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Coordinated control design for a PEMFC power system using adaptive VRFT method

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ABSTRACT

For a proton exchange membrane fuel cell (PEMFC) power system containing a methanol reformer and a DC–DC converter, it is necessary to coordinate the subsystem controllers to achieve effective power tracking control and prevent constraint violations. This study focuses on the controller design of coordinating control scheme for a PEMFC power system to maintain stable fuel utilization ratio and meet the load demand simultaneously. Because the system exhibits considerable nonlinear behavior, a process model is difficult to identify and is prone to modeling errors. Therefore, this study employs the virtual reference feedback tuning (VRFT) method to design the controllers directly using the process input–output data. To address the process nonlinearity, an improved adaptive VRFT method is developed and applied to the adaptive PID controllers design for a cascade control system. Furthermore, the design parameter of the fuel cell current controller is adaptively tuned according to the deviation of fuel utilization ratio, so that the coordinating control is realized by keeping the dynamics of the current loop consistent with that of the fuel flow loop. Simulation results show that this coordinated control design enables the PEMFC power system to track the load power demand effectively while maintaining the fuel utilization ratio constant.

1. Introduction

A fuel cell is an electrochemical reactor that can directly convert the chemical energy in fuel into electrical energy. It is one of the key technologies for developing alternative energy sources. A proton exchange membrane fuel cell (PEMFC) is a type of fuel cell that can be applied to vehicles as well as stationary and portable fuel cell applications [1]. The PEMFC has many advantages, such as a lower operating temperature, relatively high energy density, quick start-up and response time, simple maintenance. However, under certain circumstances, such as an unstable fuel supply, changes in operating temperature, rapid load changes, *etc*., its power output will be significantly affected [2,3]. The fuel required by a fuel cell (*i.e*., hydrogen) is typically provided by the fuel reformer. As the fuel reforming process might cause a short delay, and in cases where the membrane of the fuel cell is not appropriately moistened, the fuel cell cannot cope with the full load. Therefore, in addition to the fuel cell and the fuel reformer, a short-term power storage device, such as a battery, and a corresponding DC–DC converter are also required [2], which can compensate for the short-term insufficient supply of the fuel cell with its stored power. A detailed discussion on the modeling, control, and applications for PEMFC systems has been provided in Gou et al. [4].

In the entire fuel cell power system, the performance of tracking load demand is limited due to the dynamic characteristics mismatch among the subsystems. For example, if the fuel reforming speed is too slow, leading to a lack of hydrogen, then the system cannot achieve satisfactory load tracking. In addition, when some process parameters (fuel utilization ratio, oxygen excess ratio, fuel cell temperature, *etc*.) exceed the specific operating range, the operation of the fuel cell will be greatly impacted [2,3]. Fuel utilization ratio is a key operating condition, which must be kept constant as much as possible, because a fuel utilization ratio that is too low or too high will cause a wastage or lack of hydrogen, respectively. Therefore, the issue of maintaining stable fuel utilization ratio needs to be considered in PEMFC power tracking control, and this issue cannot be handled well by only considering the control of a single subsystem. It is necessary to coordinate the controllers of different subsystems, to enable the controller of each subsystem performing its own control task while also taking into account the overall performance of the fuel cell power system as well as the process constraints.

Several control methods have been developed in the literature to tackle these issues. To avoid violation of constraints, the use of fixed filter or rate limiter can prevent the input signals of the

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power tracking controller from drastic changes by the limits set for the worst-case scenario. But such approaches may result in a sluggish response [2,3,5]. Compared to the rate limiter approach, the reference governor approach can improve the response of the system while still preventing constraint violations, by reducing the set-point signals in the power tracking controller when a constraint violation is likely to occur. The predictive control method has been used to prevent constraint violations by predicting the future response of the system [2]. But these two approaches make the control system more complicated, with more computation effort required because of the static or dynamic model used in them. Wang et al. [6] proposed a coordinating control scheme by combining an internal model control based PID control and adaptive sliding model control (SMC) to keep the fuel utilization ratio stable.

Most of the previously developed control methods are model-based controller design methods that require the knowledge of either a physical or empirical process model. However, when the system has more complex dynamics, this kind of method may lead to degradation in control performance because of inevitable modeling errors. The virtual reference feedback tuning (VRFT) design method [7] can be used to design the controller directly from a set of process input–output data, without the need for a process model. It is an attractive alternative to the model-based controller design methods because the problem of modeling errors can be effectively mitigated. The conventional VRFT method was developed for linear systems and the resulting controller has limited performance for nonlinear processes. Adaptive versions of the VRFT method were proposed to design adaptive PID controllers for nonlinear processes through online updating of the database employed in the VRFT design [8,9], but the database updating method used in these works would cause excessively large variations in controller parameters and may lead to instability of the control system.

