Paper:

Model free adaptive iterative learning control for power inverter

Zhenxuan Li, Yilong Zhang, Jijia Zong, Guoxin Zhao†

Beijing Institute of Petrochemical Technology, Beijing 102617, China
E-mail: zhenxuanli, zhangyilong, zongjijia, zhaoguoxin@bipt.edu.cn
†Corresponding author

[Received 00/00/00; accepted 00/00/00]

In this paper, a model-free adaptive iterative learning control (MFAILC) scheme based on pulsewidth-modulated (PWM) is proposed for power inverter system. The goal of this work is to achieve a high-quality output voltage and robustness to disturbances and uncertainties in the inverter system. Only the measurement input/output (I/O) data of the controlled plant are used of the power inverter system. Furthermore, the repetitiveness was used by iterative learning control method. Through rigorous analysis, it is shown that the MFAILC method could deal with this class of control problem and greatly decrease the error of the current cycle by using the control input and tracking error information at the past repeated process. In addition, the feasibility and effectiveness of the proposed approach are further verified through case studies with intensive simulations.

Keywords: Power inverter, iterative learning control (ILC), model-free adaptive control (MFAC)

1. Introduction

Power inverter is a common type of power electronics equipment that plays a key role in photovoltaic, uninterruptible power supply (UPS) system, electric vehicles, battery energy storage systems, and microgrids [1–3]. Constant-voltage constant-frequency (CVCF) pulse width modulation (PWM) DC-AC converters are widely used for its simplicity. Due to nonlinear loads and parameter uncertainties, output power quality will be determined directly by the performance of a well-designed closed-loop inverter controller.

To address this, various instantaneous feedback control schemes, such as PID control, model predictive control (MPC), sliding mode control (SMC) have been proposed. PID control is widely used in DC-AC converter applications due to its simplicity, but there are some shortcomings to PID control [4]. Firstly, it is difficult to turn the PID parameters when the system structure, electrical specifications, and power grades change. Secondly, the power quality of inverter will become worse when unpredictable load change. Thirdly, inevitable phase delay is a considerable problem for grid-connected inverters.

MPC methods have achieved great success in the practical application of the power inverter systems [5, 6]. A model predictive control method to reduce the common-mode voltage of three-phase voltage source inverters is proposed in [5]. In [6], a novel discrete time model of the inverter is used to predict the state variables and improve the reliability of the fourth leg inverter. However, MPC is a model-based control method, the performance of which relies on the model accuracy, and it cannot handle variable model parameters.

Sliding mode control (SMC) is well known for its high steady-state performance, fast transient response, and strong robustness [7–9]. A discrete-time repetitive sliding mode controller with an exponential-based bi-power reaching law for three-phase voltage source inverter is proposed in [8]. In [9], a fixed switching frequency sliding mode controller is proposed for a unipolar inverter. The chattering problem, however, results in a high switching frequency and power losses, which is a challenge for designing the output filter. Thus, there must be a trade-off between the smooth switching and high-accuracy tracking when using the SMC method.

Due to nonlinear loads and parameter uncertainties, output voltage often suffers from periodic tracking errors, which are the major sources of total harmonic distortion (THD) in AC power systems. Repetitive control (RC), originating from the internal model principle is an effective tool to exactly track periodic reference curve and to remove periodic error. Nowadays, RC has been widely studied from various aspects, such as [10, 11]. Using the inherent periodic signal feature of a power inverter, many repetitive control based methods [12–15] for power inverter have been proposed.

