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Comparison of MPC and PI Control Strategies for Activated Sludge Process

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Abstract: *This paper deals with comparison of PI Controller with model predictive control (MPC) applied to benchmark simulation model no.1 (BSM1) of an activated sludge process in order to maintain the effluent quality within the limits. The objective is to compare the control strategies based on better performance with respect to effluent concentration under specified limits and operating costs. In this study, the control strategies such as PI and model predictive control (MPC) are compared and applied to control the dissolve oxygen concentration in the last aerobic reactor of the activated sludge process. Also, the nitrate concentration is controlled in the second anoxic reactor using PI control strategy. Simulations are performed using sewage treatment plant influent data. The influent fractionation is carried out using activated sludge model no.1 (ASM1). The results of the dynamic simulation indicate that model predictive control is more effective than PI control in meeting the effluent limits especially when ammonia concentration is considered significant. By comparing performance evaluation criteria, dissolved oxygen MPC and nitrate PI (MPC-PI) control strategies have achieved almost the same operating costs as with dissolved oxygen PI and nitrate PI (PI-PI) control strategies.*

Keywords *- Activated sludge process, Benchmark Simulation Model No.1, MPC, Operating cost, PI control*

I. INTRODUCTION

Activated sludge process is considered as a suitable technology for biological wastewater treatment. However, the operation of activated sludge process is difficult because of complex behavior subject to variations in the influent flow and composition. In addition, the recent restrictions on effluent quality and increased operational costs have acted as a driving force for implementing process control in the wastewater treatment plant [1].

Many control strategies have been proposed for wastewater treatment plant but it is difficult to evaluate and compare the control strategies. This is due to different plant configuration, variation in process models and lack of standard evaluation criteria. The evaluation procedure must be uniform in order to enhance the advancement and acceptance of new control strategies. Adhering to these criterions, the benchmark simulation model no.1 (BSM1) of the activated sludge process has been developed by a working group of COST (cooperation in science and technology) actions 624 and 682, along with the international water association (IWA) task group [2]. The benchmark is a simulation protocol to assess the performance and evaluation criteria of control strategies of the activated sludge process [3,4]. The evaluation criteria includes general effluent quality measure, aeration energy, pumping energy, mixing energy, sludge production and determination of operating costs [5].

In recent years, stringent regulations have been imposed on effluent concentration limits from municipal wastewater treatment plant. So, maintaining the constraint is mandatory in order to follow the environmental norms. Moreover, the performance of the treatment plant is evaluated in terms of its effluent quality limits and operating cost during dynamic condition. Thus, MPC and PI control strategies are suitable control technologies for this application in order to meet the effluent quality standards and minimizing the operating costs [6,7].

Model predictive control is the advanced control method that has been in wide use in the process operations in oil refineries and chemical industries because of its consistency on large scale processes and its capacity to maintain the effluent constraints [8]. MPC is a model-based control strategy and the success depends on the reasonably accurate process model. The main objective of an MPC controller is to prevent violations of constraints [9,10].

Recently, modeling studies have focused on assessing the effect of aeration on the performance of treatment systems [11]. The dissolved oxygen concentration is considered as the main controlled variable in the reactor that can be used in the optimization of effluent nitrogen and operating costs [12-14]. [15] have applied model predictive control on an activated sludge system. However, their works focused on the assumption of a multivariable control problem rather than based on the dissolved oxygen control [16].

In this paper, dissolved oxygen is controlled in the last aerobic reactor using either MPC or PI control strategy and nitrate is controlled in the second anoxic reactor using PI control strategy of the activated sludge process. Moreover, the simple PI control is compared with an advanced model predictive control, in view of maintaining the effluent quality within the limits in the activated sludge process. Furthermore, the control strategies are also compared in terms of the optimal performance based on energy consumption and operating costs.

II. MATERIALS AND METHODS

2.1 BSM1 model

A benchmark is a simulation environment defining a plant layout, a process model, test procedures and evaluation criteria that has been developed by working group within COST Actions 624 and 682 [3].

