system, where no fuel starvation occurs. It must be noted here that, for the small-

Table 2
Supercapacitor energy control loop parameters.

Parameter	Value	
V_{SCREF}	25	V
C_{SC}	100	F
K_{21}	0.1	WJ^{-1}
p_{SolMax} (rated)	800	W
p_{SolMin}	0	W
I_{SolMax} (rated)	28	A
I_{SolMin}	0	A
ζ_2	1	
ω_{n2}	0.8	rad s^{-1}
p_{FCMax}	500	W
p_{FCMin}	0	W
I_{FCMax} (rated)	46	A
I_{FCMin}	0	A
ζ_1	1	
ω_{n1}	0.4	rad s^{-1}

test bench, the fuel cell maximum power p_{FCMax} is set at 500 W; but, the rated fuel cell power considered here is 1200 W. Further, these two energy control loops, which generate current references i_{FCREF} , i_{SolREF} and i_{SCREF} are implemented on the real time card dSPACE DS1104 through the mathematical environment of Matlab–Simulink with a sampling frequency of 25 kHz.

3.3. Experimental results

The studied d.c.-bus of 60 V is only connected to an electronic load. To validate the dynamics of the power (current) regulation loops for each power source, Figs. 6–8 present waveforms that are obtained during the stepped power demand. Fig. 6 illustrates the fuel cell power demand, power response, voltage and current. Fig. 7 contains the photovoltaic power demand, power response,

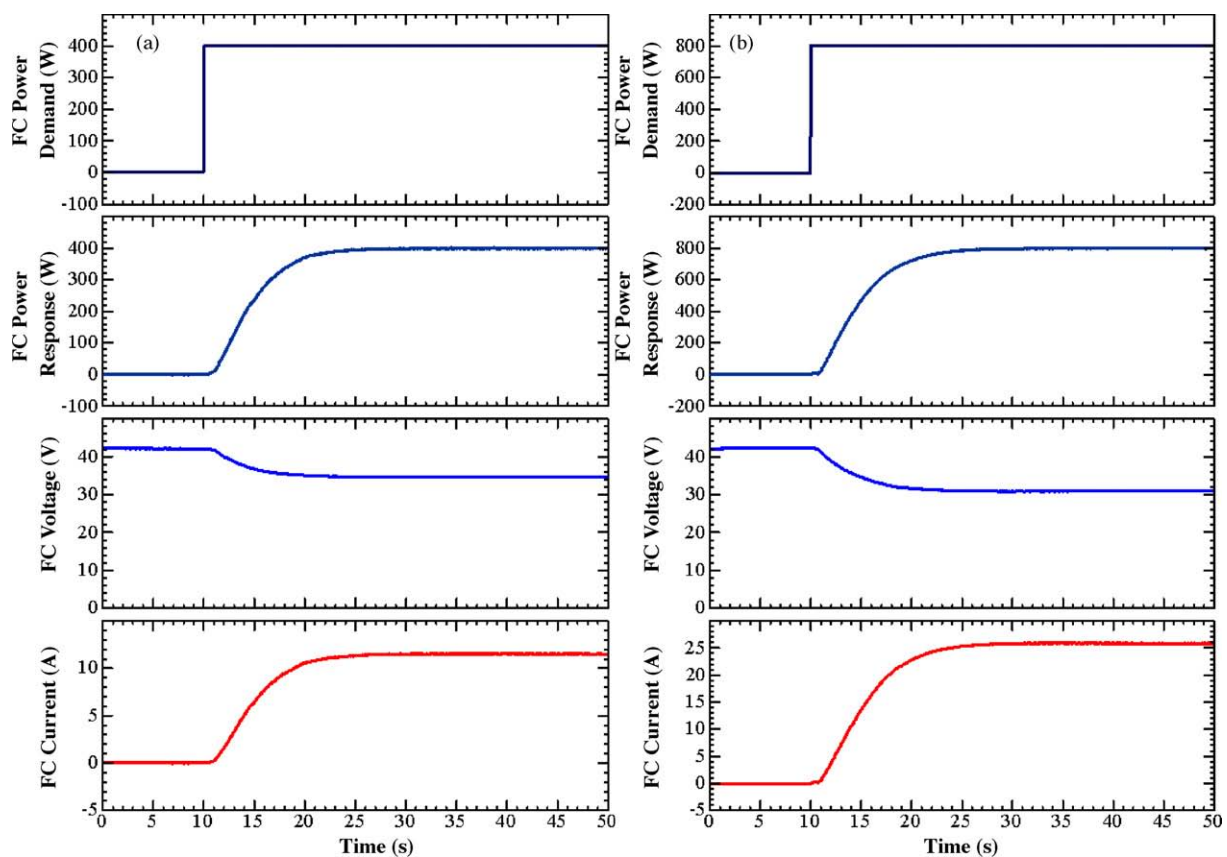


Fig. 6. Dynamic identification of fuel cell power control loop.

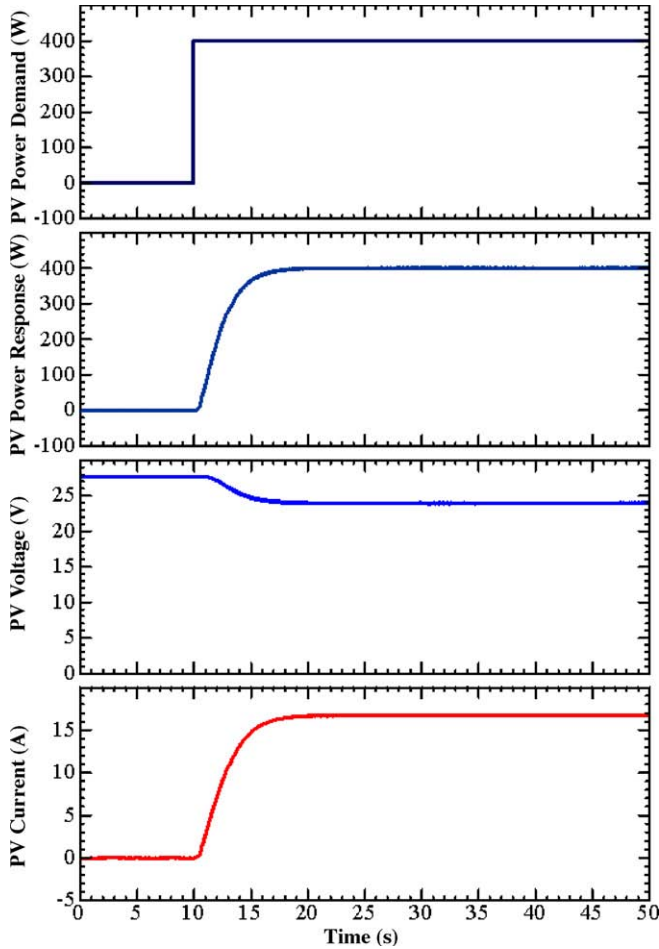


Fig. 7. Dynamic identification of photovoltaic power control loop.

voltage and current. Finally, Fig. 8 illustrates the supercapacitor power demand, power response, voltage and current. Because the fuel cell and photovoltaic powers are intentionally limited by the control algorithm (refer to Fig. 4: 'solar cell dynamic power limitation' and 'fuel cell power dynamic limitation'), a smooth transition of the power responses of the fuel cell and photovoltaic sources is observed, while the supercapacitor power dynamics are very fast. The supercapacitor can supply power from 0 to 400 W in 50 ms. It is clear that the fast response of the supercapacitor storage device can be operated with the fuel cell and solar cell main generators in order to improve system performance. The data in Fig. 6 also confirm that the fuel cell is controlled to avoid the fuel starvation phenomenon.

Because flatness-based control is model-based, it may have some sensitivity to errors in the model parameters. To authenticate its robustness, the flatness-based control was tested with the exact model parameters ($r_{FC} = 0.14 \Omega$, $r_{Sol} = 0.12 \Omega$, $r_{SC} = 0.10 \Omega$) and in the lossless parameters case ($r_{FC} = 0 \Omega$, $r_{Sol} = 0 \Omega$, $r_{SC} = 0 \Omega$). In the case of no losses, this leads to a drastically less complex estimation of the control law (Eqs. (8)–(11)). Comparisons (robustness) between the accurate parameters and the error parameters are given in Fig. 9. They generate waveforms that are obtained during the large load step from 0 to 500 W and show the d.c.-bus voltage, the load power (disturbance), the supercapacitor power, and the supercapacitor voltage (storage SOC). Because the power of the fuel cell and the solar cells are intentionally limited, the supercapacitor supplies the transient load power demand. Similar waveforms are seen in Fig. 9(a) and (b). The d.c.-bus voltage (d.c. link stabilization) is minimally influenced by the large step in load power.

Clearly the performance of the control system is hardly affected by the considered error in model parameters. Experimental testing demonstrates that errors in these parameters have relatively little effect on regulation performance. It is therefore conclude that the non-linear differential flatness-based approach provides an absolutely robust controller in this application.

Waveforms obtained during the large load cycle are presented in Fig. 10. The data show the d.c.-bus voltage, the fuel cell voltage, the photovoltaic voltage, the load power, the supercapacitor power, the fuel cell power, the photovoltaic power, the supercapacitor current, the fuel cell current, the photovoltaic current, and the supercapacitor voltage (or the supercapacitor SOC). In the initial state, the small load power is equal to 100 W, and the storage device is fully charge, i.e., $v_{SC} = 25$ V; as a result, both the fuel cell and supercapacitor powers are zero, and the photovoltaic source supplies power for the load of 100 W. At $t = 40$ s, the load power steps to the final constant power of around 900 W (positive load power transition). The following observations are made:

- The supercapacitor supplies most of the 900 W power that is required during the transient step load.
- Simultaneously, the photovoltaic power increases with limited dynamics to a maximum power point (MPP) of around 300 W, which is limited by the maximum power point tracker (MPPT).
- Concurrently, the fuel cell power increases with limited dynamics to a maximum power of 500 W.
- The input from the supercapacitor, 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 fuel cell and photovoltaic array.

At $t = 100$ s, the supercapacitor voltage is equal to 19 V. As a result, the supercapacitor supplies its stored energy y_{SC} to the d.c.-bus. This energy y_{SC_Supply} is estimated to be:

$$y_{SC_Supply} = \frac{1}{2} C_{SC} v_{SC}^2(t = 40 \text{ s}) - \frac{1}{2} C_{SC} v_{SC}^2(t = 100 \text{ s}) = 13.20 \text{ kJ} \quad (27)$$

The load power is reduced from the high constant power of 900 W to the low constant power of 100 W (negative load power transition). As a result, the supercapacitor changes from discharging to charging and demonstrates the following four phases:

- First, the fuel cell and photovoltaic array still supply their constant maximum powers to drive the load and to charge the supercapacitor.
- Second, at $t = 110$ s, the supercapacitor is approaching full charge, i.e., $v_{SC} = 23$ V. Consequently, the fuel cell power is reduced with limited power dynamics.
- Third, at $t = 120$ s, the supercapacitor is nearly fully charged, i.e., $v_{SC} = 24$ V. As a result, the photovoltaic power is reduced with limited power dynamics.
- Fourth, at $t = 160$ s, the supercapacitor is fully charged, i.e., $v_{SC} = v_{SCREF} = 25$ V. After slowly decreasing, the photovoltaic power remains at a constant power of 100 W for the load power demanded. Furthermore, the fuel cell and supercapacitor powers are zero.