In literature [16,17], RC method, which has strong ability to handle with repetitive operation systems is considered as a special case in iterative learning control (ILC). Recently, a kind of model-free adaptive iterative learning control (MFAILC) scheme [18, 19] is designed by combining the virtues of both model-free adaptive control (MFAC) and ILC schemes. Instead of linearization the system dynamics along the time axis in MFAC, iteration axis dynamic linearization model is proposed in MFAILC. Thus, both data-driven features owned MFAC and learning ablity of ILC are involved in MFAILC scheme. Also the related applications such as urban traffic control [20], multi-agent systems [21], pneumatic artificial muscle [22]

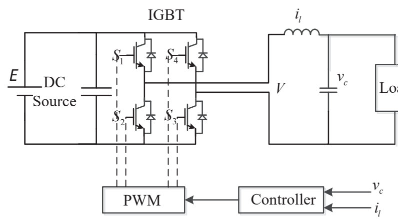

Fig. 1. Inverter system structure

and etc. can be found.

The main work of this paper is to design MFAILC scheme for the inverter system. The proposed control schemes still retain the data-driven model-free feature, that is, only the I/O data of the inverter system rather than the accurate mathematical model is not needed. Meanwhile it also possesses the iterative learning feature, that is, the controller could obtain experience from the historical data stored in the database. In other words, output tracking error will converge monotonically along the iteration axis for the periodic inverter systems.

The rest of this paper is organized as follows. In section 2, the power inverter model and problem formulation are described. In section 3, MFAILC scheme is designed for power inverter system. In section 4, an example is presented to validate the effectiveness of proposed method. Finally, conclusions are given in Section 5.

2. Problem formulation

2.1. Inverter model

A power inverter consists of a DC source, insulated gate bipolar transistor (IGBT) inverter bridge, an output filter, and loads, as shown in Fig. 1. Where E is the DC source voltage, V is the AC side voltage, i_L is the measurable inductance current,i_R is the current flowing through the load which exhibits nonlinear dynamics. v_c is the voltage across the capacitor. $v_c = E$ or $-E$ is the switching input controlled by the designed algorithm.

The model of the power inverter can be described as follows [23]:

$$\begin{cases} C\frac{dv_c}{dt} = i_L - i_R \\ L\frac{di_L}{dt} = V - v_c \end{cases} \quad \text{(1)}$$

System of the power inverter (1) can be rewritten as the following state space model

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad \text{(2)}$$

where $x = [v_c \ i_L]$ is the state variable, $u = [V \ i_R]$ is the control input, y is the system output. The nominal value of inductor, capacitor and load resistance are L, C and R respectively.

Also,

$$A = \begin{pmatrix} 0 & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{pmatrix}, B = \begin{pmatrix} 0 & -\frac{1}{C} \\ \frac{1}{L} & 0 \end{pmatrix}, C = \begin{pmatrix} 1 & 0 \end{pmatrix}$$

.

A sampled-data form of (2) with a sampling period of t can be written as

$$\begin{aligned} x(k+1) &= Gx(k) + Hu(k) \\ y(k) &= Cx(k) \end{aligned} \quad \text{(3)}$$

where $x(k) = [v_c(k), i_c(k)]^T$, $u(k) = V(k)$, $y(k) = v_c(k)$ are the system state, control input and the inverter system output at time instant k.

$G = \begin{bmatrix} \varphi_{11} & \varphi_{12} \\ \varphi_{21} & \varphi_{22} \end{bmatrix}, H = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix}$.

With the coefficients therein being $\varphi_{11} = 1 - \frac{t^2}{2LC}$, $\varphi_{21} = -\frac{t}{LC} + \frac{t^2}{2LC^2R}$, $\varphi_{12} = T - \frac{t^2}{2CR}$, $\varphi_{22} = 1 - \frac{t}{CR} - \frac{t^2}{2LC} + \frac{t^2}{2C^2R^2}$, $g_1 = \frac{t^2}{2LC}$, $g_2 = \frac{t}{LC}(1 - \frac{t}{2CR})$.

