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Implementation and Control of a Double-input DC/DC Converter for PEMFC/Battery Hybrid Power Supply

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Abstract—Proton exchange membrane fuel cell (PEMFC) has a time-delay feature on its electrical characteristic. So other energy sources with relatively higher response rate and better dynamic performance is necessary for assisting and sharing responsibility with PEMFC in hybrid power supply system. Multi-input DC/DC converter, which has higher efficiency, less component count, lower cost and simpler control method, is a promising candidate for developing multi-source hybrid system. In this paper, a double-input buck converter (DIBC) topology and its control method are proposed and designed. The target of regulating both the DIBC output voltage and output current of PEMFC is proved to be feasible. A prototype of PEMFC/battery hybrid power supply system based on the proposed DIBC topology is developed for verifying the correctness of the presented theory and design. Experimental result shows ideal output characteristics and control effect of the prototype.

Keywords—proton exchange membrane fuel cell; time delay; double-input buck converter; hybrid power supply

I. INTRODUCTION

Confronted with global warming problem, atmosphere pollution and energy crisis, many governments and organizations in the world are actively involving the pursuit of replaceable energy sources, which are usually known as renewable energy sources. Renewable energy source is a large category which includes solar, wind, water, bio-energy, hydrogen, etc. Proton exchange membrane fuel cell (PEMFC), which is a high-efficient energy conversion device by using the renewable energy source hydrogen as its fuel, has been attracting more and more attentions and interest of the world, owing to its irreplaceable and distinguished advantages such as zero pollution byproducts, high efficiency and stability, low operating temperature and noise, and so on. Recently PEMFC has been widely studied and considered as a promising alternative power source for future development. It has a wide range of application in portable power devices, automotive industry, residential and stationary power system, uninterruptable power supply, etc [1-5].

In all of the power generation system, a power converter is needed to process kinds of energy sources. Electrical characteristics of a source such as voltage, current and power can be changed into certain values by a converter, for the sake of meeting different supply requirements from various devices. Multi-input power converters are applied to enable multi-source technology. The advantages of using a multi-input converter (MIC) are high-efficiency, reduction of component count, low cost and control simplicity. As a result, MIC has gained popularity in power electronic applications including electric, hybrid, and plug-in hybrid electric vehicles; fuel cell systems; photovoltaic systems; wind generation; power factor correction, etc [6]. A modified-forward multi-input converter for renewable energy which can not only process solar energy but deal with wind power was proposed in [7]; A systematic approach to derive double-input converters by using a single-pole triple-throw switch as a building block was presented in [8]; [9] put forward a multi-input converter which is capable of bidirectional operation and responsible for power diversification and optimization; In [10], the method for synthesizing an MIC was inspired by adding an extra pulsating voltage or current source to a PWM converter with appropriate connection; [11] represented a new telecom power system using local fuel cell and micro turbine and utilized a new multi-input buck-boost converter as an interface between the micro sources and the dc bus; In [12], a wind-PV-HCPV-battery hybrid dc source system via MIC was designed for general house using the comprehensive supervisor mode to manage and coordinate the operation of the subsystems; A multi-input Triple-Half-Bridge bidirectional dc-dc converter when this converter was applied to the fuel cell (FC) electrical vehicle drive system was presented in [13].

A double-input buck converter (DIBC) topology is proposed and analyzed in the paper, and its control method and programming flow are designed to realize the target of regulating both DIBC output voltage and output current of PEMFC simultaneously. A prototype of PEMFC/battery hybrid power supply system based on the proposed DIBC is developed

for proving the validity of the presented theory and designed control method.

