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Time Delay Compensation for Dialysate Preparing Process Using Immune-LQI Controller

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Abstract

Time delay in control systems may cause instability; therefore, it is necessary to compensate for its effect by designing appropriate controller. Time delay is present in the dialysate papering process due to the physical distance between the concentrate injection points and the points of conductivity measurements. In this research, an Immune-LQI controller which was previously designed to regulate dialysate conductivity, is tested in presence of time delay. The Immune-LQI controller combines Linear Quadratic Integrator (LQI), Immune Control (IC), Fuzzy Logic (FL) and Genetic Algorithm (GA). For the purpose of comparison, the well-known Smith predictor with Proportional Integral Derivative controller (PID-Smith), LQI, and PID have been designed. The results proved the superiority of Immune-LQI as it resulted in 1.70 % improvement in rise time, 77.80 % in overshoot, and 43.47 % in settling time, when compared with LQI.

Keywords: Linear Quadratic Integrator Controller, Immune Controller, Fuzzy Logic Controller, Dialysate Conductivity Model.

تعويض زمن التأخير في عملية تحضير سائل الديلزة باستخدام المتحكم LGI– المناعي

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الملخص

يمكن أن يسبب التأخير الزمني عدم الاستقرار في نظم التحكم، لذلك فانه من الضروري تعويض أثره بتصميم المتحكم المناسب. يتواجد التأخير الزمني في عملية تحضير سائل الديلزة بسبب وجود المسافة الفيزيائية الفاصلة بين نقاط ضخ المركب ونقاط قياس الناقلية. في هذا البحث فان المتحكم LQI– المناعي الذي تم تصميمه مسبقا لتنظيم ناقلية سائل الديلزة تم اختباره بوجود التأخير الزمني. يدمج المتحكم LQI– المناعي بين المتحكم الخطي التربيعي التكاملي (LQI)، والتحكم المناعي (IC)، والمنطق الضبابي (FL)، والخوارزمية الجينية (GA). تم لغرض المقارنة تصميم متنبئ سميث المعروف مع المتحكم التناسبي التفاضلي التكاملي (PID–Smith)، والمتحكم LQI، والمتحكم PID. أظهرت النتائج أن المتحكم LQI– المناعي كان الأفضل حيث أعطى تحسينا قدره 1.70% في زمن الصعود، و77.80% في التجاوز المئوي و43.47% في زمن الاستقرار، بالمقارنة مع المتحكم LQI.

الكلمات المفتاحية: المتحكم الخطي التربيعي التكاملي، المتحكم المناعي، المنطق الضبابي، نموذج ناقلية سائل الديلزة.

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Introduction

Dialysis aims to remove waste products, such as toxins (e.g., urea) and excess solution, that accumulate in the body due to inadequate kidney function. It maintains the safety levels of certain electrolytes such as potassium, sodium and bicarbonate (Ahmad, 2013-a, 201). Two essential components are required for blood purification by dialysis: a semipermeable membrane and a plasma-water-like solution called dialysis solution or dialysate. Dialysate is a chemical solution that is prepared carefully and accurately (Ledebo, 2002, S79). The preparation of the dialysate is of high importance for the success of blood purification process. To prepare the dialysate, two concentrate components (acid and bicarbonate) are pumped simultaneously to treated water. The addition process of concentrate components is critical because if the permissible values are exceeded, the process of electrolyte transfer will be reversed (from the dialysate to the blood). The dialysate quality is checked by monitoring its conductivity (measured in mS/cm), which is related to the concentration of electrolytes in the dialysate. The conductivity is usually kept constant during the dialysis session by continuously monitoring and controlling it (Ahmad, 2013-b, 232).

Time delay is defined as the time separating the beginning of an event at one point in the system from that event at another point in it. Researchers refer to time delay using terms, such as dead time (Normey & Camacho, 2008, 412; Ari, 2000, 6), or transport lag. Biological systems, in addition to other systems such as physical, chemical, industrial, and other systems, suffer from time delay in their dynamic behaviors. The delay may exist in the system itself or originate from the controller (Normey & Camacho, 2008, 413). Time delay is mainly responsible for increasing the disturbance in the control systems, causing the control systems to oscillate, and causing distortion and instability in the control response.

There are many reasons for the occurrence of time delay in control systems. Examples includ the time delay between the actuator and the sensor, the time delay that appears when approximating a higher-order mathematical model to a lower one, the time delay resulting from mathematical calculations or processing within the controllers, and the time delay within the transfer of information, energy and fluids among others. When control systems suffer from a clear time delay in their response, it is possible to improve the performance of feed-back systems by using compensators that depend in their structure on a predictive structure known as dead time compensation (Asim, 2010). Most of these compensators are based on knowledge of the mathematical model.