2.2. Iteration axis dynamic linear

Using the repetitive feature of inverter system, the repetitive controller/(iterative learning controller) is designed in this paper. Introducing the repeated operation index i into the inverter system (3), we can obtain

$$\begin{aligned} x(k+1,i) &= Gx(k,i) + Hu(k,i) \\ y(k,i) &= Cx(k,i) \end{aligned} \quad \text{(4)}$$

where $u(k,i)$ and $y(k,i)$ are the control input and the inverter system output at time instant k of the $i-th$ iteration, $i = 1, 2, \cdots$ and $k \in \{1, 2, \cdots, N\}$, $N = \frac{T}{t}$, and T is period of inverter output voltage, t is the sampling interval.

In the practical inverter system, there may be many uncertainties, such as variable parameters, unmodeled dynamics, nonlinearity, disturbances, and noise. First of all, the accurate values of capacitance and inductance are difficult to get, only the nominal values can be obtained. In addition, the temperature drift of the electron component parameters often occurs because of the high-speed switching and heavy loads of the IGBT. Moreover, unpredictable changes of the load are frequently happened. Thus traditional model-based controller design will affect the power quality of the inverter. For the MFAILC method, only the I/O data of the controlled plant are required to design the controller, rather than the accurate mathematical model of the plant.

Without losing generality, the model (4) can be written as the follows equation

$$\begin{aligned} y(k+1,i) = f(&y(k,i), \cdots, y(k-n_y,i), \\ &u(k,i), \cdots, u(k-n_u,i)) \end{aligned} \quad \text{(5)}$$

where n_y and n_u are two unknown positive integers, and $f(\cdots)$ is an unknown nonlinear function.

Assumption 1: The partial derivative of $f(\cdots)$ with respect to the $n_y + 2th$ variable is continuous.

Assumption 2: Suppose that $k \in \{1, 2, \cdots, N\}$ and $i = 1, 2, \cdots$, and when $|\Delta u(k,i)| \neq 0$, system (5) satisfies the generalized Lipschitz condition along the iteration axis, that is,

$$|\Delta y(k+1,i)| \leq b\,|\Delta u(k,i)|$$

where $\Delta y(k+1,i) = y(k+1,i) - y(k+1,i-1)$, $\Delta u(k,i) = u(k,i) - u(k,i-1)$; $b > 0$ is a finite positive constant.

Lemma 1 [24]: Consider nonlinear system (5) satisfying Assumptions 1 and 2. If $|\Delta u(k,i)| \neq 0$, then there exists an iteration-dependent time-varying parameter $\varphi_c(k,i)$, called pseudo partial derivative (PPD), such that system (5) can be transformed into the following compact form dynamic linearization (CFDL) data model:

$$\Delta y(k+1,i) = \varphi_c(k,i)\Delta u(k,i) \quad (6)$$

with bounded $\varphi_c(k,i)$ for any time k and iteration i.

3. Control system design for power inverters

The control objective aims at looking for a suitable control input signals $u(k,i)$ for a given desired reference $y_d(k), k \in \{0,1,\cdots T\}$, the tracking error $e(k+1,i) = y_d(k+1) - y(k+1,i)$ converges to zero when the iteration number i goes to infinite. For the inverter system, the desired reference is a standard sinusoidal signal with constant amplitude and constant frequency.

Rewrite (6) as

$$y(k+1,i) = y(k+1,i-1) + \varphi_c(k,i)\Delta u(k,i) \quad (7)$$

Consider the cost function of the control input as follows:

$$J(u(k,i)) = |e(k+1,i)|^2 + \lambda|u(k,i) - u(k,i-1)|^2 \quad (8)$$

where $\lambda > 0$ is a weighting factor, which is introduced to restrain the changing rate of the control input.