II. PRINCIPLE AND TIME-DELAY FEATURE OF PEMFC

A. Operation Principle of PEMFC

To directly convert chemical energy of hydrogen from the surface of catalyst layers into electrical energy is the most distinguished capability and specialty of PEMFC. Fig. 1 demonstrates the whole operation procedure of the PEMFC. The hydrogen gas with a given pressure, flow-rate, humidity and temperature, which can be regarded as the PEMFC's fuel, is pumped into the channels inside the PEMFC and flows to the anode side of each cell. The location where electrochemical reaction really takes place is membrane electrode assembly (MEA) that sandwiches proton exchange membrane (PEM) between two catalyst layers. After penetrating through the gas diffusion layer located on the anode of the MEA, the hydrogen splits into hydrogen ion and electron under the help of catalyst, which is called reduction reaction. The separated electron goes through external load circuit loop to flow back into the cathode side while the hydrogen ion is transported through the PEM that allows hydrogen ion only to pass, and arrives on the cathode catalyst layer. Meanwhile, the oxygen gas also reaches on the cathode side from the air inlet channel or by absorbing surrounding air (open-cathode designed FC) directly. By this way, the hydrogen ion, the electron and the oxygen meet at the cathode catalyst layer of each cell and combine together into water while producing heat. If the gases to anode and cathode of the PEMFC are continuously supplied, the constant current will form through external circuit once the load is connected to the electrodes of the FC, which makes the FC a DC power generation device. The basic electrochemical reaction equations in the operation period of the PEMFC can be simply represented as follows:

Figure 1. Flowchart of operation principle of PEMFC

B. Time-delay Feature of PEMFC

The hydrogen gas is provided from the gas pipes into the inside channels of the PEMFC stack rather than directly stored inside the stack itself. Only if the “fuel” is piped into the cells and reaches the catalyst layer on the anode electrode of each cell sufficiently, the stack begins chemical reaction and generates current. This process needs to consume time. Consequently, the specific feature on the structure and operating principle makes PEMFC a time-lag system [1].

When time delay is considered into PEMFC system, the voltage of PEMFC will remain at zero (or a low level) until reactant gases outside are piped in and arrive at the anode and cathode electrodes, respectively. Only when the hydrogen begins to ionize into electron and hydrogen ion, the voltage starts to rise up. So at the beginning of the startup, the interval between the time point when hydrogen begins to be pumped into the stack and the time point when open circuit voltage of each cell begins to rise up from 0 is assumed as the delay-time. The length of the delay-time depends on the structure of the stack, gas flow rate, and gas pressure. Additionally, cells at different places in PEMFC have different startup response features.

III. DOUBLE-INPUT BUCK CONVERTER

A. Proposed Circuit Topology

Now most of the converter topologies of renewable sources used in practical areas are limited to the structures that all DC/DC converters are parallel connected onto the bus terminal for driving external loads [14-17]. Each converter can only handle a single kind of renewable energy and be controlled independently. So every source should require for an individual DC/DC converter if a hybrid system using two or three or even more renewable energy sources needs to be developed and all sources are required to exert their maximum advantages. This kind of circuit structure design, which needs a large amount of components, will increase development cost, enhance difficulty on installation and control, reduce system stability and reliability. Therefore, multi-input power converter, which has higher efficiency, less component count, lower cost and simpler control method, becomes a promising candidate for developing multi-source hybrid power supply system in practical use.

A double-input buck converter (DIBC) topology is proposed, as Fig. 2 shows, for fulfilling the expectations of the control target. Two separated power sources S_1 and S_2 with a pair of source-to-source MOSFETs (M_1 -to- M_2 , M_3 -to- M_4) linked behind are parallel connected as converter's inputs. The two sources share a common inductor L . The structure design of source-to-source MOSFETs, which is also known as the four-quadrant switch structure [18], can pave way for the future bidirectional converter study and development. Because of a parasitic diode inside MOSFET, M_2 (or M_4) can be regarded as a diode to prevent from opposite current flowing back into the PEMFC branch when unidirectional buck converter is in practice. The alternative that diode replaces MOSFET can be applied in this proposed circuit. It is assumed that S_{M12} is put on M_1 and M_2 simultaneously as well as S_{M34} on M_3 and M_4 . Each