It is evident that the d.c.-bus voltage waveform is stable during the large load cycle, which is critically important when employing supercapacitors to improve the dynamic performance of the whole system using the proposed control law.

Finally, Fig. 11 presents waveforms that are obtained during the long load cycles measured on 5 December, 2009. The waveforms are

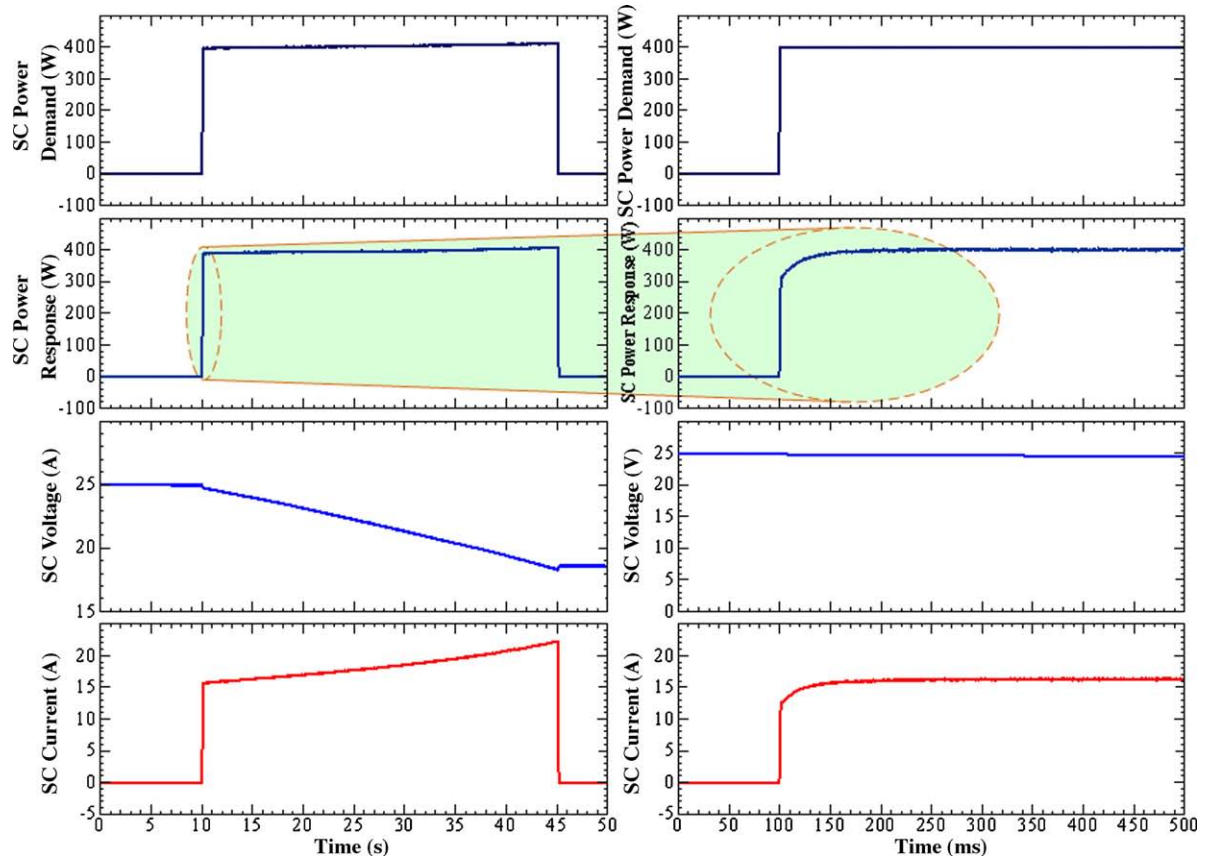


Fig. 8. Dynamic identification of supercapacitor power control loop.

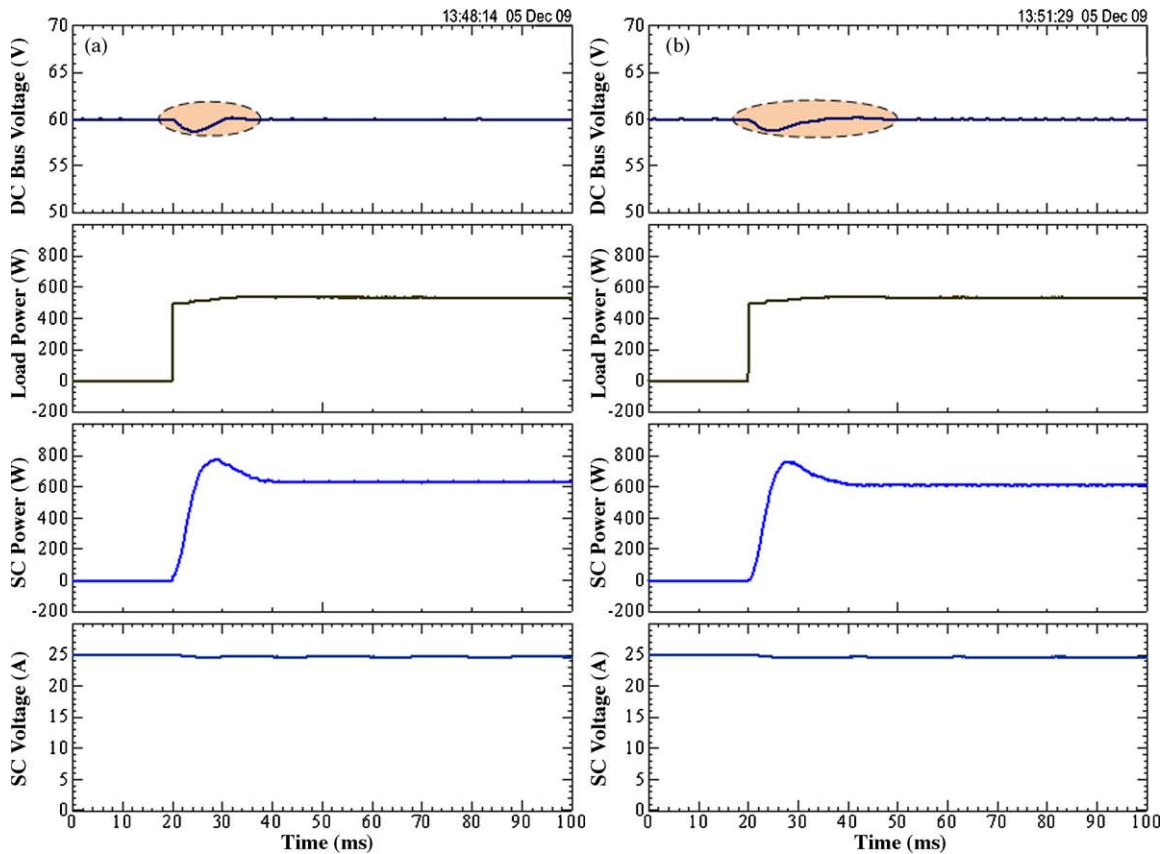


Fig. 9. Comparison of d.c. link stabilization of hybrid energy source during large load step. (a) exact model ($r_{FC} = 0.14 \Omega$, $r_{Sol} = 0.12 \Omega$, $r_{SC} = 0.10 \Omega$) and (b) error model (robustness) ($r_{FC} = 0 \Omega$, $r_{Sol} = 0 \Omega$, $r_{SC} = 0 \Omega$).

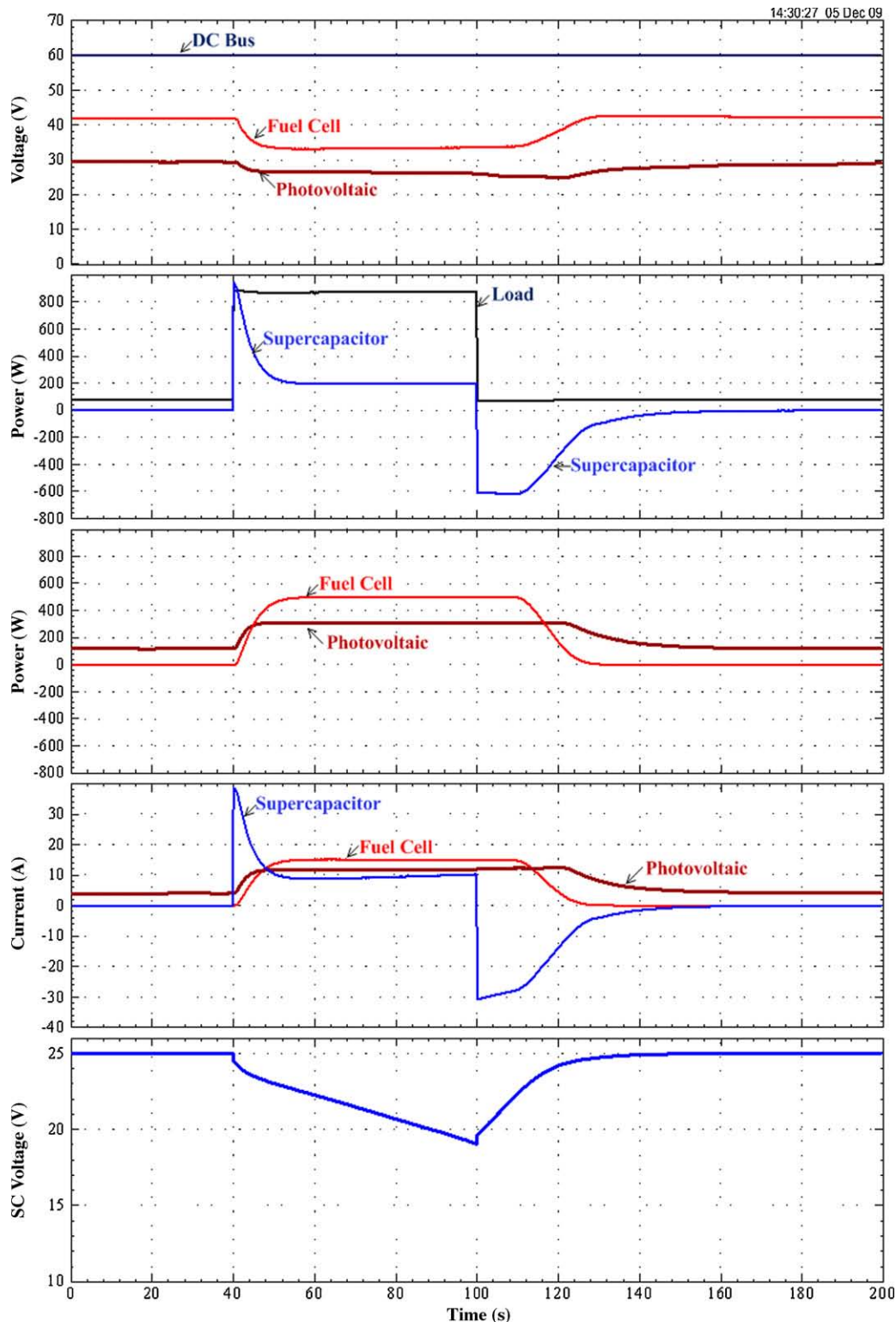


Fig. 10. Hybrid source response during load cycle.

similar to the test bench results in Fig. 10. During the experiment, the FC maximum power was set to 500 W, and the PV maximum power (depending on solar radiation, weather conditions and temperature) was limited by the MPPT. For example, at 15:01:40, the PV maximum power was approximately equal to 180 W; at 15:02:30, the PV maximum power was about 180 W; at 15:03:20, the PV maximum power was around 180 W; and from 15:05:50 to 15:08:20, the PV maximum power was reduced to 0 W, because of the cloudy

conditions. In particular, it was found that the power plant was always energy balanced $p_{Load}(t) \approx p_{FC}(t) + p_{Sol}(t) + p_{SC}(t)$ by the proposed original control algorithm.