2.2 Plant description

The layout of the BSM1 activated sludge process (Figure 1) represents nitrification with pre-denitrification [3]. It consists of five reactors with a total volume of 5999 m3 connected by a settler with a volume of 6000 m3. The first two reactors are maintained under anoxic (mixed and non-aerated) condition which includes a volume of 1000 m3 each and next three reactors are kept at aerobic condition of volume 1333 m3 each.

In the activated sludge process, nitrogen removal takes place in two stages. The first stage is nitrification were ammonia is oxidized to nitrate by using autotrophic biomass under aerobic condition. Denitrification takes place in the second step, which reduces nitrate to nitrogen by using heterotrophic biomass under anoxic condition. The two anoxic reactors are placed at the beginning of the activated sludge process to aid pre-denitrification reaction and are followed by three aerobic reactors that are used for nitrification reaction. All five reactors are completely mixed. The activated sludge process combines nitrification with pre-denitrification in a configuration that is mainly used for nitrogen removal and elimination of carbonaceous organic matter. In order to maintain the biomass population, the sludge from the settler is recycled to the anoxic reactor (sludge recycle, Qr). Also, the internal recirculation flow (Qa) is introduced to the first anoxic reactor to enhance nitrogen removal. Furthermore, the excess sludge is removed as waste (Qw) from the settler underflow.

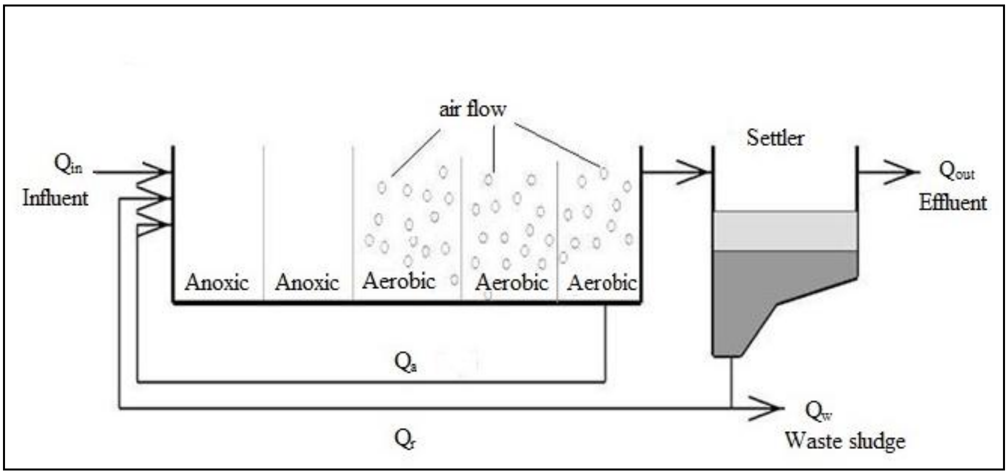

Fig. 1 Schematic representation of BSM1 Activated sludge process

2.3 Process model

The activated sludge model no.1 (ASM1) proposed by [17] is used to simulate the biological processes within the reactors. The settler is implemented as a non-reactive, ten-layer system with a double exponential settling velocity model proposed by [18] is also chosen to describe the behavior of the settler.

2.4 Influent loads

The influent variables data are collected from the sewage treatment plant (STP) located in Tamilnadu, India. The influent load data are presented in terms of influent flow rate (Figure 2) and influent variables (Figures 3-4). The influent flow rate shown in figure 2 is taken from the benchmark influent file of dry weather condition. The influent variables such as chemical oxygen demand (COD) and total nitrogen are collected from STP and these data are evaluated using ASM1 state variables (Table 1).