From (7) and the definition of $e(k+1,i)$, Equation (8) can be rewritten as

$$\begin{aligned} J(u(k,i)) &= |y_d(k+1) - y(k+1,i-1) \\ &\quad -\phi_c(k,i)(u(k,i) - u(k,i-1))|^2 \\ &\quad +\lambda|u(k,i) - u(k,i-1)|^2 \\ &= |e(k+1,i-1) \\ &\quad -\phi_c(k,i)(u(k,i) - u(k,i-1))|^2 \\ &\quad +\lambda|u(k,i) - u(k,i-1)|^2 \end{aligned} \quad (9)$$

Get the partial derivative of equation (9) with respect to $u(k,i)$, and using the optimal condition $(1/2)\left(\partial J/\partial u(k,i)\right) = 0$, we have,

$$\begin{aligned} u(k,i) &= u(k,i-1) \\ &\quad + \frac{\rho\phi_c(k,i)}{\lambda + |\phi_c(k,i)|^2} e(k+1,i-1) \end{aligned} \quad (10)$$

where the step factor $\rho \in (0,1]$ is added to make the controller algorithm (10) more general.

Since $\varphi_j(k,i)$ is not available, controller algorithm (10) cannot be applied directly. It should be estimated using the input and output data of the inverter system.

We present the following cost function to estimate the PPD

$$\begin{aligned} J(\phi_c(k,i)) &= |\Delta y(k+1,i-1) \\ &\quad -\phi_c(k,i)\Delta u(k,i-1)|^2 \\ &\quad +\mu\left|\phi_c(k,i) - \hat{\phi}_c(k,i-1)\right|^2 \end{aligned} \quad (11)$$

where $\mu > 0$ is a weighting factor to constrain the change of estimated value between successive iterations.

Using the optimal condition $(1/2)\left(\partial J/\partial\hat{\varphi}_j(k,i)\right) = 0$, we have

$$\begin{aligned} \hat{\phi}_c(k,i) &= \hat{\phi}_c(k,i-1) + \frac{\eta\Delta u(k,i-1)}{\mu + |\Delta u(k,i-1)|^2} \\ &\quad \times(\Delta y(k+1,i-1) - \hat{\phi}_c(k,i-1)\Delta u(k,i-1)) \end{aligned} \quad (12)$$

where the step factor $\eta \in (0,1]$ is added to make the PPD estimation algorithm (12) more general, and $\hat{\phi}_c(k,i)$ is the estimation value of $\phi_c(k,i)$.

On the basis of the PPD estimation algorithm (12), controller algorithm (10) is rewritten as

$$\begin{aligned} u(k,i) &= u(k,i-1) \\ &\quad + \frac{\rho\hat{\phi}_c(k,i)}{\lambda + \left|\hat{\phi}_c(k,i)\right|^2} e(k+1,i-1) \end{aligned} \quad (13)$$

To cause the parameter estimation algorithm (12) to have a strong tracking ability, we present a resetting algorithm as follows:

$$\begin{aligned} &\hat{\varphi}_c(k,i) = \hat{\varphi}_c(k,1) \\ &If \quad \hat{\varphi}_c(k,i) \leq \varepsilon \quad or \quad \Delta u(k,i-1) \leq \varepsilon \\ &or \quad sign\left(\hat{\varphi}_c(k,i)\right) \neq sign\left(\hat{\varphi}_c(k,1)\right) \end{aligned} \quad (14)$$

where ε is a small positive constant and $\hat{\varphi}_j(k,1)$ is the initial value of $\hat{\varphi}_j(k,i)$.

Equations (12), (13) and (14) are the designed control algorithms for inverter system. A strict mathematical proof of the stability of the proposed scheme can be found in reference [23].

MFAILC scheme for the inverter control system can be formalized via the Algorithm 1. T is the total running time and i_{max} is the preset maximum learning number.

Algorithm 1: MFAILC for inverter control

1. Set iteration number $i = 1$ and initialize the database
2. Set time instant $k = 1$ and initialize controller parameters
3. Estimate PPD $\varphi_j(k,i)$ using formula (12) and (14)
4. Calculate control input $u_(k,i)$ using formula (13)
5. Store new data generated in time instant k and iteration number i in the database
6. If $k < \frac{T}{t}$, set $k = k+1$ and go to step 3. Otherwise, go to step 7
7. If $i < i_{\max}$, set $i = i+1$, and go to step 2. Otherwise, end the procedure

Table 1. Simulation parameters.