The important variable necessary to balance the energy in this complex system is the d.c.-bus energy or voltage. From the experimental validation, the d.c.-bus voltage is automatically controlled at the constant set-point, i.e., $v_{Bus} = 60$ V. This experiment confirms that the energy in the system is well managed. The fuel cell and

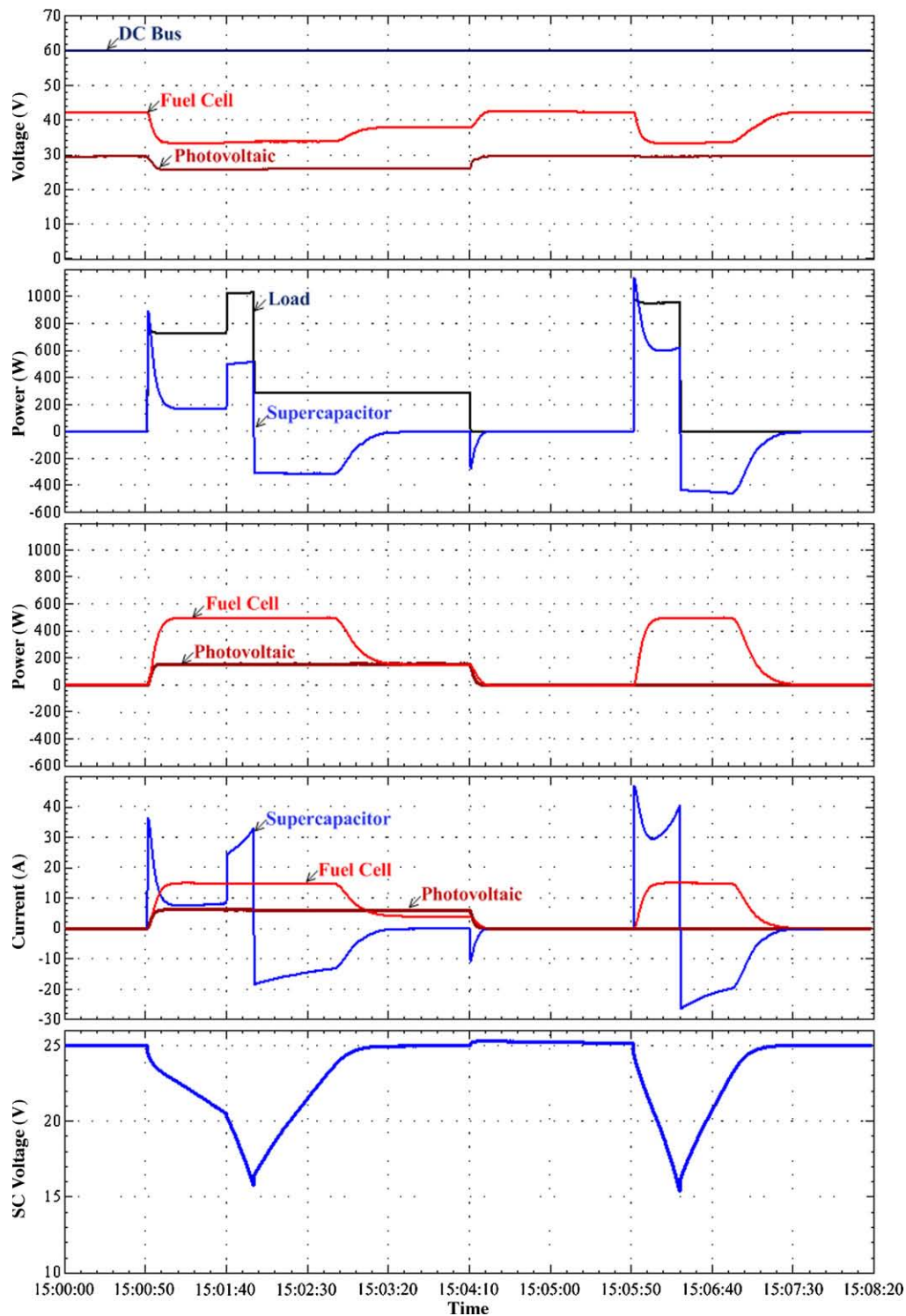


Fig. 11. Hybrid source response during long load cycles.

solar cell powers are limited at their maximum powers, and the fuel cell power dynamics are controlled; as a result, there is no fuel starvation problem and the fuel cell stack lifetime is increased [46–48].

4. Conclusions

Energy management of multi-power sources has been proposed as a solution for a hybrid energy system that uses renewable energy from solar cells, fuel cells and a supercapacitor as an energy stor-

age device. A supercapacitor can advance the load, following the characteristics of the main sources by providing a stronger power response to changes in the system load. During essential steps in the load, the supercapacitor provides the energy balance needed during load transition periods. Adding energy storage to the distributed power systems improves power quality and efficiency.

Experimental verification with a small-scale hybrid test bench (Nexa Ballard fuel cell power generator: 1.2 kW, 46 A; Ekarat Solar Cell power module: 800 W, 31 A; Maxwell supercapacitor storage device: 100 F, 32 V) has demonstrated the excellent performance of

the whole system, and has validated the proposed energy management principle.

Acknowledgments

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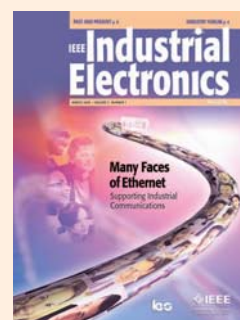
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Fuel Cell High-Power Applications

*An Overview
of Power
Converters
for a Clean
Energy
Conversion
Technology*

PHATIPHAT THOUNTHONG,
BERNARD DAVAT, STÉPHANE RAËL,
and PANARIT SETHAKUL

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Energy consumption plays an important role in our modern civilization and daily life, which is heavily dependent on burning fossil fuels. The increasing threat of the fast depletion of resources such as petroleum, coal, and natural gas forces people to seek regenerative energy sources, such as solar, wind, geothermal, and hydroelectric energies. Another way of saving valuable natural resources and solving the environmental problem is to develop cleaner and more efficient energy conversion devices. In recent years, fuel cell (FC) research and development have received much attention for their higher energy conversion efficiency and lower or nongreenhouse-gas emissions than thermal engines in the processes of converting fuel into usable energies [1]–[3]. The power and energy efficiency of an FC is highly dependent on thermodynamics, electrode kinetics, and reactant mass transfer, as well as materials and components for assembling the FC. These factors have been addressed throughout the FC history and are now still the major challenges for FC research and development [4]–[6].

In industry, United Technologies Corporation (UTC) Fuel Cells is involved in FC systems for space and defense applications. UTC Fuel Cells activity began in 1958 and led to the development of the first practical FC application used to generate electrical power and potable water for the Apollo space missions. Since 1966, all of the more than 100 manned U.S. space flights, including the Space Shuttle, have operated with FCs supplied by UTC companies. In 1991, UTC Fuel Cells manufactured its first PureCell 200 power plant, the world's first and only commercial FC power. The PureCell 200 FC produces 200-kW of electricity and 700,000 BTUs of heat. The unit can be powered by natural gas, propane, butane, hydrogen, naphtha, or gases from waste. Since their first flight in 1981, UTC Fuel Cells power plants have provided electric power for more than 100 shuttle missions. They shipped a 50-kW hydrogen-air

FC power plant to the U.S. Department of Energy (DOE) and the Ford Motor Company. In 1998, UTC Fuel Cells delivered a 100-kW methanol power plant, with 40% efficiency, to Nova Bus for installation in a 40-ft, hybrid drive electric bus under a DOE/Georgetown University contract [7], [8].

General Motors is involved in the development of FCs for stationary power as well as the more obvious automotive markets [9]–[11]. In February 2004, they began the first phase of installation operations in Texas at Dow Chemical Company, the largest facility in the world. These FC systems are used to generate 35 MW of electricity [12].

Fuel cells produce dc voltage outputs, and they are always connected to electric power networks through power conditioning units such as dc/dc and dc/ac converters.

Axane (France) is also working on FC technology. Three markets that are likely to provide large commercial outlets [13], [14] are:

- portable multiapplication generators (500 W–10 kW)
- stationary applications (more than 10 kW)
- mobile applications for small hybrid vehicles (5–20 kW).

FCs produce dc voltage outputs, and they are always connected to electric power networks through power conditioning units such as dc/dc and dc/ac converters. Power conversion and control functions form the basis of what has come to be known as the field of power electronics. In recent years, power electronics technology has been spurred by needs for efficient control of industrial applications and the development of more reliable lightweight switching power supplies for a sophisticated system. This article reviews the current research of power electronic converters for FC high-power applications.

FC Technology

An FC is a device that converts the chemical energy of a fuel directly to electrical energy. Its concept was pro-

posed approximately 170 years ago when William Robert Grove conceived the first FC in 1839, which produced water and electricity by supplying hydrogen and oxygen into a sulfuric acid bath in the presence of porous platinum electrodes [1]. The process by which this is done is very similar to the electrochemical process by which a battery generates power; at one electrode, a fuel such as hydrogen is oxidized, and at the other electrode an oxidant such as oxygen is reduced. The reactions exchange ions through a solid or liquid electrolyte and electrons through an external circuit, as shown in Figure 1 [15], [16].

The theoretical value of a single cell voltage of FC is 1.23 V. It is never reached even at no load. At the rated current, the voltage of an elementary cell is about 0.6–0.7 V [17]–[19]. Therefore, an FC is always an assembly of elementary cells that constitute a stack, as Figure 2 depicts.

There are many different types of FCs, with the principal differences between them being the type of electrolyte and/or the type of fuel that they use. For instance, both the phosphoric acid FC (PAFC) and the molten carbonate FC (MCFC) have a liquid electrolyte, whereas a solid oxide FC (SOFC) has a solid, ceramic electrolyte [20]–[22]. A proton exchange or polymer electrolyte membrane FC (PEMFC) and a direct methanol FC (DMFC) may have the same solid polymer electrolyte, but the DMFC uses liquid methanol for fuel whereas the PEMFC uses gaseous hydrogen [23], [24].