source is parallel connected with a big voltage-regulation electrolytic capacitance (C_1 for S_1 , C_2 for S_2) for being charged by source when MOSFET is controlled to switch off and supplying power in company with source when MOSFET is on. Therefore, no interrupted current status in operation will come out and control of source output current (or power) can be implemented. C_{buf1} , R_{buf1} and D_{buf1} in S_1 branch (C_{buf2} , R_{buf2} and D_{buf2} in S_2 branch) jointly compose a shutoff buffer circuit for dispersing power loss during switch-off period of M_1 - M_4 . D and C are used to keep output current and voltage of the DIBC uninterrupted and constant. The reference positive directions of voltage or current of each component are assumed and marked in Fig. 2 as well.

Figure 2. Proposed double-input buck converter topology

B. Operation Principle

The operation principle of the DIBC can be sorted into three modes. The corresponding switching patterns of the DIBC used in the paper are described in Fig. 3.

Figure 3. Switching patterns of the proposed DIBC

In Fig. 3, $0-t_1$ is the time length that S_{M12} is on duty, t_1-t_2 is the time length that S_{M34} is on duty, t_2-t_3 is the time length that M_1 - M_4 are off. The relation of D_1 , D_2 , and D_3 can be concluded into

$$D_1 + D_2 + D_3 = 1 \quad (1)$$

Mode I: S_1 is on, S_2 is off. Only S_1 supplies load through M_1 , M_2 and L , which can be referred to a classical one-input buck converter. Meanwhile, S_2 charges C_2 , which keeps output current of S_2 continuous. v_L is the subtraction between v_{S1} and v_O . The inductor current ripple in Mode I can be derived by the following equation

$$\Delta i_{L1} = \int_0^{t_1} \frac{v_{S1} - v_O}{L} dt = \frac{v_{S1} - v_O}{L} D_1 T_s \quad (2)$$

Mode II: S_1 is off, S_2 is on. Similar to Mode I, only S_2 supplies load through M_3 , M_4 and L , which constructs one-input buck converter. Meanwhile, S_1 charges C_1 , which keeps output current of S_1 uninterrupted. That v_{S2} subtracts v_O obtains v_L . The inductor current ripple in Mode II is expressed as follows

$$\Delta i_{L2} = \int_{t_1}^{t_2} \frac{v_{S2} - v_O}{L} dt = \frac{v_{S2} - v_O}{L} D_2 T_s \quad (3)$$

Mode III: both S_1 and S_2 are off. S_1 and S_2 both cut off and load is powered by the energy storing in L and C . D is on, making a closed loop circuit of current for load. v_L equals $-v_O$. The inductor current ripple in Mode III is derived as follows

$$\Delta i_{L3} = \int_{t_2}^{t_3} \frac{-v_O}{L} dt = -\frac{v_O}{L} D_3 T_s \quad (4)$$

According to the theory of energy conservation, if the system is in stable operation, it can be considered that the variation of inductor current in one operation cycle is zero. The following equation therefore can be derived

$$\Delta i_{L1} + \Delta i_{L2} + \Delta i_{L3} = 0 \quad (5)$$

Using Eq. (2) to (4) in Eq. (5), Eq. (5) can be modified as

$$\frac{v_{S1} - v_O}{L} D_1 T_s + \frac{v_{S2} - v_O}{L} D_2 T_s - \frac{v_O}{L} D_3 T_s = 0 \quad (6)$$

Taking Eq. (1) into consideration, Eq. (6) can be converted into

$$v_O = v_{S1} D_1 + v_{S2} D_2 \quad (7)$$

Even there existing capacitances on both S_1 and S_2 inputs, the energy that flows in or out of the capacitances absolutely gains from the sources. So based on energy conservation theory, the average current of S_1 or S_2 in one operation cycle, ignoring circuit power lose, can still be expressed as

$$\begin{cases} i_{S1} = f(D_1, i_O) \\ i_{S2} = f(D_2, i_O) \end{cases} \quad (8)$$