Symbol	Value	Description
E	400 V	DC input voltage
L	2.5 mH	inductance
C	60 uF	capactitance
i_{max}	50	maximum learning number

4. Simulation

In order to verify the effectiveness of the proposed method, simulation studies are carried out on MATLAB software. Furthermore, different power loads are installed to demonstrate the adaptability of the proposed MFAILC scheme.

The period of inverter output voltage is 0.02s, and the sampling interval is 100μs . More parameters are listed in Table 1.

The desired output voltage $y^* = 220\sqrt{2}sin(100\pi t)V$.

For MFAILC, λ and μ are two main parameters. Multiple situations with different values of λ and μ has been tested in [20]. The values of λ and μ mainly affect the convergence speed and have less effect on the steady state error performance. For simplicity, the proposed MFAILC scheme parameters are set as follows, $\eta = 1$, $\mu = 2$, $\sigma = 3$, $\lambda = 1$, $\varepsilon = 0.01$, $\hat{\varphi}(k,1) = 0.1$. The control input of the first iteration is set to 0. The initial state value $y(0,i) = 0$ when iteration i evolves.

Comparative simulation which using the traditional PID control is involved. The corresponding structure and parameters are given as follows.

$$u(k+1) = K_p * e(k+1) + K_i * Ee + K_d * (e(k+1) - e(k))$$

where $Ee = \sum_{i=1}^{k+1} e(i)$, $K_p = 2$, $K_i = 0.07$ and $K_d = 0.02$.

Figure 2 shows the profile of the maximum tracking error using the proposed MFAILC scheme in iteration domain. And the tracking error in iteration index is defined as $e_{max}(i) = \max_{k\in\{1,\cdots,100\}} |e(k,i)|$. Also, the tracking error $e_{max}(i)$ decreases gradually along the iteration axis. It can be seen that the output voltage is stable after $7-8$ cycles of adjustment under the proposed MFAILC scheme. Thus, the learning ability of the proposed scheme can be fully demonstrated.

PID control which is treated as a comparative method is also applied to the inverter system. Figure 3 and 4 show the desired output voltage tracking curve and error tracking curve respectively at 1st iteration. It can be seen that the actual output voltage can't track the desired one well using the proposed MFAILC scheme. Roughly tracking for the desired output voltage can be achieved under PID control strategy.

Figure 5 shows the output voltage tracking error comparison between the proposed MFAILC scheme and PID control at 49th and 50th iteration. It is easy to see that the tracking error under PID control has been maintained at a relatively fixed amplitude. After several cycles of learning, the proposed MFAILC scheme is stable in a very small amplitude fluctuation.

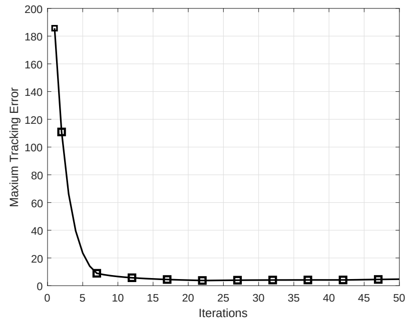

Fig. 2. Profile of the maximum learning error $e_{max}(i)$

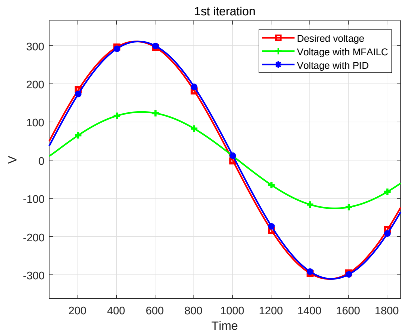

Fig. 3. Waveform of inverter output voltage at 1st iteration

Figure 6 is waveform of output voltage using MFAILC scheme and PID control at 50th iteration. It can be seen that the tracking precision of MFAILC is higher than that of PID control after several learning cycles.