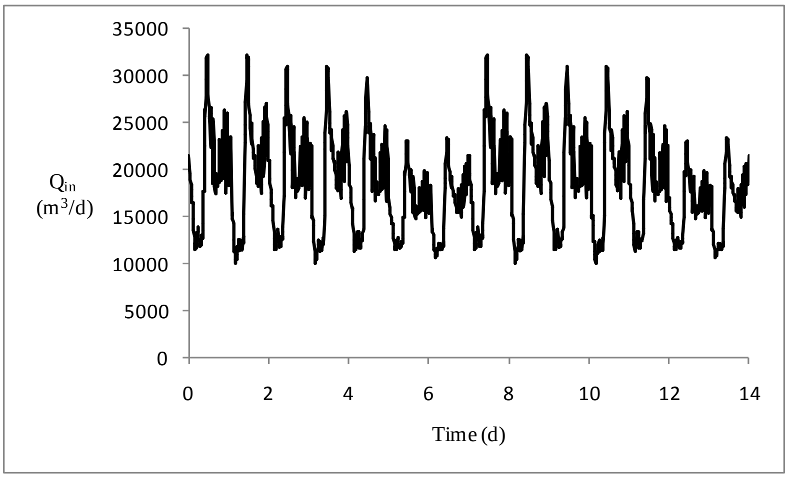

Fig. 2 Influent flow rate

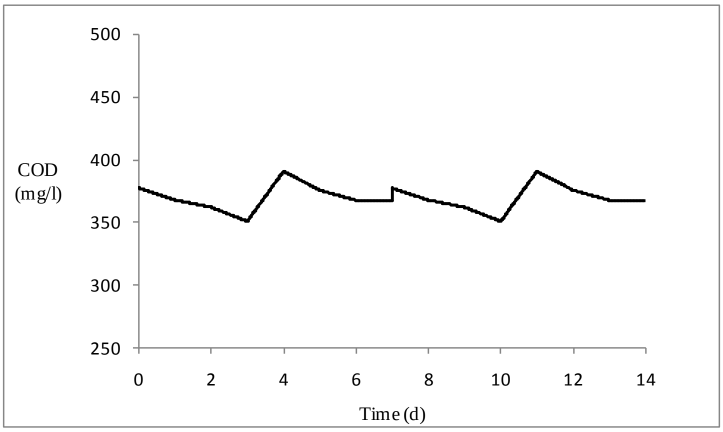

Fig. 3 Influent COD

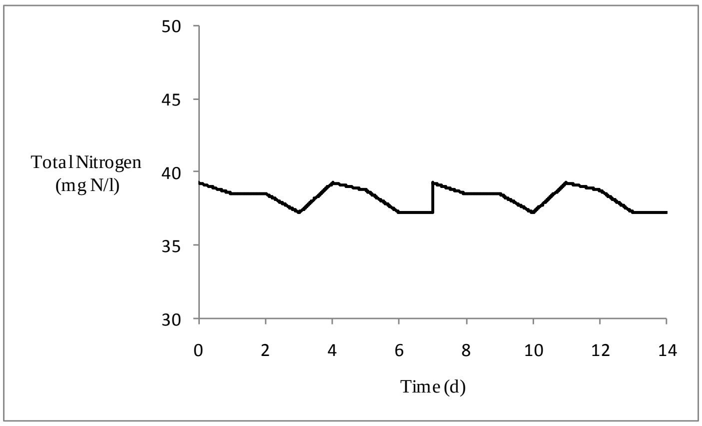

Fig. 4 Influent total nitrogen

The simulation is performed in the BSM1 activated sludge process using Matlab-Simulink®. The simulation is first run at steady state condition using average influent composition followed by the dynamic condition using 14 days of STP data at 15 min sampling period. Then, the performance of the BSM1 activated sludge process is evaluated over the period of last 7 days of dynamic condition as suggested by [19].