If D_1 and D_2 in Eq. (7) are replaced by i_{S1} , i_{S2} and i_O in Eq. (8), the following conclusion can be reached

$$v_O i_O = v_{S1} i_{S1} + v_{S2} i_{S2} \quad (9)$$

Multiplying voltage by current gets power. From Eq. (9), it can be seen that the average output power of DIBC equals to algebra addition of the two sources power, which makes the realization of multi-input hybrid supply power system using the DIBC available. The relation between v_O and that of the two sources is indicated in Eq. (7), while the relation between i_O and output currents of two sources is represented in Eq. (8). Both duty cycle of S_1 and S_2 together determine the value of v_O . It can be easily verified that D_1 and D_2 can have infinite combination, supposing v_O keeps constant. i_{S1} (or i_{S2}) is related to i_O and its duty cycle D_1 (or D_2) only, being independent to i_{S2} and D_2 (or i_{S1} and D_1). As a result, it provides a possibility to make the two parameters of the DIBC v_O and i_{S1} (or i_{S2}) be under control simultaneously. v_O can be controlled by means of finding a certain combination of D_1 and D_2 with a proper control method, while D_1 (or D_2) from the same combination can determine the output current of S_1 (or S_2) as well.

IV. CONTROL SYSTEM DESIGN

The target of control system is to regulate current of one source on the premise of maintaining the output voltage of the DIBC firstly. The characteristic of input-output relation of the DIBC is proved to be able to make it happen, as mentioned in previous chapter. A closed loop control method is proposed to realize the control target on the DIBC, as Fig. 4 represents.

Figure 4. Schematic of closed loop control method for the proposed DIBC

The output voltage regulation loop uses double closed-loop design, which makes v_O be the outer loop and i_C be the inner loop, to improve control accuracy and response speed. Two PI controllers (PICs) are applied here to track and regulate D_{buck} . The system firstly compares feedback of v_O with v_{Oref} . If the feedback is higher, a negative value will get into the PIC1 that will produce a lower i_{Cref} than before. Then i_{Cref} will subtract the recent i_C feedback value to acquire a lower error which will then be sent to the PIC2 for producing a decreased final control signal D_{buck} that is used to bring down the present value of v_O . Since v_O is related to both D_1 and D_2 as Eq. (7) presents, it is therefore defined that D_1 plus D_2 equals D_{buck} . On the other side, another closed loop is imported for maintaining i_{S1} or i_{S2} . It might as well be assumed S_1 is the source whose output current is needed to be controlled. If i_{S1} feedback value is getting lower, the error between i_{S1ref} and i_{S1} will become larger. After regulating through PIC3, the output D_{1temp} will increase than before in order to raise i_{S1} value. But before use, D_{1temp} should be multiplied by D_{buck} . That is because D_1 and D_2 together determine the value of v_O . So if D_1 is changing, D_2 will be correspondingly modified for keeping v_O stable. The subtraction of D_{buck} and D_1 is served as D_2 . In addition, there

has dead-time between D_1 and D_2 in order to prevent the situation that both S_1 and S_2 are on duty.

V. EXPERIMENT AND RESULT ANALYSIS

A. Experiment

The prototype of the proposed DIBC and its DSP control system is developed to validate the correctness of the theory and the effectiveness of the control strategy. Fig. 5 demonstrates experimental installation of the PEMFC/battery hybrid DIBC power supply prototype.

Figure 5. Photograph of experimental installation

The Ballard Nexa 1.2 kW 47-cell fuel cell system (BNFCs) is served as S_1 , while a Phylion 10-cell 10Ah lithium battery is chosen as S_2 . The PCB board integrates with the DIBC circuit, interface circuit and TMS320F2808 control system. The programmable electronic load band (KIKUSUI PLZ1004W, 1.5-1500 V, 0-200 A) is connected to the PCB board to provide preset constant resistance load which is changing with time. The upper computer that is installed CCS 3.3 and RS232 communication software is responsible for giving operation and control orders to DSP while receiving feedback information from the prototype for supervision. The details on components selection are listed in Table. I.