Currently, there are three general areas of application for FC technology: portable power, distributed power, and transportation. For each application, it is generally found that one type of FC is better suited than the others to satisfy the requirements of

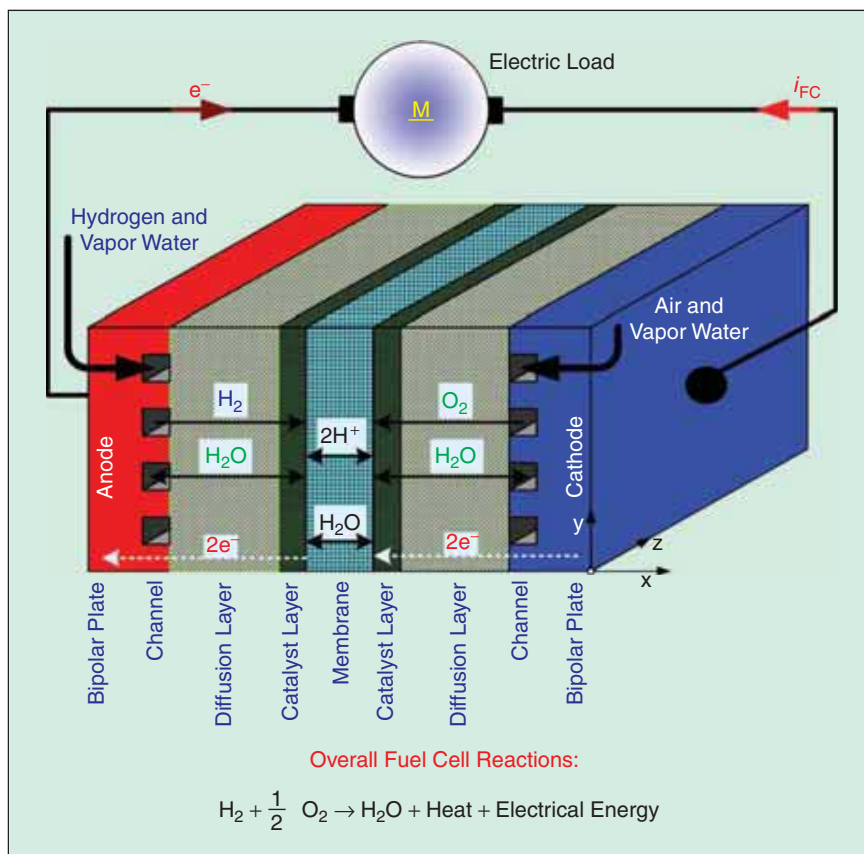


FIGURE 1 – Different layers of an elementary cell of PEMFC.

the application. The DMFCs are attractive for several applications in view of their lower weight and volume. The DMFCs are increasingly being developed to replace or support batteries, mainly for the high energy density of methanol. The DMFCs are promising candidates as portable power sources because they do not require any fuel processing and operate at low temperatures (30–60 °C) [25]–[27]. The SOFC, because of its high power density and high grade waste heat that may be used in cogeneration applications, is a front-runner in distributed power applications at the industrial level [28]–[31]. The PEMFC has many of the qualities required of an automotive power system including relatively low operating temperature, high power density, and rapid startup [32]–[34]. In addition, PEMFC may also be used in residential and commercial power systems [35].

An FC stack requires fuel, oxidant, and coolant in order to

operate. The composition, pressure, and flow rate of each of these streams must be regulated. In addition, the gases must be humidified and the coolant temperature must be controlled. To achieve this, the FC stack must be surrounded by a fuel system, fuel delivery system, air system, stack cooling system, and humidification system. Once operating, the output power generated by the FCs must be conditioned

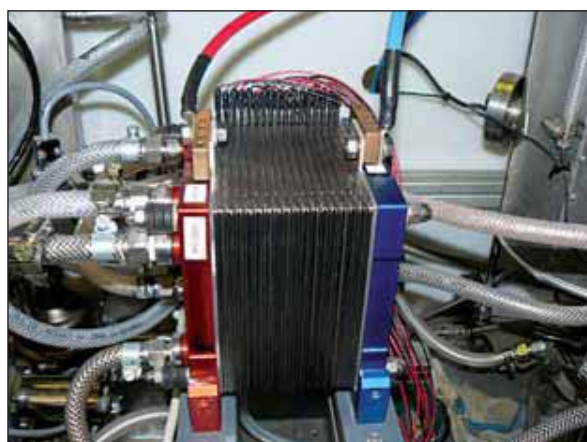


FIGURE 2 – An PEMFC (16 cells, 500 W, 50 A, and around 11 V) manufactured by the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) Company. It is being functioned at the GREEN laboratory.

and absorbed by a load (converter). Suitable alarms must shut down the process if unsafe operating conditions occur, and a cell voltage monitoring system must monitor FC stack performance. These functions are performed by electrical control systems. As an example, Figure 3 shows a simplified diagram of the PEMFC system. When an FC operates, its fuel (hydrogen and air) flows are controlled by an FC controller, which receives current demand. This current demand is the FC current reference i_{FCREF} (see Figure 3) coming from the energy management controller. The fuel flows must be adjusted to match the reactant delivery rate to the usage rate by the FC controller [36], [37].

FC Characteristics

As mentioned earlier, an FC power source is always connected to the dc bus by a step-up converter. Switching characteristics of the PEMFC (500 W, 40 A) at steady-state when connecting with a boost converter are presented in Figure 4. It can be seen that the PEMFC contains a complex impedance component, which it is not purely resistive at a high switching frequency of 25 kHz [36].

Thounthong et al. [38] (who worked with a 500-W PEMFC system by ZSW Company), Corrêa et al. [39], [40] (who worked with a 500-W Ballard and 500-W Avista PEMFC system), and Zhu et al. [41] (who worked with a 500-W PEMFC system) have demonstrated that the electrical response time of an FC is generally fast, being mainly associated with the speed at which the chemical reaction is capable of restoring the charge that has been drained by the load. On the other hand, because an FC system is composed of many mechanical devices, the whole FC system has slow transient response and slow output power ramping [42], [43].

For clarity about the FC dynamics, Figure 5 illustrates a Nexa PEMFC system (1.2 kW, 46 A), and Figure 6 depicts the FC voltage response to a current

Therefore, the constraints to operate an FC are as follows:

- 1) The FC power or current must be kept within an interval (rated value, minimum value or zero).
- 2) The FC current must be controlled as a unidirectional current.
- 3) The FC current slope must be limited to a maximum absolute value (for example, $4 \text{ A} \cdot \text{s}^{-1}$ [53]), to prevent an FC stack from the fuel starvation phenomenon.
- 4) Switching frequency of the FC current must be greater than 1.25 kHz, and the FC ripple current must be lower than around 5% of rated value, to ensure minor impact to the FC conditions [54], [55].

FC Power Conditioning

The power conditioning system provides regulated dc or ac power appropriate for the application. It is the major component of an FC distributed system. The output of the FC is an unregulated dc voltage (see Figure 6), and it needs to be conditioned in order to be of practical use. The power conditioner section converts the FC power to usable power for different applications. The power conditioning unit also controls electricity's frequency and maintains harmonics to an acceptable level. The purpose of conditioners is to adapt the electrical current from FC to suit the electrical

needs of the application. FC operates giving direct current and at a low voltage; thereby, the step-up (boost)

converter (dc/dc converter, named here FC converter) is always selected to adapt the low dc voltage delivered

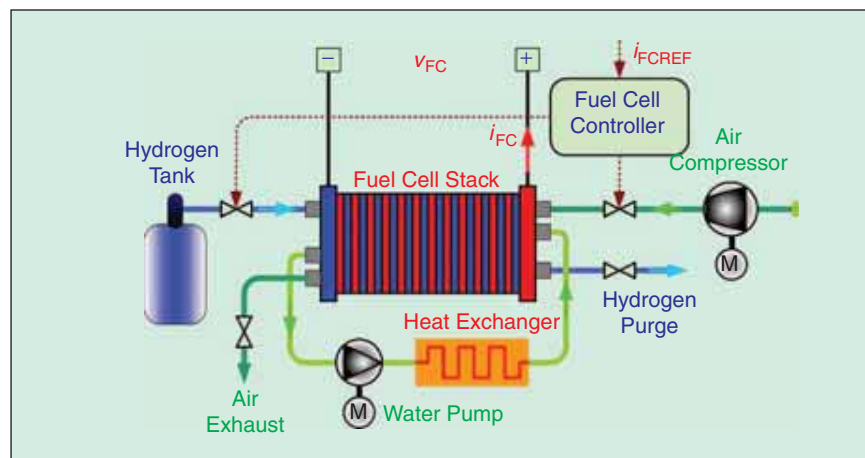


FIGURE 3 – Simplified diagram of the PEMFC system. V_{FC} , i_{FC} , and i_{FCREF} are the FC voltage, current, and current demand, respectively.



FIGURE 4– Switching characteristics of a 500 W PEMFC of 25 kHz at the FC current supply of (a) 10 A and (b) 40 A (rated current).

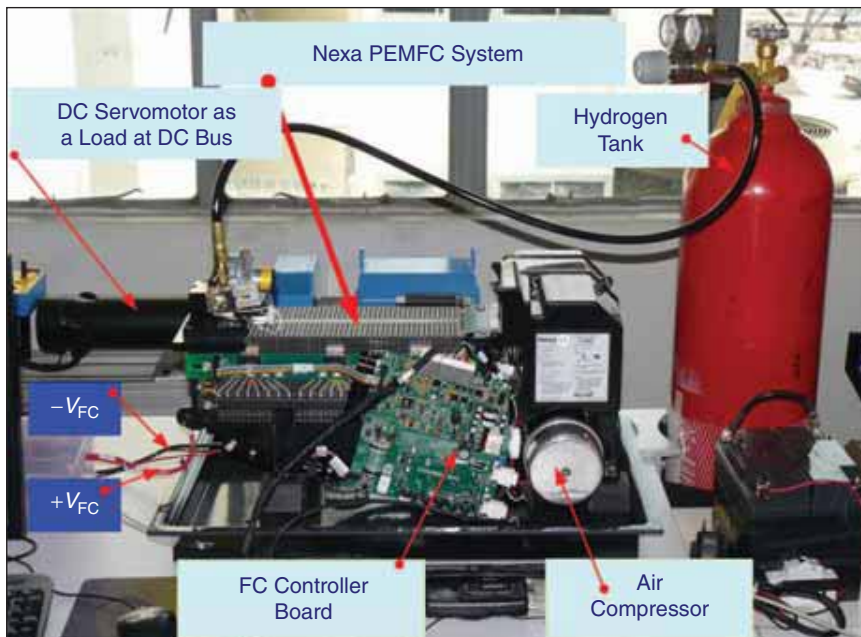


FIGURE 5 – A Nexa PEMFC (1.2 kW, 46 A). It is being functioned at the TFIL laboratory.