TABLE 1 Average influent composition for sewage treatment plant

Component	Unit	Value
Total COD	mg COD/l	363.7
Soluble inert organic matter, S_I	mg COD/l	30
Readily biodegradable substrate, S_S	mg COD/l	60
Particulate inert organic matter, X_I	mg COD/l	50.58
Slowly biodegradable substrate, X_S	mg COD/l	193.12
Active heterotrophic biomass, X_{BH}	mg COD/l	30
Total Kjeldahl Nitrogen, TKN	mg N/l	37.85
Ammonia-nitrogen, S_{NH}	mg N/l	20
Soluble biodegradable organic nitrogen, S_{ND}	mg N/l	6.076
Particulate biodegradable organic nitrogen, X_{ND}	mg N/l	11.77
Influent flow rate, Q	m^3/day	21320

2.5 Evaluation criteria

The evaluation criteria are defined in the benchmark for comparing the performance of various control strategies in the activated sludge process [3,5]. The operational costs are evaluated based on the sum of different costs such as energy costs for aeration energy, pumping energy and mixing energy and sludge disposal cost. Therefore, the operational costs (OP) per day is calculated as

$$\mathbf{OP = CE\ (AE + PE + ME) + CS\ (SP)} \qquad (1)$$

Where CE is the cost of energy, AE is aeration energy, PE is pumping energy, ME is mixing energy, CS is cost of sludge disposal and SP is sludge production for disposal. From the industrial electricity tariff slab in India, cost of energy (CE) is Rs 8.05/kWh. The cost of sludge disposal (CS) was US$ 80/ton in 2011 [20]. However, for Indian conditions, based on the information from sewage treatment plant, the approximate cost of sludge disposal (CS) is `500 / ton.

The aeration energy (AE) is calculated as a function of the saturated oxygen concentration, the volume of aerobic reactors and $K_L a$ based on the following relation

$$AE = \frac{S_o^{sat}}{t_{obs}\,(1.8)(1000)} \int_{t=7d}^{t=14d} \sum_{i=3}^{5} V_i . K_L a_i\,(t).\,dt \qquad (2)$$

Where S_o^{sat} is saturated oxygen concentration (g. O_2 / m^3), t_{obs} is total length of the evaluation period in days ($t_{end} - t_{start}$), V_i is volume of reactor i (m^3) and $K_L a_i$ is oxygen transfer coefficient (d^{-1}).

The mixing energy (ME) is a function of the anoxic tank volume. It is calculated as

$$ME = \frac{24}{t_{obs}} \int_{t=7d}^{t=14d} \sum_{i=1}^{5} 0.005\,V_i\,.\,dt \qquad (3)$$

The pumping energy (PE) is a function of the internal recycle flow rate (Q_a), sludge recycle flow rate (Q_r) and waste sludge flow rate (Q_w). It is calculated using the equation

$$PE = \frac{1}{t_{obs}} \int_{t=7d}^{t=14d} (0.004\,Q_a + 0.008\,Q_r + 0.05\,Q_w)\,dt \qquad (4)$$

$$SP = \frac{1}{t_{obs}.\,1000}\left(M_{TSS}(t_{end}) - M_{TSS}\,(t_{start}) + 0.75 \int_{t=7d}^{t=14d} (X_{S_w} + X_{I_w} + X_{BH_w} + X_{BA_w}).\,Q_w(t).\,dt\right) \qquad (5)$$

The amount of solids accumulated in the activated sludge process is equal to the amount of solids in all the reactors and also in the settler. The amount of total solids from the waste sludge flow rate are X_{S_w}, X_{I_w}, X_{BH_w} and X_{BA_w} which represents the concentration of slowly biodegradable substrate, particulate inert organic matter, active heterotrophic biomass and active autotrophic biomass in the waste sludge respectively. The activated sludge process should be operated under effluent constraints. The control strategies such as PI-PI and MPC-PI are selected to maintain the effluent concentration within the regulation limits, regardless of the variations of influent wastewater. The average value of effluent concentrations should follow the constraints listed in Table 2 [19]. Sludge production (SP) for disposal is evaluated based on the amount of solids accumulated in the process and the total solid flow from the waste sludge flow rate (Q_w) over the period of last 7 days of dynamic condition [19].

TABLE 2 Constraints on the process

S.No	Variable	Constraint (mg/l)
1	Ammonia (S_{NH})	4
2	Total Nitrogen (TN)	18
3	BOD_5	10
4	COD	100
5	Total Suspended solids (TSS)	30

III. RESULTS AND DISCUSSIONS

In this section, the control strategies are applied to the activated sludge process such as dissolved oxygen concentration (SO) in the last aerobic tank need to be controlled using PI controller (Figure 5) and MPC controller (Figure 6) and compare the control performance. The other variable is nitrate concentration (SNO) in the second anoxic tank is controlled using PI controller (Figure 5 & 6).