Since the PEMFC power system is a highly nonlinear system, it is quite difficult to obtain an accurate process model, and therefore is suitable for the application of the VRFT method. In addition, coordinated control of the power system can be more easily achieved through the VRFT method because the VRFT design allows the closed-loop response to follow a reference trajectory. To keep fuel utilization ratio stable and produce power on demand, this study, based on the coordinating control scheme proposed in [6], applies the VRFT method to controllers design for the PEMFC power system. The control structure contains a hydrogen flow rate control loop of the methanol reformer, and a power-current cascade control system of the PEMFC and the converter. Considering the nonlinear features of the system, this study proposes an improved adaptive VRFT design method and, for the first time, extends the adaptive VRFT method to the design of cascade controllers. At the same time, this study also puts forward a design method to coordinate the dynamic characteristics between the output current from the converter and the hydrogen flow rate from the reformer, ensuring that the PEMFC power system keeps track of the external load demand while maintaining stable fuel utilization ratio. Therefore, the primary contributions of this paper are the development of improved adaptive VRFT method to design the cascade controllers for nonlinear systems, its application to a PEMFC power system, and the design of a closed-loop coordinating scheme to maintain the fuel utilization ratio constant.

The remainder of this paper is organized as follows. Section 2 presents the extensions of the VRFT design framework to the controller design for cascade control and nonlinear systems. Section 3 presents the coordinated design of the subsystem controllers in the PEMFC power system. In Section 4, simulation results based on the model of the PEMFC power system given in Appendix are presented to demonstrate the effectiveness of the proposed design. Finally, concluding remarks are presented in Section 5.

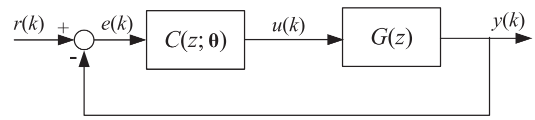

Fig. 1. Feedback control system.

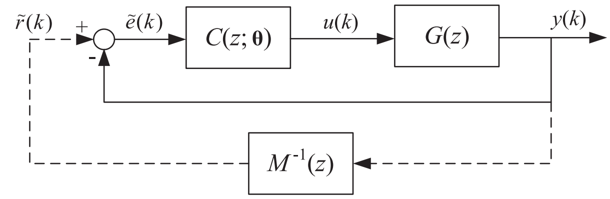

Fig. 2. Schematic diagram of the virtual reference signal.

2. VRFT-based controller design method

The virtual reference feedback tuning (VRFT) [7] is a data-driven control approach where the tuning of feedback controller is transformed into an identification problem. The controller design method used in this study is an extension of conventional VRFT design, including the controller design of a cascade control system and the adaptive controller design of nonlinear systems.

2.1. The VRFT method

Consider a feedback control system consisting of a process $G(z)$ and a controller $C(z;\ \boldsymbol{\theta})$ with controller parameter $\boldsymbol{\theta}$, as shown in Fig. 1. Suppose a model of the process is unavailable but a set of N input–output data points $\{u(k), y(k)\}_{k=1\sim N}$ can be obtained from an open-loop experiment. By specifying a reference model $M(z)$ that describes the desired closed-loop dynamics, the design goal is to obtain controller parameter $\boldsymbol{\theta}$ so that the corresponding feedback control system in Fig. 1 behaves as closely as possible to the reference model.

Using the reference model and available output signal $y(k)$, a "virtual" reference signal $\tilde{r}(k)$ can be computed as

$$\tilde{r}(k) = [M(z)]^{-1} y(k) \tag{1}$$

where z is the shift operator ($z^{-1}x(k) = x(k-1)$). This virtual signal represents the reference signal that has to be applied in closed-loop to obtain $y(k)$ as the closed-loop response. If the control strategy as shown in Fig. 2 is applied, the controller that shapes the closed-loop behavior to the reference model would generate $u(k)$ when the controller input is $\tilde{e}(k) = \tilde{r}(k) - y(k)$, the virtual error. The controller tuning becomes a standard identification problem and the controller parameter $\boldsymbol{\theta}$ can then be found by solving the following optimization problem

$$\min_{\boldsymbol{\theta}} J(\boldsymbol{\theta}) = \min_{\boldsymbol{\theta}} \sum_k \left[u(k) - C(z;\ \boldsymbol{\theta})\tilde{e}(k)\right]^2 \tag{2}$$

More detailed discussions on the VRFT are referred to [7]. If the controller $C(z;\ \boldsymbol{\theta})$ is parameterized linearly with respect to the parameters (e.g., a PID controller), the optimization problem in Eq. (2) can be solved by the least-squares technique, as illustrated as follows.

Consider a PID controller given by

$$C(z;\ \boldsymbol{\theta}) = K_P + \frac{K_I}{1 - z^{-1}} + K_D\left(1 - z^{-1}\right) \tag{3}$$