5. Conclusion

In this article, a data-driven MFAILC scheme has been proposed for the inverter system. Actual inverter model is transformed into a compact form dynamic linearization (CFDL) data model. The proposed control schemes still retain the desired data-driven model-free feature, and meanwhile possess the ability to guarantee monotonic convergence of the output tracking error along the iteration axis for the repetitive runs. The performance of the proposed scheme is verified by using Matlab simulations. In addition, due to its model-independent and repetitive disturbance rejection features, the proposed scheme has a strong robustness to the operating environment and parameter changes, and it could easily be used for many different power inverter systems.

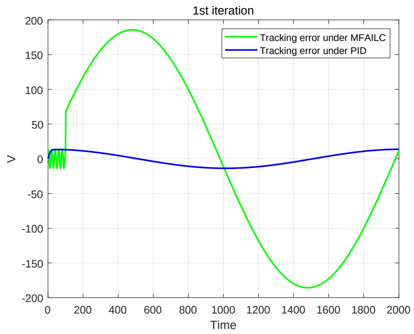

Fig. 4. Tracking error comparison with MFAILC and PID control at 1st iteration

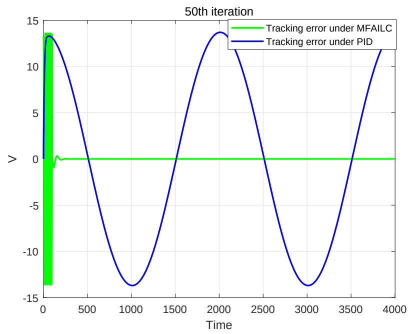

Fig. 5. Tracking error comparison with MFAILC and PID control at $50th$ iteration

Acknowledgements

This work was supported by the Science and Technology Plan of Beijing Municipal Commission of Education (KM202110017005).

References:

[1] Sadabadi M S, Karimi A, Karimi H. Fixed-order decentralized/distributed control of islanded inverter-interfaced microgrids[J]. Control Engineering Practice, 2015, 45: 174-193.

[2] Wu G Y, Sun L, Lee K Y. Disturbance rejection control of a fuel cell power plant in a grid-connected system[J]. Control Engineering Practice, 2017, 60: 183-192.

[3] Zhang L H, Ma H B, Born R, et al. Single-step current control for voltage source inverters with fast transient response and high convergence speed[J]. IEEE Transactions on Power Electronics, 2016, 32(11): 8823-8832.

[4] Tao C W, Wang C M, Chang C W. A design of a DC-AC inverter using a modified ZVS-PWM auxiliary commutation pole and a DSP-based PID-like fuzzy control[J]. IEEE Transactions on Industrial Electronics, 2015, 63(1): 397-405.

[5] Kwak S S, Mun S K. Model predictive control methods to reduce common-mode voltage for three-phase voltage source inverters[J]. IEEE transactions on power electronics, 2014, 30(9): 5019-5035.

[6] Yaramasu V, Rivera M, Narimani M, et al. Model predictive approach for a simple and effective load voltage control of four-leg inverter with an output *LC* filter[J]. IEEE Transactions on Industrial Electronics, 2014, 61(10): 5259-5270.

[7] Vieira R P, Martins L T, Massing J R, et al. Sliding mode controller in a multiloop framework for a grid-connected VSI with LCL filter[J]. IEEE Transactions on Industrial Electronics, 2017, 65(6): 4714-4723.

[8] Li Z W, Zang C Z, Zeng P, et al. Control of a Grid-Forming Inverter Based on Sliding-Mode and Mixed H_2/H_∞ Control[J]. IEEE Transactions on Industrial Electronics, 2016, 64(5): 3862-3872.