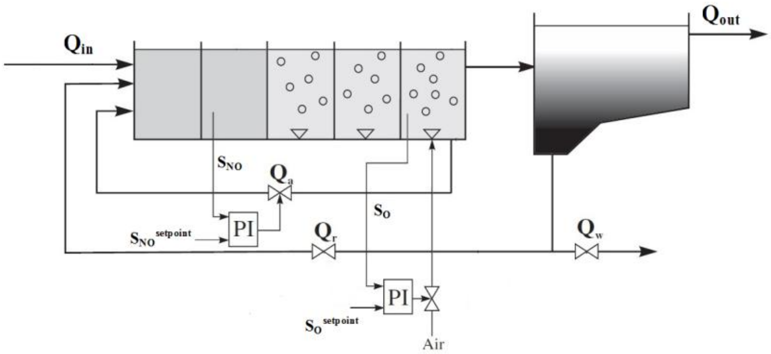

Fig. 5 BSM1 activated sludge process with PI-PI control

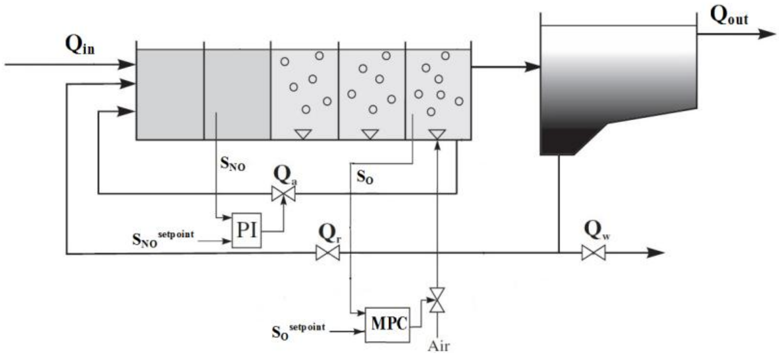

Fig. 6 BSM1 activated sludge process with MPC-PI control

The values of the tuning parameters of PI and MPC control strategies are shown in Table 3-4.

TABLE 3 Parameters of PI controllers

Parameter	Dissolved oxygen PI controller	Nitrate PI controller
Controller gain (K_c)	500	15000
Integral time (T_I), days	0.001	0.05

TABLE 4 Parameters of MPC control

Parameter	Dissolved oxygen MPC controller
Sampling time, min	15
Prediction horizon	10
Control horizon	1

The dissolved oxygen control is considered as significant in the activated sludge process, both from an economic and a biological perspective. The dissolved oxygen concentration in the aerobic reactor must be sufficiently high to provide enough oxygen to the biomass in such a way to achieve the biodegradation of organic matter and nitrification. Otherwise, a very high dissolved oxygen concentration causes the denitrification reaction to be less efficient in the anoxic reactor. The purpose of this control strategy is to control the dissolved oxygen concentration in the last aerobic reactor at the set-point of 2 mg/l using either MPC or PI controller by manipulating the oxygen transfer rate. The response of the dissolved oxygen concentration plot is shown in Figure 7.