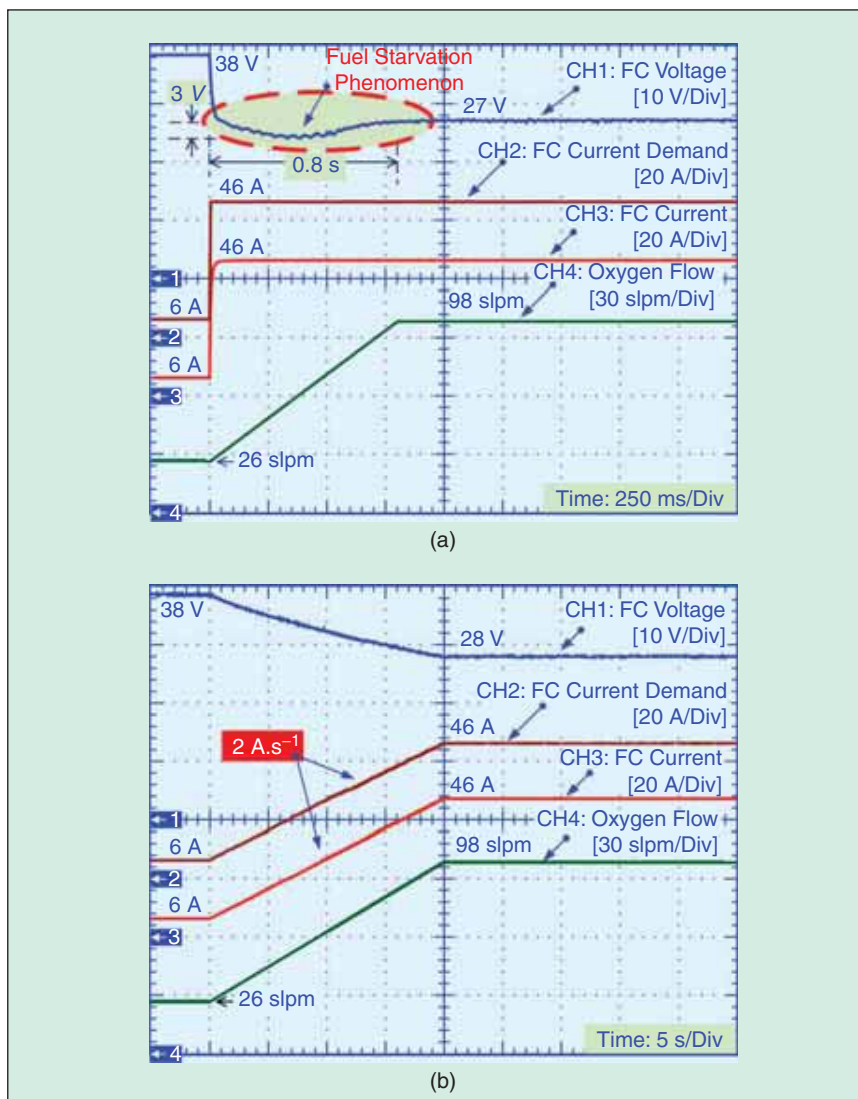


FIGURE 6 – FC dynamic characteristics to (a) current step and (b) controlled current slope of $2 \text{ A} \cdot \text{s}^{-1}$.

by the FC to the utility dc bus followed by an inverter (Figure 7) [56]. In general, the load for the boost stage is a filter and the inverter system.

The inverter is used for the interfacing of the FC system to the power grid to provide the grid with voltage/current with proper frequency phase and magnitude where the input for the inverter comes from the boost converter stage and the inverter (with the filter) becomes the load for the boost converter. The power conditioner is also used for the grid connection of the FC. An electrical power-generating system that uses FC as the primary source of electricity generation and is intended to operate synchronously, and in parallel with the electric utility network is a grid-connected FC system [57], [58]. Such systems may also include storage devices and other generating sources and may operate on site loads independent of the utility network during outages.

To employ the FC as a main power source in dynamic applications (such as an electric vehicle [59]–[61] and railway vehicle [62]–[64]), the electrical system must have at least an auxiliary power source (storage device) to improve the dynamic performances of the whole system, when electrical loads at a dc bus demand high power in a short time (for example, vehicle acceleration and deceleration), as portrayed in Figure 8. Moreover, one can take advantage of this auxiliary power source to achieve an actual hybrid source to disassociate mean power sizing from peak transient power sizing, the aim being a reduction in volume and weight, and in the case of FCs used as main energy source, the possibility of regenerative braking [38], [65]. For example, some authors have described the study of the FC/battery hybrid power source [66]–[70] and the FC/supercapacitor hybrid power source [71]–[73].

For the past ten years, much research has been conducted on the utilizations of FCs in high power applications. Today, the required FC power is in the range of 1 kW to 2 MW:

- 1–2 kW for unmanned aircrafts [74] and 40–700 kW for manned aircraft [75]–[78]

- 50–100 kW for urban cars [9], [33], [79]–[85]
- 100–200 kW for buses and light trams [7], [86]–[88]
- 600 kW–1 MW for tramways and locomotives [62]–[64], [89]–[92] (for example four motors of 180-kW peak are installed on a tramway, two motors per boggy. The total power installed is 800 kW)
- 480 kW–2 MW for distributed generation systems (grid parallel connection) [8], [93].

To increase the power and voltage levels, several configurations for the FC association can be envisaged as depicted in Figure 9 [93]–[98]. For association of the converter inputs, we can connect several FC in series and then connect them to a converter or each FC to a converter. The FC parallel connection is currently complicated because of complexity of controlling the output power distribution in each FC. For association of converter outputs, the output of a converter can be connected in series for a high output voltage or in parallel for a low output voltage.

FC Power Converter

Different power converter topologies can be used for the power electronic interface between the FC and the utility dc bus. For the dc link

A large research effort is underway to develop the FC for applications ranging from small portable electronic devices to automotive transport, as well as residential combined heat and power supplies.

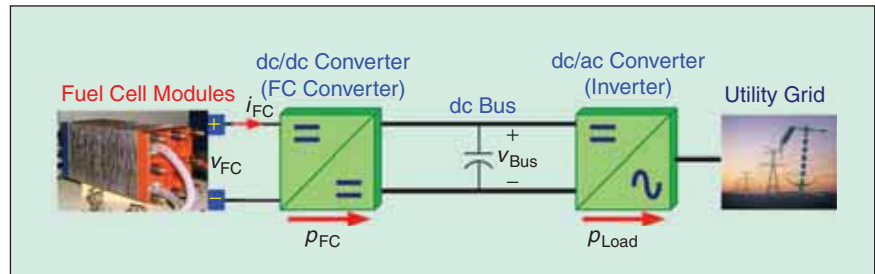


FIGURE 7 – FC power system.

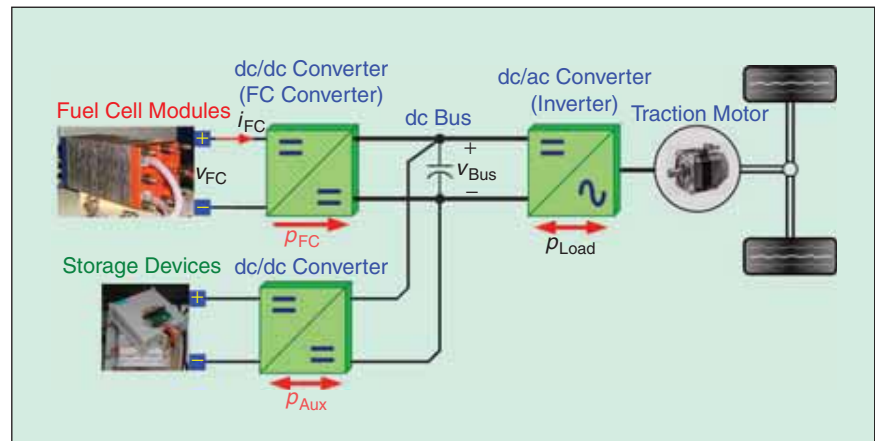


FIGURE 8 – Fuel cell powered vehicle.

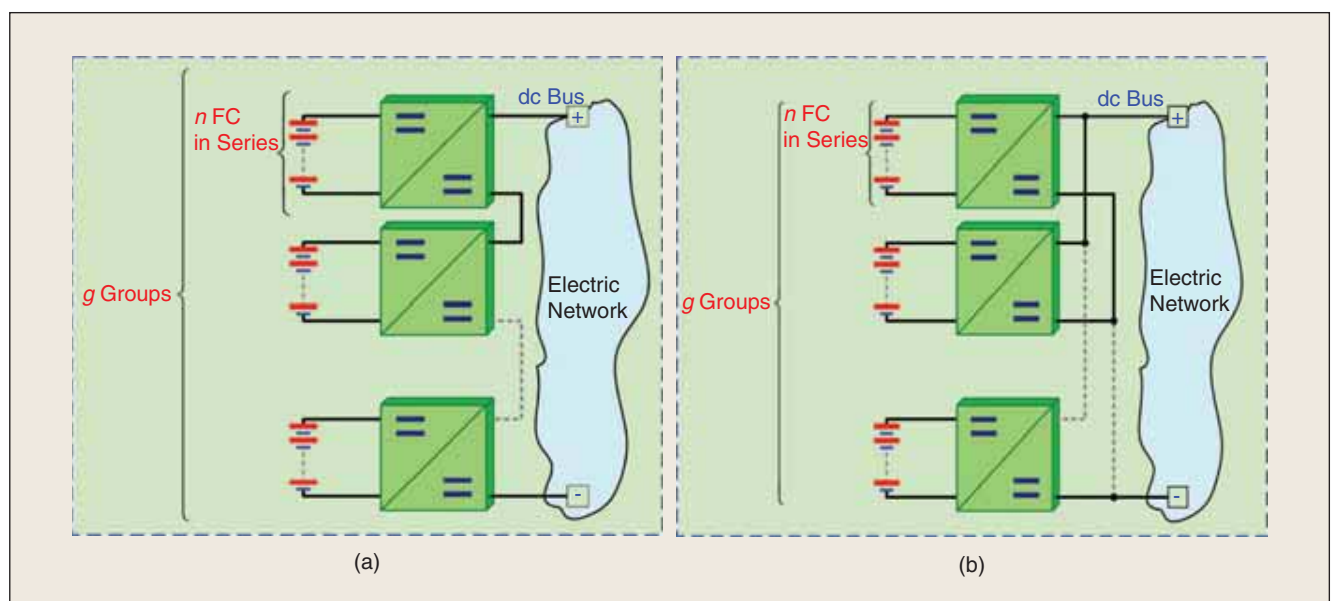


FIGURE 9 – Modular stack FC architectures connected to the dc bus: (a) output connected in series and (b) output connected parallel. n : number of FC in series in each group, g : number of FC-converter groups.

