Multiobjective design of fuzzy neural network controller for wastewater treatment process

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A B S T R A C T

In this paper, an improved multiobjective optimal control (MOOC) strategy is developed to improve the operational efficiency, satisfy the effluent quality (EQ) and reduce the energy consumption (EC) in wastewater treatment process (WWTP). First, the adaptive kernel function models of the process, which can describe the complex dynamics of EQ and EC, are developed for the proposed MOOC strategy. Meanwhile, a multiobjective optimization problem is constituted to account for WWTP. Second, an improved multiobjective particle swarm optimization (MOPSO) algorithm, using a self-adaptive flight parameters mechanism and a multiobjective gradient (MOG) method, is designed to minimize the established objectives. And then the optimal set-points of dissolved oxygen (SO) and nitrate (SN) are obtained in the treatment process. Third, an adaptive fuzzy neural network controller (FNNC) is applied for realizing the tracking control of the obtained set-points in the proposed MOOC strategy. Finally, Benchmark Simulation Model No.1 (BSM1) is introduced to evaluate the effectiveness of the proposed MOOC strategy. Experimental results show the efficacy of the proposed method.

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1. Introduction

The scope for wastewater treatment process (WWTP) has been broadened in recent decades. Not only the discharge limits are getting stricter, also the new regulations such as energy efficiency are being implemented [1,2]. Therefore, the operation of WWTP should continuously meet the discharge standards and reduce the operational cost [3,4]. However, with the phenomena of the micro-organisms, the stochastic perturbations and the variability of the influent, WWTP is a complex biological and biochemical reaction process [5,6].

To operate WWTP with high-efficiency process performance, the optimal control strategy has been considered. However, it is well known that the key limitations of the optimal control strategy for WWTP are the formulation of the optimization problem, the calculation of the optimal set-points and high-accuracy tracking control. In most applications of the optimal control strategy, the optimization objectives are designed by supposing the system as a discrete-time or a continuous-time model [7–9]. For example, Santin et al. presented a two-level hierarchical control strategy under the goal of effluent limits as well as the operational costs [10]. Effluent quality (EQ) and energy consumption (EC) models were considered as a single objective in the proposed control strategy. An optimal control strategy was utilized to operate WWTP within the best possible conditions [11]. In this optimal control strategy, the optimal objective was designed to evaluate the enhancement of the operation in terms of EC and EQ. And a weight coefficient method was applied to make the benchmark EC and EQ models as a single objective problem. Moreover, Zeng et al. applied an economic model predictive control (EMPC) to optimize EC and EQ in [12]. Since the processes of WWTP are really complicated, it would be preferable to utilize the multiobjective optimization and control approaches for coping with the operations of WWTP [13]. At the same time, the single objective optimization approaches are difficult to reflect the trade-off relationship among coupling objectives, and the weight coefficients are determined casually and subjectively [14]. These ways of approaching the multiobjective problem for WWTP are not the suitable manners of handling these issues [15,16].

To deal with the complex organic removal process and reflect the complicated relationship in WWTP clearly, Hreiz et al. developed a multiobjective dynamic optimization operating strategy of a small-size wastewater treatment plant [17]. The results provided the relationship of the treatment quality and the operating
cost. In addition, to obtain the trade-off between treatment performance and the operating cost, Dai et al. proposed a multiobjective optimization algorithm for solving the conflicting relationship of EQ, EC and operation stability [18]. The results demonstrated that this multiobjective optimal method could obtain better control performance than the traditional methods. In the above multiobjective optimization process, the optimization objectives were constituted by the benchmark models. Therefore, one obvious disadvantage is that the model parameters are invariant. Meanwhile, the optimization algorithms have received a special attention for optimal control [19–21]. Sweetapple et al. investigated the efficiency of optimization strategy for reducing the greenhouse gas emissions from wastewater treatment economically [22]. A multiobjective evolutionary algorithm, named non-dominated sorting genetic algorithms-II (NSGA-II), was utilized to obtain the optimal control values for a wastewater treatment plant, with the objectives of minimizing the greenhouse gas emissions, reducing the operational consumptions and meeting the effluent limits. Marques et al. introduced a multiobjective simulated annealing algorithm (SAA) to verify the conflicting objectives in [23]. For SAA, a multiobjective decision model with environmental impacts and energy consumption was detailed and the Pareto front could be obtained. The results demonstrated that this SAA could deal with conflicting objectives. Considering the nonlinearity and complexity of biochemical behavior included in wastewater treatment reactors, a multiobjective control strategy was implemented to simultaneously optimize the effluent chemical oxygen demand and the biogas flow rate in an anaerobic bioreactor using NSGA-II and genetic algorithm–artificial neural network (GA-ANN) [24]. This multiobjective control strategy considered two operational objectives, EQ and the maximum production rate of biogas. The results demonstrated that the optimal balance between EQ and biogas flow rate of the anaerobic bioreactor could be achieved. However, the slow calculation speed, as well as the complex operations of crossover influenced the generation and convergence of the optimal solutions. To avoid the complex operation of crossover and mutation, Zhang et al. introduced a multiobjective particle swarm optimization (MOPSO) based on the control vector parameterization (CVP) to solve the multiobjective optimization problem [25]. Akbas et al. proposed a MOPSO algorithm to increases the biogas production and biogas quality by optimizing the maximization of biogas quality and biogas production in [26]. The experimental results certified the effectiveness of the multiobjective optimization method. Recently, MOPSO algorithm, attracted great attention for its fast convergence rate and concise structure, has been applied to many different fields [27,28]. However, the main drawback of the classical MOPSO algorithm is that it easily gets into local optimal solution [29,30].