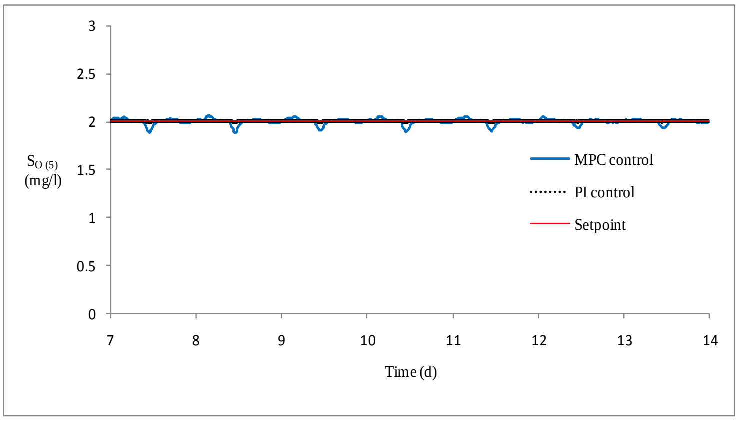

Fig. 7 Dissolved oxygen (S_o) concentration in the last aerobic tank

The nitrate (S_{NO}) concentration in the second anoxic reactor is controlled by using PI controller at the set-point of 1 mg/l, the internal recycle (Q_a) flow rate is regulated which leads to save the pumping energy.

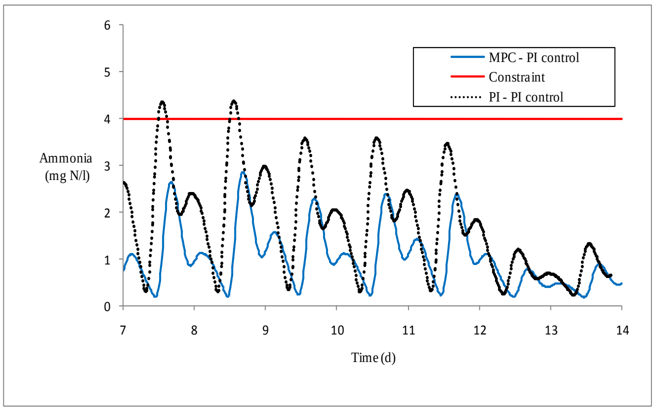

Fig. 8 Effluent Ammonia (S_{NH}) concentration

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The horizontal solid constant line in Figure 8 represents the constraint. For the case of PI-PI control strategy (shown in dotted line), the concentration of ammonia is slightly violated above the effluent limit. The reason for this violation is the influent load and influent flow rate are high during these periods (7.6d to 8.75d = 1.15 d). The percentage of time in violation is 16.4.

In the case of MPC-PI control strategy (shown in solid line), the effluent ammonia concentration (Figure 8) is maintained below the effluent limit. This is due to the control sequence is calculated based on set-point, a process model, measured disturbances and outputs [21]. In this study, the benchmark model with dissolved oxygen measurement is used as the process model of the predictive controller and all influent disturbances are measured over the prediction horizon.

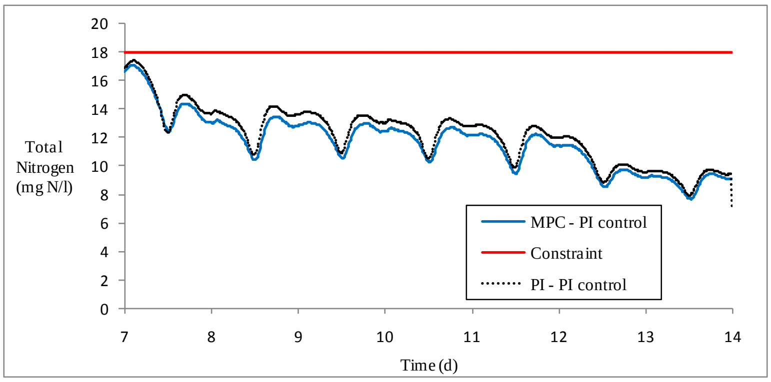

Fig. 9 Total nitrogen concentration in the effluent

Figure 9 shows the response of total nitrogen concentration in the effluent. The effluent total nitrogen concentration is maintained well within the constraint. This is due to the complete denitrification reaction takes place in the second anoxic tank using PI control strategy.