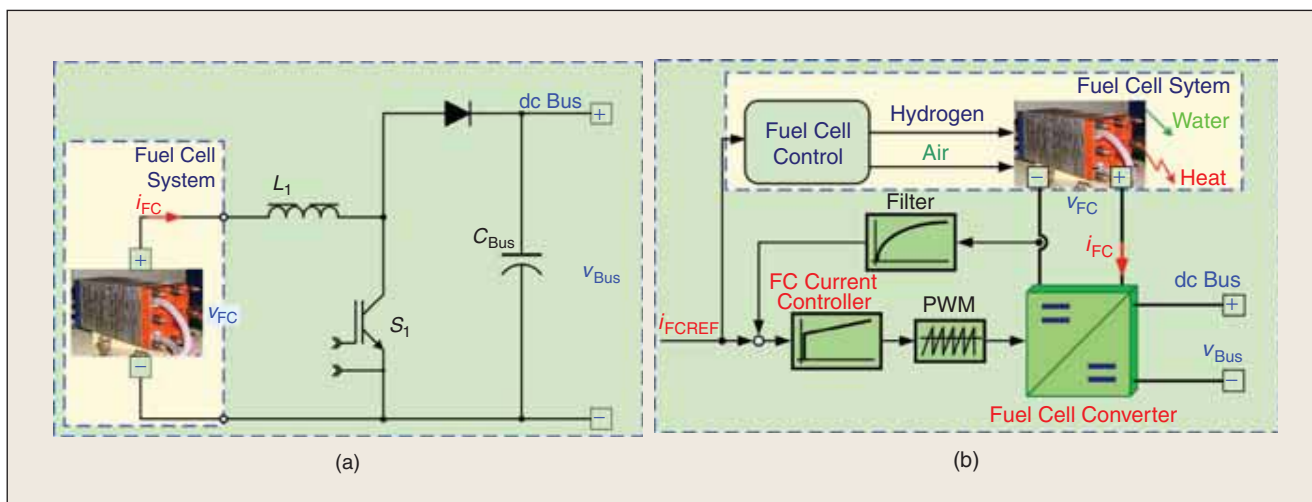


FIGURE 10 – Classical fuel cell boost converter: (a) power circuit and (b) FC current regulation loop.

voltage level, it is depending on its applications:

- 270 V or 350 V for the standard on the all-electric aircraft [78]
- 48 V [99], 120 V [100], or 400–480 V [30], [93], [101] for stand-alone or parallel grid connections
- 42 V (PowerNet) a new standard voltage for automobile systems [34], [102], [103]

- 270–540 V for electric (FC) vehicles [60], [65], [82]

- 350 V (transit bus systems) to 750 V (tramway and locomotive systems) [7], [63], [64], [87], [89]–[92], [104].

Basically, low-voltage, high-current structures are needed because of the FC electrical characteristics. A classical boost converter is often selected as an FC converter [38], [93], [99]–[101],

[105]–[107], because it can be operated in the current control mode in a continuous condition mode, as portrayed in Figure 10. Then, one does not need a blocking diode and passive filter between an FC and a converter. Based on the load conditions, the boost converter can be commanded to draw a specific amount of current from the FC with a ripple well defined by the frequency, size of the inductor, and duty ratio. The FC boost converter sizes of 0.5 kW [38]; 1 kW [100], [101], [105]; 5 kW [99]; 27 kW [106]; and 50 kW [93] have been studied. However, a classical boost converter will be limited when the power increases or for higher step-up ratios. In that way, the use of paralleling power converters with interleaved technique may offer some better performances.

Parallel Power Converter with Interleaved Switching Algorithm

The subject of paralleling power converters was on the sideline of design engineering tasks for decades. Latest efforts in standardization, miniaturization, and the proliferation of high current, low voltage power supplies have directed additional attention to various techniques to parallel power modules. The fundamental difficulty using parallel power processing circuits is to ensure that the load current is properly distributed among the parallel connected power modules. Only then can the design be optimized for the highest

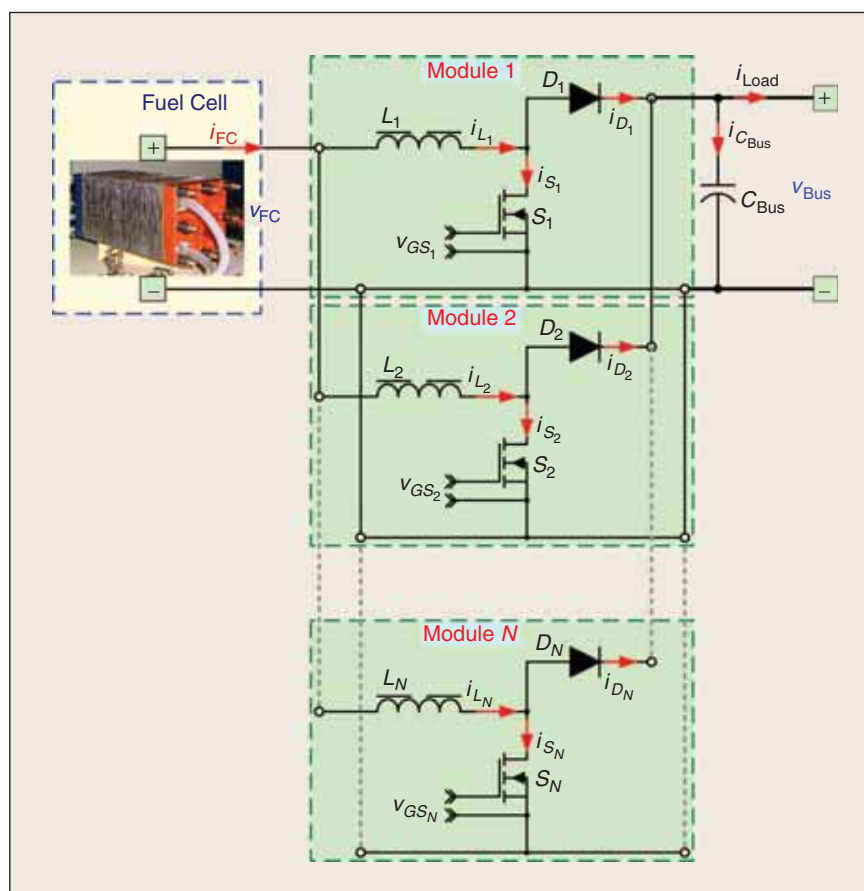


FIGURE 11 – Multiphase paralleled step-up converters for FC high-power applications.

reliability and lowest cost by ensuring equal temperature rise and by minimizing the power rating of the individual components.

The major problems of using a single dc/dc converter connected with FC in high power applications are as follows:

- difficulty of the design of magnetic component: ferrite core and Litz-wire size
- high FC ripple current, which may lead to reduce its stack lifetime.

Therefore, by paralleling converters with interleaving technique, these problems can be avoided [108]–[111]. A high-power dc distributed power system supplied by FC invokes the need to parallel power modules with interleaving technique. Active ripple cancellation methods can yield even higher performance. Today, the active method of interleaving is well known [94], [96], [98]. In the interleaving method, the modules operate at the same switching frequency. Their switching waveforms are displaced in phase over a switching period with respect to one another by $2\pi/N$ radians, with N being the number of converters in parallel. It is important to note here that, according to [54] and [55], a high FC current ripple plays an important role in its catalyst lifetime. Especially,

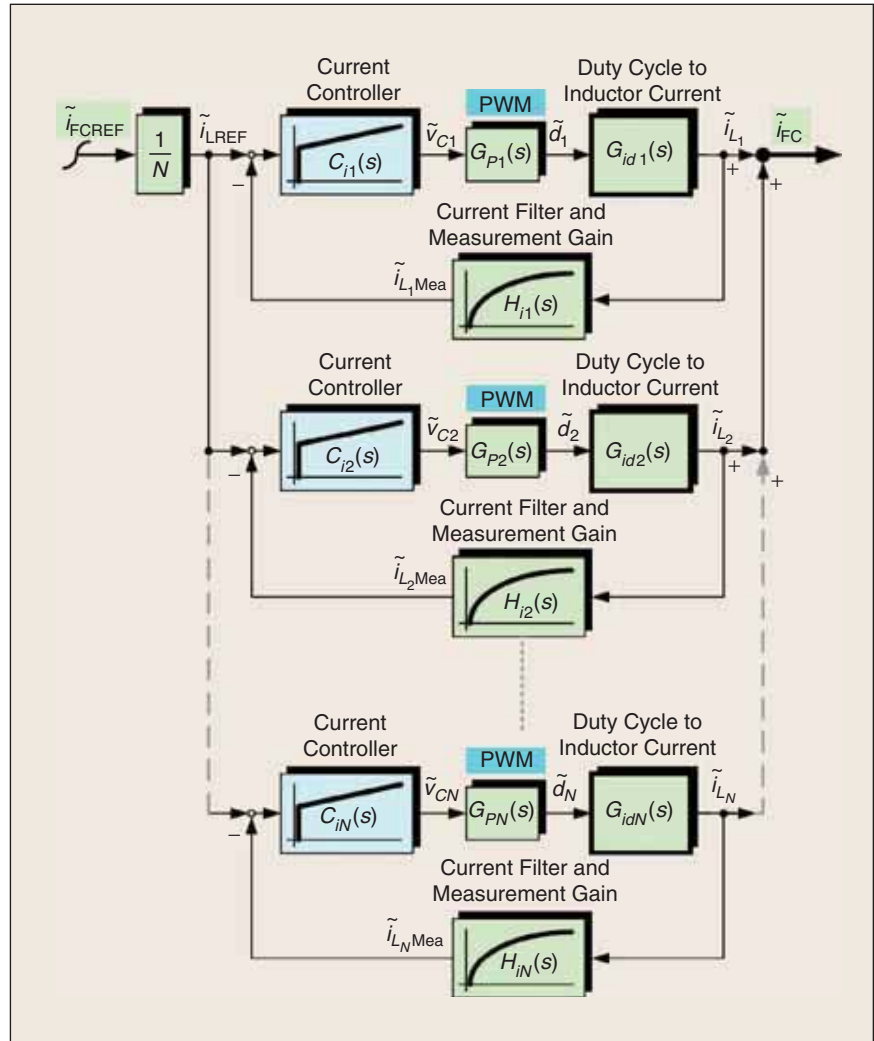


FIGURE 12 – Current sharing technique of N -phase parallel modules (here, boost converters).

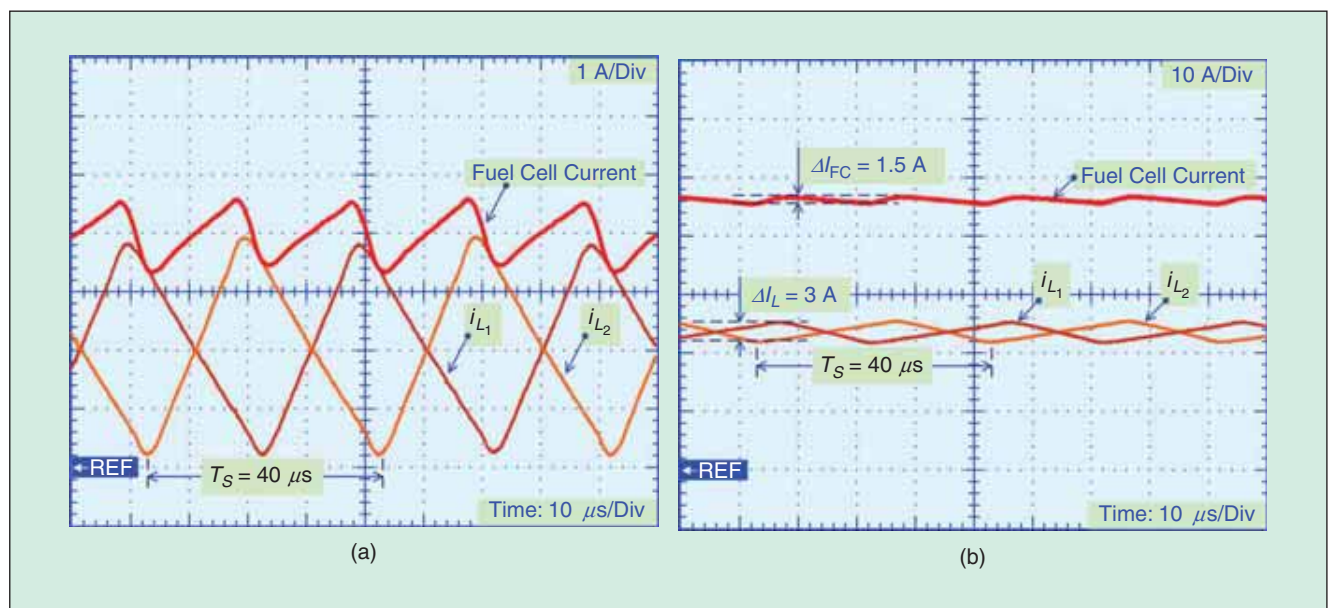


FIGURE 13 – Steady-state waveforms of the two-cell interleaved converter system at an FC current command of (a) 4 A ($v_{fc} = 35.8$ V) and (b) 46 A rated current ($v_{fc} = 26.3$ V).