TABLE I. PERFORMANCE INDEX OF THE PROTOTYPE-USED SOURCES AND COMPONENTS

V_O	24-42 V	D	MBR60H100CTG (60 A, 100 V)
V_{S1}	26-42 V	C_1, C_2, C	ECOS2AA102CA (1000 μ F, 100 V, ESR:182 m Ω)
V_{S2}	37-41 V	$M_1 \sim M_4$	IRFP4468PBF (290 A, 100 V)
I_{S1}	0-46 A	D_{buf1}, D_{buf2}	S5B (5 A, 200 V)
I_{S2}	0-20 A	C_{buf1}, C_{buf2}	0.1 μ F
L	42.25 μ H	R_{buf1}, R_{buf2}	1.5 Ω

The frequency of PWM control signal to MOSFET is 100 kHz. v_{Oref} of the prototype is set to be 30 V, i_{1ref} for BNFCs is set to be 5 A. Environmental temperature is 25 $^{\circ}$ C. 99.99% pure hydrogen gas is supplied to the BNFCs with the pressure of 2 bar. When the system status converts from "standby" to "in operation", 1.5-10 Ω (3-20 A) step change load is connected to the prototype, and there are 17 times of load change designed in one test and each step maintains for 0.5 s. Voltages and currents of S_1 , S_2 and converter's output are

monitored and recorded by oscilloscope (Tektronix DPO 4034) with 1 MHz scan frequency.

B. Result Analysis

Fig. 6 presents the experimental result from the recorded data. The output voltage of the DIBC is regulated at 30 V and the current of the BNFCs maintains at 5 A. When load current demand is higher than 5 A, the battery current takes responsibility for the transient change part of the load current timely. Fig. 7 shows details on battery and FC current transient responses when load is changing from 6 A to 14 A in step shape. After load current has soared, the FC current appears a 3 A pulse for about 0.01 s and soon be regulated back to 5 A. Fig. 8 shows details on load, battery and FC voltage varying situation when load demand changes from 6 A to 14 A at 0.07 s and turns back to 6 A at 0.7 s. Load voltage maintains constant at 30 V and its ripple is controlled within ± 1 V. At 0.07 s, FC voltage has a fall, the lowest value of which is 34.4 V. At 0.7 s, a small peak with 36 V as its maximum emerges.

Figure 6. Experimental current and voltage waveforms related to electrical characteristics of the prototype

Figure 7. Battery and FC current responses to a 6-14 A load step change

Figure 8. Load, battery and FC voltage transient responses to a 6-14-6 A load step change

VI. CONCLUSION

Experiments of electrical characteristics have indicated that PEMFC has time-delay feature both on startup and load changing procedure, and large transients provided by PEMFC should be reduced for prolonging the operation lifetime of PEMFC. As a result, other energy sources with relatively higher response rate and better dynamic performance are needed to assist PEMFC in hybrid power supply system. Multi-input DC/DC converter, which has higher efficiency, less component count, lower cost and simpler control method, is an ideal candidate for hybrid system. In the perspective of mathematics and control theory, the proposed DIBC topology has been proved to be able to realize the control target of regulating both output voltage of the DIBC and output current of PEMFC simultaneously. v_o can be controlled by means of finding a certain combination of D_1 and D_2 with a proper control method, while D_1 (or D_2) from the same combination can determine the output current of S_1 (or S_2) as well. A prototype based on the proposed DIBC and its control and supervision system have been developed and tested. The experimental results have showed the ideal control effect and stable electrical characteristics, which has verified the correctness of the presented thoughts and design. Future work will focus on power management design for the proposed DIBC, adoption of more advanced control methods, and optimization of circuit topology for meeting the performance index of practical use.

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