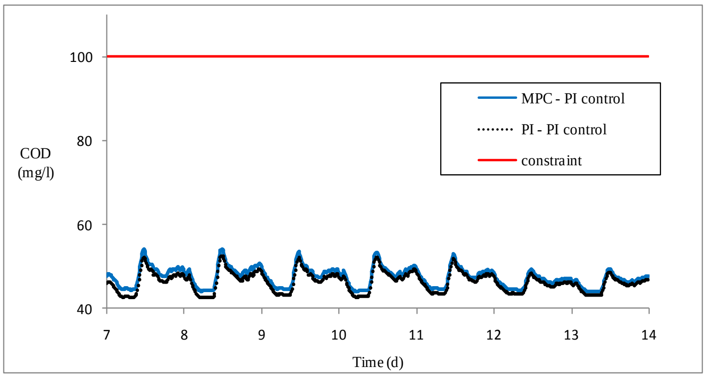

Fig. 10 Response of COD concentration in the effluent

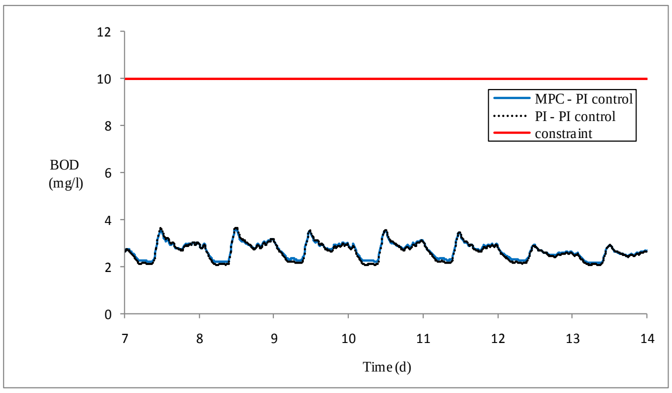

Fig. 11 Response of BOD concentration in the effluent

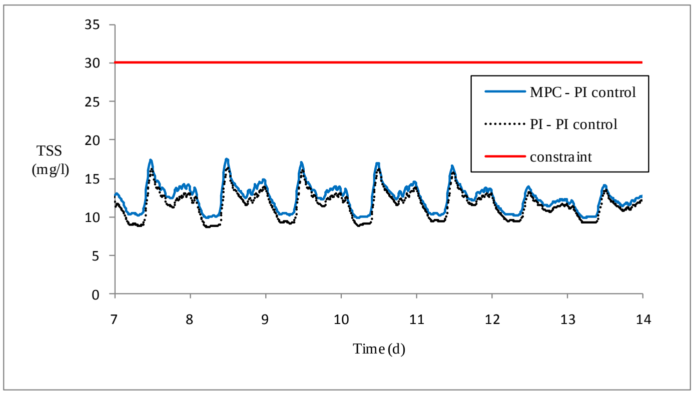

Fig. 12 Response of TSS concentration in the effluent

From the Figures 10-12, it is observed that the response of BOD, COD and TSS concentration in the effluent are maintained within the constraint in the case of PI-PI and MPC-PI control strategies.

The performance of PI-PI and MPC-PI control strategies are evaluated using the criteria described in section 2.5 and the calculated values are given in Table 5. Normally, aeration cost plays a major role in the operating costs compared to other costs. As shown in Table 5 the aeration energy is slightly increase with MPC-PI controllers because of the higher energy needed for better ammonia removal and also maintained the ammonia concentration within the constraint. Thus comparing the performance of controllers, MPC-PI control strategies have achieved almost the same operating costs as with PI-PI control strategies.

TABLE 5 Evaluation criteria for PI-PI and MPC-PI control strategies

Variable	Units	PI-PI	MPC-PI
Aeration Energy	kWh/d	3493.17	3525.93
Pumping Energy	kWh/d	291.61	291.61
Mixing Energy	kWh/d	240	240
Sludge production for disposal	ton/d	2.017	2.438
Operating costs	` per day	33407.98	33882.2
% of time, effluent ammonia violation	%	0.164	0

IV. CONCLUSION

This article assessed the objective of comparing control strategies of MPC-PI and PI-PI in terms of effluent quality under specified limits and operating costs in activated sludge process using a benchmark simulation model. The simulation response indicates that the advanced MPC controller gives better performance with respect to constraints than simple PI control especially effluent ammonia concentration. This study also shows that MPC-PI controllers have achieved nearly similar operating costs as with PI-PI controllers.

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