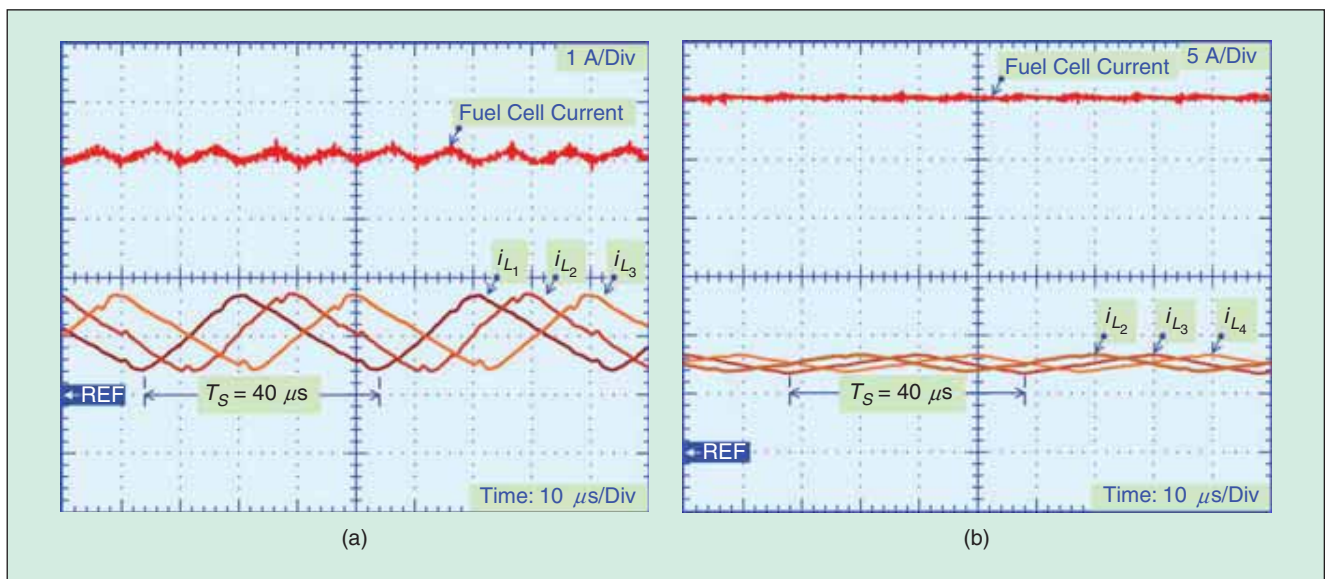


FIGURE 14 – Steady-state waveforms of the four-cell interleaved converter system at an FC current command of (a) 4 A ($v_{FC} = 35.8$ V) and (b) 30 A ($v_{FC} = 28.9$ V).

sharp current rise/fall and large magnitude of current ripple should be avoided. The multiphase parallel converters for FC high-power applications are depicted in Figure 11.

The most sophisticated and most accurate current sharing implementations rely on a closed loop negative feedback system, very similar to those control loops used to regulate

the output voltage of a power supply, as portrayed in Figure 12 [112], [113]. To make this approach work, two piec-

tor currents of the modules and the other is the desired amount of FC current reference i_{FCREF} . Since the goal is to evenly distribute the FC current, the desired FC current is the FC current divided by the number of parallel modules. Therefore the task is two fold; measure the inductor currents and generate the average inductor current set-points.

There are three general areas of application for FC technology: portable power, distributed power, and transportation.

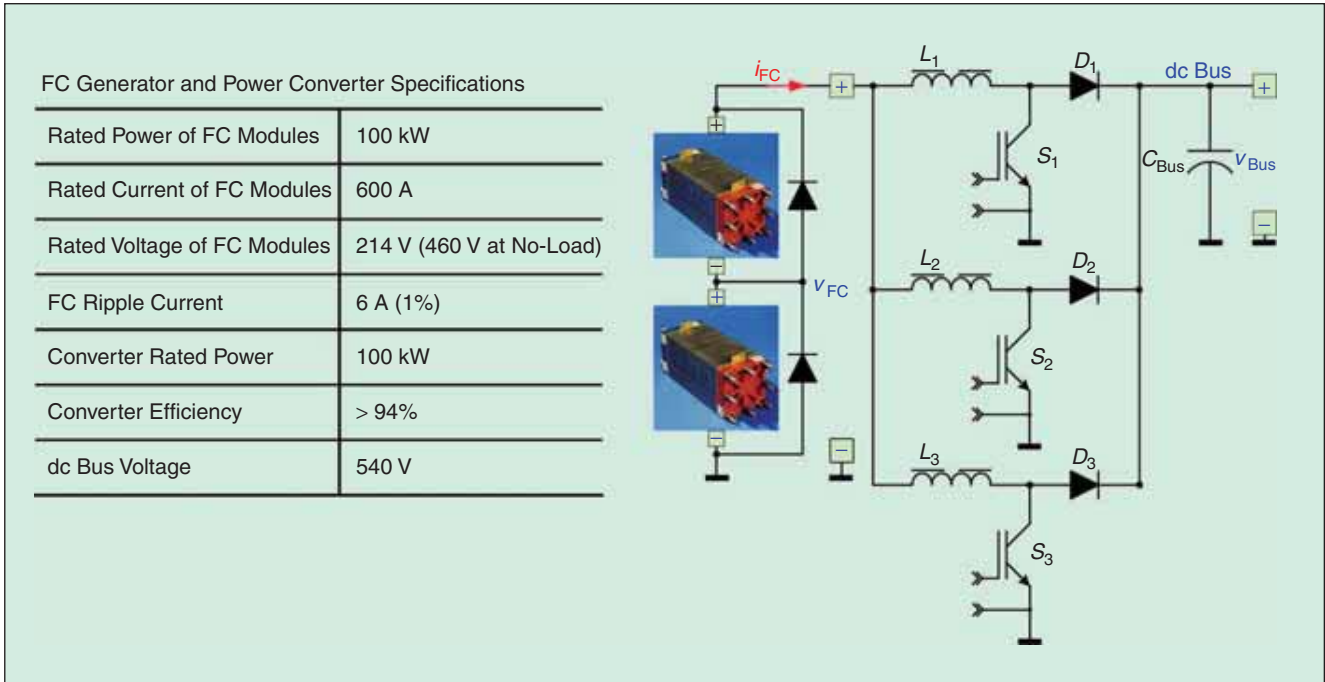


FIGURE 15 – 100-kW FC converter of three-phase interleaved boost converters with two FC modules in series [98].

According to Thounthong et al. [114], [115], who worked with a Ballard Nexa PEMFC unit (1.2-kW, 46-A, see Figure 5), they have already demonstrated the experimental results of the two- and four-phase paralleled boost converters for FC applications. The oscilloscope waveforms in Figures 13 and 14 portray the steady-state characteristics of the interleaved converters at different FC current demands, the load at dc bus being adjusted in order to obtain a constant dc bus voltage of 60 V (here rated value). Figure 13 illustrates the FC current, and the first and the second inductor currents of the two-phase parallel converter at the average FC current reference of 4 A and 46 A (rated current), respectively [114]. Figure 14(a) presents the FC current and the first, second, and third inductor currents of the four-phase parallel converters at the average FC current reference of 4 A. For the last test, Figure 14(b) shows the FC current and the second, third, and fourth inductor currents of the 4-phase parallel converters at the average FC current reference of 30 A [115].

One can observe again that the FC current is the sum of the inductor currents and that the FC ripple current is 1/*N* the individual inductor ripple currents. Absolutely, the FC ripple current of the four-cell interleaved converter is lower than the two-cell interleaved converter. So, the FC ripple current of

The PEMFC is well suited to automotive power applications and may be used in residential and commercial power systems.

the four-cell interleaved converter is nearly zero. It means that the FC mean current is close to the FC rms current. In addition, it can be seen the FC ripple frequency is *N*-times the switching frequency of 25 kHz.

According to Hwang et al. [116], an FC converter size of 1 kW with four-phase interleaved boost cells had been also presented. For an FC converter size of 150 kW (technical specification:

$V_{FC} = 250\text{--}450\text{ V}$, $V_{Bus} = 548\text{ V}$, weigh 50 kg) with two-phase interleaved boost converters had been fabricated and tested [117]. Its volume and weight is less than one third of a single phase boost converter, the FC ripple current is less than 10%, and its efficiency is over 97%. According to Vulturescu et al. [98], the design of an FC converter size of 100 kW with three-phase interleaved boost converters with two

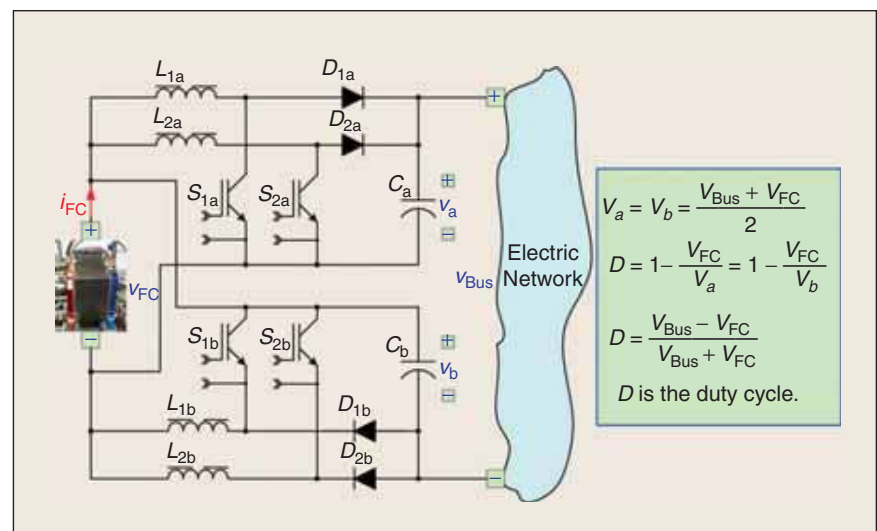


FIGURE 16 – 120-kW two-blanches interleaved double dual boost converters [96].