In this paper, to realize the optimal control operation with EC reduction while retaining standard EQ, an improved multiobjective optimal control (MOOC) strategy is proposed. The main contributions of this paper are as follows: First, the dynamic optimization objectives concerning EC, EQ and effluent constraints are designed by using the adaptive kernel function. Then, a MOOC problem is formulated by taking the dynamic optimization objectives for WWTP. Second, an improved multiobjective optimization algorithm, taking advantage of multiobjective particle swarm optimization (MOPSO), is developed to minimize all the objectives simultaneously. The improved MOPSO algorithm, with a self-adaptive flight parameters mechanism and multiobjective gradient (MOG) method, is designed to acquire the compromise solution directly in the cost space instead of weighting the individual objectives as a single objective function. Then, the real-time set-points of dissolved oxygen (S\textsubscript{O}) and nitrate (S\textsubscript{NO}) can be achieved. Third, as the adaptability of the proposed MOOC strategy is important for applications, a fuzzy neural network controller (FNNC), using a second-order Levenberg-Marquardt (L-M) algorithm, is introduced to trace the obtained set-points of S\textsubscript{O} and S\textsubscript{NO}. Experimental results show that this proposed MOOC strategy can improve the operation performance of WWTP.

The remainder of this paper is organized as follows. Section 2 gives the benchmark simulation platform. In Section 3, the formulation of the optimization objectives, the improved MOPSO algorithm and the adaptive FNNC approach are described to address the optimal control problems for WWTP. The results of the proposed MOOC strategy are presented in Section 4. Meanwhile, several optimal control strategies are proposed for describing the comparisons. Finally, Section 5 concludes the paper.

2. Problem definition

In WWTP, the main reaction processes are carried out by the biochemical reaction units and the secondary sedimentation unit. In these units, S\textsubscript{O} in the fifth aeration zone and S\textsubscript{NO} in the second anoxic zone are the most important control variables. These two variables are critical to the biochemical reaction and the nitration reaction, which are manipulated by the oxygen transfer coefficient (K\textsubscript{a}) and the internal recycle (Q\textsubscript{r}). To evaluate and compare different optimal control strategies uniformly, the Benchmark Simulation Model No.1 (BSM1), developed by the International Association on Water Pollution Research and Control, is proposed in this section. The influent flow rate and the influent ammonium nitrogen (NH) concentration under three different weather conditions—dry, rain and storm within two weeks, are introduced in BSM1. Both the influent flow rate and influent NH are considered as the disturbances. And the variations of two disturbances are shown in Figs. 1 and 2.

The control effects are assessed by two levels. The first level relates to the local control loops, accessed by the integral of the squared error (ISE) and integral absolute error (IAE)

\[
\text{ISE} = \int_{t=7\text{days}}^{t=14\text{days}} e^2 dt / (14 - 7),
\]

\[
\text{IAE} = \int_{t=7\text{days}}^{t=14\text{days}} |e| dt / (14 - 7),
\]

where e is the control error, ISE and IAE are taken as a proof to show the efficiency of the proposed control strategy.
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