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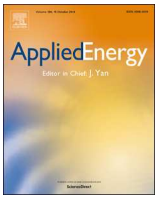

Data-driven oxygen excess ratio control for proton exchange membrane fuel cell

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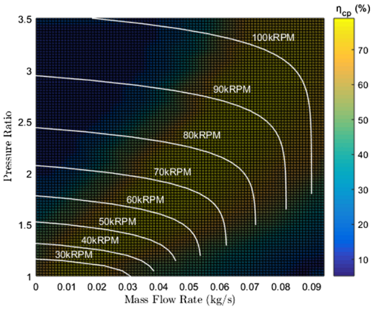
HIGHLIGHTS

- The transient overshoot phenomenon is addressed as a new control difficulty.
- The control difficulties are handled well by the data-driven control scheme.
- The energy-saving goal of the air supply is extended from static to dynamic.

GRAPHICAL ABSTRACT



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ABSTRACT

Efficient oxygen excess ratio (OER) control is of great importance for proton exchange membrane fuel cell because it is closely associated with the economic efficiency and safety. As widely investigated, OER control is challenging due to the difficulties of system nonlinearity, parametric uncertainty and load disturbances. In this paper, an underlying difficulty for OER control is addressed by pointing out the overshoot response. To this end, this paper employs active disturbance rejection control which is able to handle the various difficulties in a data-driven manner. It treats the nonlinearity, uncertainty and disturbances as a lumped term, which is then estimated online via analyzing the real-time data. The estimated lumped term is canceled timely such that the remaining dynamics behaves like an integrator without overshoot term therein. The data-driven and conventional proportional-integral controllers are tuned and compared based on the linearized transfer function model, showing the potential superiority of the proposed method in terms of the uncertainty and disturbance rejection, anti-windup and overshoot reduction. The nonlinear simulation based on the nonlinear mechanism model further demonstrates it good flexibility under different operating conditions. Moreover, it requires less compressor movement efforts, leading to a dynamic energy-saving effect and thus prolonging the durability and lifetime of the compressor.

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1. Introduction

1.1. Foreword

In the past few years, proton exchange membrane fuel cell (PEMFC) has made booming commercial progress in automobile application, because of the advantages such as zero emission, long cruising distance, low noise and refueling convenience [1]. As PEMFC tends to be applied in large-scale applications with rated power more than 100 kW [2], it is no longer feasible to operate constantly at the steady-state rated condition, even in the case where a battery or super-capacitor is used in parallel for peak load tracking [3] and extra power absorption [4], such as in a prototype truck shown in Fig. 1. In a congested traffic the vehicle may subject to a low speed move for a long time, and thus it is inevitable to reduce the power output of the PEMFC in a load-varying mode. In this regard, the issues of dynamics and control become prominent during the transients of acceleration and deceleration [5].

A detailed dynamic model for PEMFC developed in [6] has been studied extensively from control perspectives. Fig. 2 shows the schematic of the PEMFC control system, which consists of four subsystems, i.e. stack temperature control [7], humidity control [8], anode pressure control [9] and cathode air breathing control [10].

The air breathing control loop manipulates the input voltage of the compressor to control the oxygen excess ratio (OER), aiming to avoid oxygen starvation while maximizing the net power output, i.e., the difference between the stack power output and the parasitic power consumed by the compressor operation. In the moment of the rapid load current increase, the chemical reaction inside the fuel cell is greatly accelerated, resulting in excessive oxygen consumption and even oxygen starvation which may cause permanent damage to the cell. The oxygen excess ratio in the cathode needs to be maintained greater than 1 [11]. Nevertheless, it does not mean the bigger OER always leads to the better condition, because in the meantime it leads to more parasitic power loss and may reduce the net power [12]. Fig. 3 gives an optimal OER reference at different load currents for the PEMFC stack model. It can be seen that the optimal OER, ranging from 2 to 3, increases with the load current decreasing.