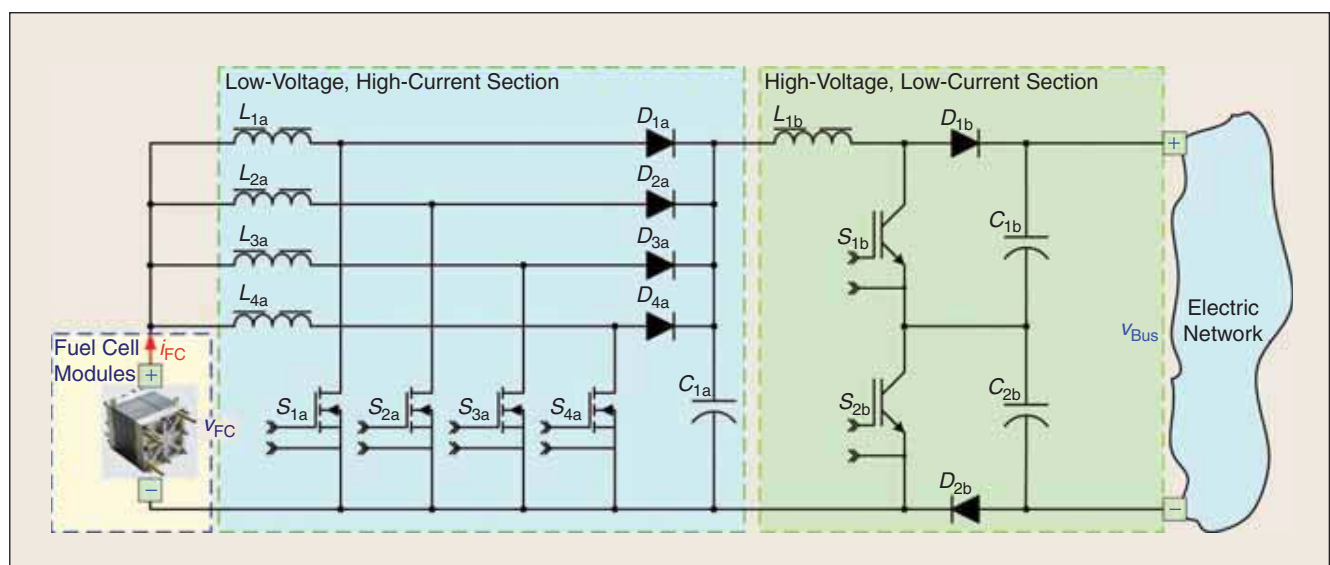


FIGURE 17 – 200-kW cascade-parallel boost converter for the FC power converter.

FCs hold great promise as a clean energy conversion technology.

FC modules in series has been studied for French urban transportation networks, as depicted in Figure 15. In addition, a three-phase interleaved boost modules based on the commercial standard Lopak5 of insulated gate bipolar transistors (IGBTs) by Asea Brown Boveri Ltd. (ABB) for 250–1,000-kW FC converter at the dc link voltage

of 750 V has been proposed in [118]. For the FC urban car, the 94-kW FC converter with the multiphase interleaved boost converters at the dc link voltage of 320 V had been designed and used in the HydroGen3 FC vehicle of General Motors (GM) Company [119].

To increase the higher voltage conversion ratio, Viet et al. [96] have

proposed the two-branches interleaved double dual (IDD) boost converters for an FC converter: 20–120 kW, as shown in Figure 16. One summarizes that this scheme can boost the FC input voltage from 60–700 V utility dc bus at the FC current of 333 A (20 kW).

Another possibility to increase the voltage conversion ratio of the FC high-power converter is cascade-parallel boost converter, as Figure 17 illustrates. This similar concept has been proposed in [120]–[122]. One might suppose that this power converter can

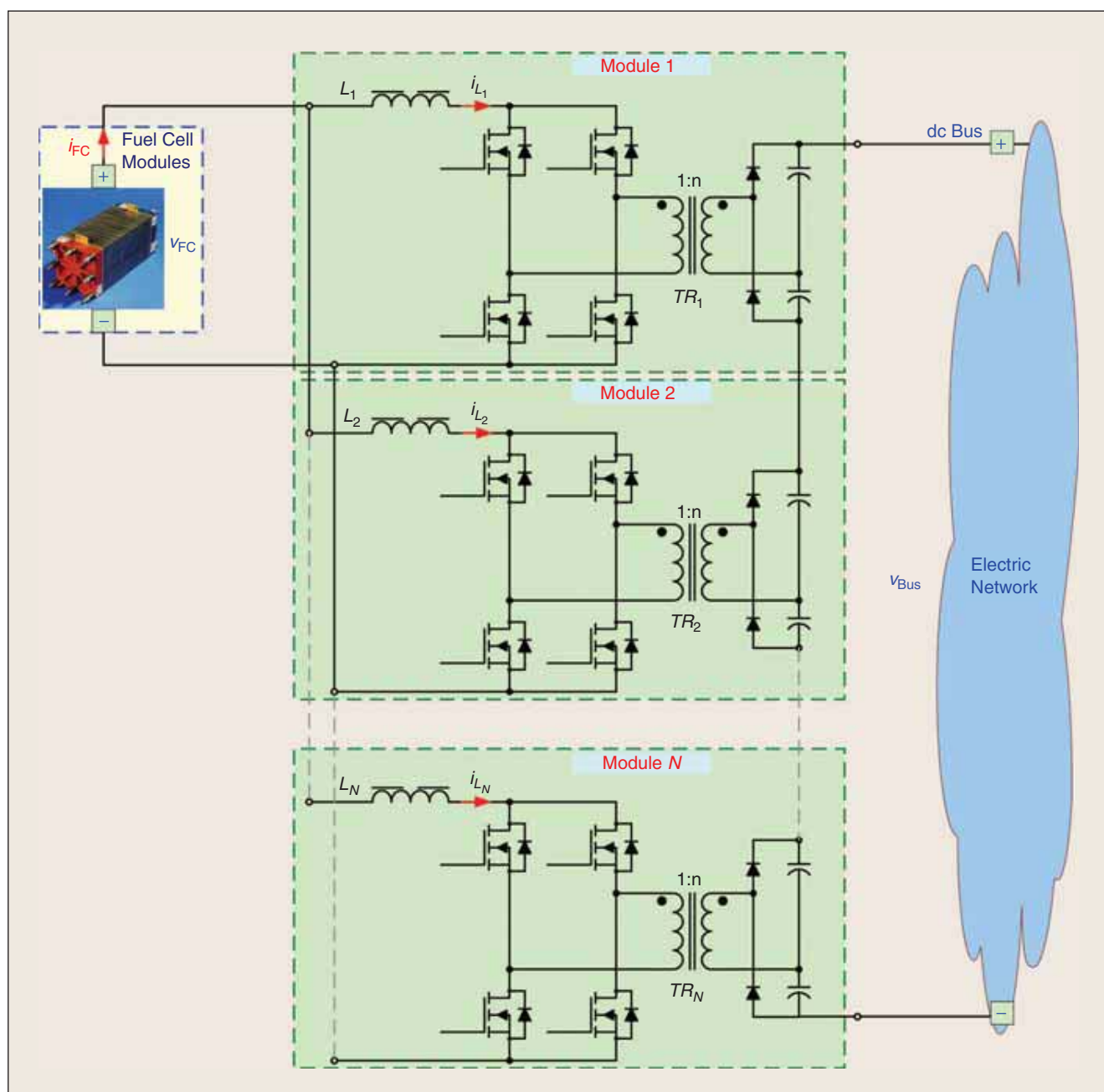


FIGURE 18 – Interleaved current-fed full bridge converters with a parallel input and a series output for FC high power applications.

operate up to 200 kW with the voltage conversion ratio of eight.

For ground isolation and high voltage step-up ratio (but more complicated), interleaved boost/flyback [123], [124], push-pull [125]–[127], and half bridge and full bridge [128]–[132] can be considered as candidate topologies for the FC converter. Advantages and disadvantages of these converters are discussed in [127], [128], and [132]. The most popular ground isolation circuit today for high-power applications is the full-bridge dc/dc converter, because of reasonable device voltage ratings and soft switching possibility [133], [134].

Considering the ripple and direct current control requirement, an isolated current-fed full bridge converter topology shows some promise [134]–[136]. It has small current ripple and high efficiency. To reduce the size of the magnetic components and further improve the converter efficiency, a multiphase interleaved current-fed full-bridge converter is proposed in [113], as shown in Figure 18. By paralleling input of the converter system, input current, and hence the power, can be equally shared between the modules of the converter system. Therefore, current stress on the semiconductor devices on the input side is reduced. On the other hand, the series connection on the output side results in lower voltage ratings for output capacitors and diodes. Furthermore, phase shifted pulse-width modulation (PWM) is used for the interleaved full-bridge converter. So, the input current ripple frequency and the output voltage ripple frequency increase. Hence, for the same input current and output voltage ripple requirement, smaller input inductors and output capacitors can be used.

The advantages of the parallel converter with interleaving technique are as follows:

- 1) Size and volume of passive devices (inductor and capacitor) are reduced.
- 2) Ripple of the input and output waveforms are reduced.
- 3) Ripple frequency of the input and output waveforms are increased
- 4) Power converter is modular. It enhances reliability of the system, and increases converter power

The power and energy efficiency of an FC is highly dependent on the thermodynamics, electrode kinetics, and reactant mass transfer, as well as materials and components for assembling the FC.

rating by paralleling phases, not by paralleling multiple devices.

- 5) Thermal management is simple. The primary driver in all paralleling schemes for lower power applications is the decentralized heat dissipation of the parallel power converters.
- 6) Current ratings of power electronic components are reduced, because current ratings are proportional to the continuous power rating of the circuit.

Conclusions

FCs hold great promise as a clean energy conversion technology. A large research effort is underway to develop the FC for applications ranging from small portable electronic devices to automotive transport, as well as residential combined heat and power supplies. These applications have a large emerging market and widespread adoption should lead to a reduced dependence on fossil fuels as well as encourage the development of a hydrogen economy.

FCs produce low dc voltage, so that it is most often connected to electric networks through a step-up dc/dc converter. This article first introduces electrical characteristics, power electronic requirements, and different types of FCs and is then followed by a discussion of the various topologies of step-up dc/dc converters used for FCs' power-conditioning system. The examinations of several different approaches to power-conditioning systems for single and multiple FC combinations have been reviewed.

High-power dc distributed power systems supplied by FC invokes the need to parallel power modules with interleaving technique. By method of the parallel converter modules with interleaving algorithm for an FC generator

for high-power applications, inductor size (ferrite core and Litzwire) are simple to design and fabricate, and the FC ripple current can be virtually reduced to zero. As a result, the FC mean current is nearly equal to the FC rms current. The main drawback of the multiphase approach is added circuit complexity, requiring measurement and balancing of each phase current as the larger number of control components illustrates.

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There are many different types of FCs, with the principal differences between them being the type of electrolyte and/or the type of fuel that they use.

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