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

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ABSTRACT

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

Introduction

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

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

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

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

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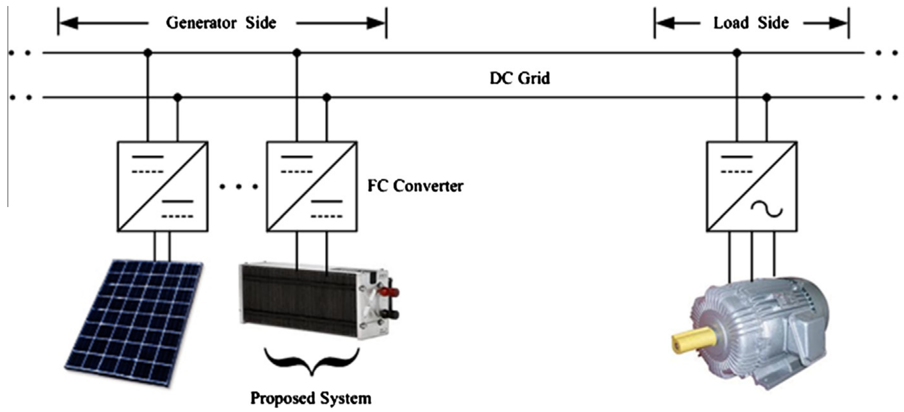

Fig. 1. DC distributed system supplied by renewable energy.

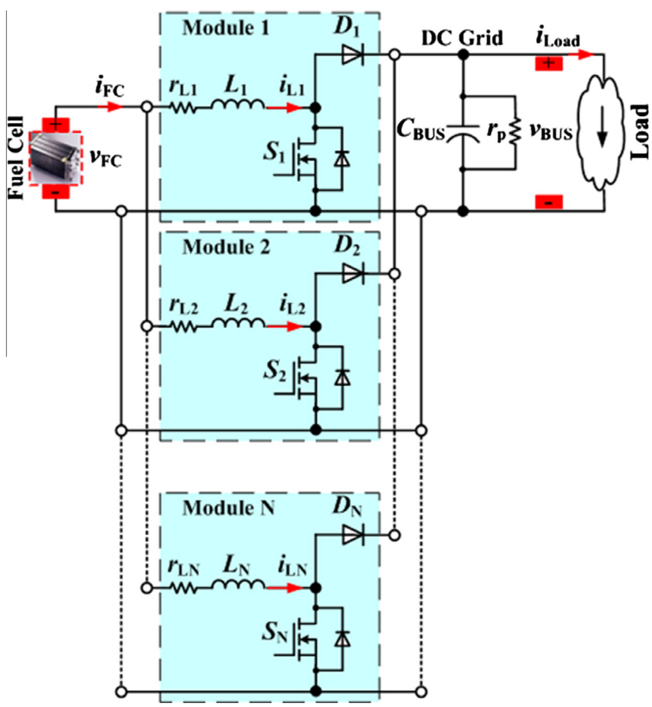

Fig. 2. FC converter: parallel boost converters for FC applications.

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

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

Power converter modeling

Principally, high-current low-voltage converters are required by reason of the electrical properties of FCs [2,3]. A conventional step-up converter is generally chosen as a FC converter. Nevertheless, when the power expands the conventional converters will be limited. To overcome this limitation, the utilization of a parallel power converter (multiphase converters in parallel) with an interleaved technique can provide improved performance [9,10]. However, the previous researches [9,10] implemented the converter using a multiple-loop control approach. As a basic principle, the interleaved technique consists of phase shifting the control signals of various converter cells N in parallel [2,7]. The schematic diagram of the proposed multiphase interleaved boost converter for FC applications is shown in Fig. 2. In the case of ideal converters, with the equivalent series and parallel resistances representing losses, the state equation of the converter and the output voltage shown in Fig. 2 are given as:

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

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

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

Control strategy

Differential flatness principle

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