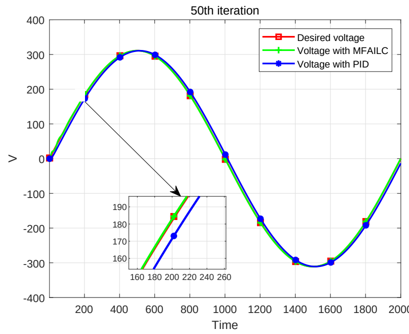

Fig. 6. Waveform of inverter output voltage at $50th$ iteration

[9] Abrishamifar A, Ahmad A, Mohamadian M. Fixed switching frequency sliding mode control for single-phase unipolar inverters[J]. IEEE Transactions on Power Electronics, 2011, 27(5): 2507-2514.

[10] Xu J X, Yan R. On repetitive learning control for periodic tracking tasks[J]. IEEE Transactions on Automatic Control, 2006, 51(11): 1842-1848.

[11] Sun M X, Wang Y Y, Wang D W. Variable-structure repetitive control: A discrete-time strategy[J]. IEEE Transactions on Industrial Electronics, 2005, 52(2): 610-616.

[12] Zhang K, Kang Y, Xiong J, et al. Direct repetitive control of SPWM inverter for UPS purpose[J]. IEEE Transactions on Power Electronics, 2003, 18(3): 784-792.

[13] Chen D, Zhang J M, Qian Z M. An improved repetitive control scheme for grid-connected inverter with frequency-adaptive capability[J]. IEEE Transactions on Industrial Electronics, 2012, 60(2): 814-823.

[14] Tzou Y Y, Jung S L, Yeh H C. Adaptive repetitive control of PWM inverters for very low THD AC-voltage regulation with unknown loads[J]. IEEE Transactions on Power Electronics, 1999, 14(5): 973-981.

[15] Meng Q, Hou Z S. Active disturbance rejection based repetitive learning control with applications in power inverters[J]. IEEE Transactions on Control Systems Technology, 2020.

[16] Chi R H, Hou Z S, Xu J X. Adaptive ILC for a class of discrete-time systems with iteration-varying trajectory and random initial condition[J]. Automatica, 2008, 44(8): 2207-2213.

[17] Wang Y Q, Gao F R, Doyle III F J. Survey on iterative learning control, repetitive control, and run-to-run control[J]. Journal of Process Control, 2009, 19(10): 1589-1600.

[18] Chi R H, Hou Z S. Dual-stage optimal iterative learning control for nonlinear non-affine discrete-time systems[J]. Acta Automatica Sinica, 2007, 33(10): 1061-1065.

[19] Bu X H, Yu Q X, Hou Z S, et al. Model free adaptive iterative learning consensus tracking control for a class of nonlinear multiagent systems[J]. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 2017, 49(4): 677-686.

[20] Ren Y, Hou Z S, Sirmatel I I, et al. Data driven model free adaptive iterative learning perimeter control for large-scale urban road networks[J]. Transportation Research Part C: Emerging Technologies, 2020, 115: 102618.

[21] Ren Y, Hou Z S. Robust model-free adaptive iterative learning formation for unknown heterogeneous non-linear multi-agent systems[J]. IET Control Theory Applications, 2019, 14(4): 654-663.

[22] Ai Q, Ke D, Zuo J, et al. High-order model-free adaptive iterative learning control of pneumatic artificial muscle with enhanced convergence[J]. IEEE Transactions on Industrial Electronics, 2019, 67(11): 9548-9559.

[23] Zhang B, Wang D W, Zhou K L, et al. Linear phase lead compensation repetitive control of a CVCF PWM inverter[J]. IEEE Transactions on Industrial Electronics, 2008, 55(4): 1595-1602.

[24] Hou Z S, Jin S T. Model free adaptive control: theory and applications[M]. CRC press, 2019.