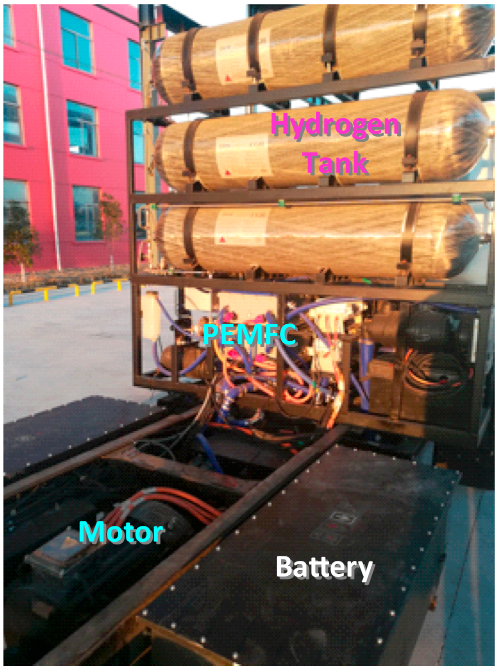

Fig. 1. A prototype fuel cell truck developed at Bing Energy in Jiangsu Province, China.

1.2. State-of-the-art

Various advanced OER control strategies have been investigated to handle the difficulties in terms of the system nonlinearity, parametric uncertainty and load disturbance rejection. The initial efforts date back to the work in [6] and [13], which employed the open-loop feedforward, state feedback and proportional integral (PI) control techniques based on the linearized model. To mitigate the nonlinearity, a two-step design was proposed in [14], where the feedback linearization is first utilized to achieve the global linearization, followed by is the subsequent *H*-infinity controller design. Given that the parameter variations over time is inevitable due to the causes like clogging of air filters and contamination of gas diffusion layers [15], sliding mode control strategy [16] were developed to improve the performance of the air supply, taking advantage of its strong ability in disturbance rejection and the parametric uncertainties mitigation. Adaptive control was employed in [17] to prevent the compressor surge during the dynamic air supply. Besides, model predictive control (MPC) has also been studied [18] to achieve the receding horizon optimization against the nonlinearity, actuator constraints and parametric uncertainty.

Although promising, the aforementioned methods seems somewhat complicated and obscure for engineers who are more familiar with the conventional proportional-integral-derivative (PID) controller. Evidently, the conventional PID is not able to deal with the complex air supply system because of the nonlinearity and parametric uncertainty. To this end, recent years have witnessed efforts in enhancing PID control performance via artificial intelligence approaches, such as neural network [19] and fuzzy logics [20]. However, such modifications inevitably introduce much more tuning parameters to achieve a reasonable learning efficiency, thus leading to a burdensome workload for the engineers.

1.3. Motivations

In the past researches, a significant phenomenon, that have not received enough attention it deserves, is the set-point tracking overshoot during the transient of OER moving. Even in the latest literatures, the overshoot still appears to be an obstacle, in spite of the intervention of the artificial intelligence (See Fig. 15 in [20]).

Another overlooked point is the amount of power consumed during the transient regulation. The OER reference depicted in Fig. 3 is only able to guarantee the system optimum in steady state. The power consumption during the transient OER move is seldom discussed in the previous literatures.

Taking into account the transient overshoot and power consumption, this paper aims to investigate the feasibility of a different control solution, active disturbance rejection control (ADRC), which is emerging as an evolution of PID via data-driven modification [21]. The ADRC was originally developed in 1990s by rethinking the contemporary flourishing model-based control research which tends to be more mathematical and rely heavily on the mathematical model. It chooses a different path by mining the data online instead of relying on an elaborate model built offline [22]. In the ADRC, all the discrepancies between the hypothetical linear model and the real plant are lumped as a total disturbance under a ‘unifying concept,’ that includes nonlinearity, external load disturbance and internal modelling uncertainties. The design philosophy can be presented as a controller-rejecter pair. The rejecter works in real time to estimate the disturbance and counteract by analyzing the controller output and the process output data. Thanks to the counteraction effect of the rejecter, the controller, designed for the nominal model, can be fixed, simple, but efficient.

Featured by its simplicity and efficiency, the ADRC has already been applied widely in motion controls [23]. Recently, the authors have also applied ADRC in energy systems, such as fuel cell voltage control [24], boiler control [25], regenerative heater control [26] and superheater