The Smith compensator is considered one of the oldest, most famous and most widely used dead time compensators (Asim, 2010; Shubhasree, & Vijay, 2015, 2727; Fang, Fenglin , & Dandan, 2016, 120). The Smith compensator appeared in the late fifties to improve the performance of traditional PI and PID controllers in systems that suffer from a clear time delay in their response. It is used to remove the time delay from the characteristic equation of closed loop system, which in turn leads to a clear improvement in the performance of the system. However, one of the most important weaknesses of this method is its high sensitivity to the accuracy of the mathematical model.

1.1 Literature Review

There are many studies present Smith compensator with controllers PI and PID and others, including a Smith compensator integrated with modern controllers such as fuzzy and adaptive controllers, swarm and genetic algorithms (GA) in order to eliminate the effect of time delay in the control loop. The researchers Anand and Poorani (Poorani, & Anand, 2013, 218) studied how to maintain the heat exchanger at the required temperature, as the PID controller failed to control the system due to the time delay. Therefore, a Smith compensator was used, and the simulation result showed an improvement in the response specification. Rao and Chidambaram combined three controllers and a filter to form an improved Smith Compensator in order to control the processes that suffer from fixed time delays (Rao, & Chidambaram, 2005, 8293). As the first controller was used to control the servo motor, the second to adjust the regulation, and the third to deal with the external disturbances, a first-class filter was added to improve the robustnees of the controller.

Predictive network controller with an adaptive control loop was designed to deal with the random time delay to reduce its effect on the control system, in addition to including a filter with Smith compensator to improve the robustness of the controller against external disturbances (Velagic, 2008). Ahmet, Ozgur (Ahmet, & Ozgur, 2012) presented a new hybrid scheme for the Smith compensator to overcom the problem of periodic perturbations experienced by time-delay control systems. This new scheme was a combination of a fuzzy-PI controller and a Smith compensator with a filter.

To control a non-linear system, with two inputs and two outputs, consist of two tanks, two controllers were designed, each of which controls the liquid level in a tank. The control system was described with a specific mathematical model that includes a specific time delay related to the length of the tube at the output of each tank. Many controllers (PID, internal model controller IMC, fuzzy with PID and fuzzy with IMC)were designed. the response of the IMC controller was better than the PID, and the fuzzy controller with IMC was the best in terms of rise time, settling time, overshoot and peak time (Anuradha, & Rajendra, 2017, 1112).

To overcome the problem of time delay in networked control systems, a PID controller, fuzzy logic(FL), and a Smith Compensator were designed to control a servo motor, and it was found that the Smith controller is better (Meghanasingh, 2017, 995). The fuzzy PID controller with a Smith compensator showed good performance when there is a wide range of fixed and variable time delays with packet losses for a linear system (Ahmad, S., Ahmad, M., Mohammad, E., & Mohammed, S., 2016, 438). A number of controllers were compared for a nonlinear system (Fang, Fenglin, & Dandan, 2016, 122) with time delay and packet loss, and it was found that the fuzzy PID controller based on the swarm optimization algorithm and based on the genetic algorithm is better than the fuzzy-PID and the normal PID, and that the controller based on the swarm algorithm is better than that based on the genetic algorithm. It was found that the fuzzy controller based on an adaptive fuzzy system is able to eliminate the variable time delay (Chien-Liang, & Pau-Lo, 2010, 75).

Artificial Immune System (AIS) is an attractive method to improve traditional PID controller. AIS algorithm had more ability to find the global optimum solution when compared with Ziegler-Nichols tunning method (Muna & Saad, 2016, 35). The solution accuracy and convergence speed of the AIS with Social Learning mechanisms was better than other algorithms (Mingan, Shuo, Chunhui, Zhonghua, & Yu, 2017). Immune PID controller was quicker with a smaller overshoot than the conventional PID controller and fuzzy PID (Sharad, & Gagandeep, 2011, 187). Immune PID controller optimized with GA and FL was ideal (Xin-hua, Xiao-hu, Xiao-hu, Sheng-peng, & Zhong-ben, ,2014). PID was connected with Immune controller (IC) to have three structures of an immune-PID control system (Tariq, Ekhlas, & Eman, 2019, 178). A control system based on IC was more stable than two-position controller (Jiawei, Fabrice, Abderrafiaa, Vincent, & Marcelo, 2013).

The concept of conductivity measurement, which has been called the "effective ionic dialysance" method, have been reported since early 1990s. In the 1993, two papers were published, nearly at the same time, showing that instantaneous ionic dialysance can be measured, without the need for any blood or dialysate sampling and at no extra cost. The measurement was simply done by using two conductivity probes placed at the dialyzer inlet and outlet, or a single probe alternately activated at the outlet (Petitclerc, Goux, Reynier, & Bene, 1993, 587; Polaschegg, 1993, 186). This allows repeated measurements of ionic dialysance, which can be used to obtain the mean value for the dialytic session as a whole (Ahmad, 2013-b, 431).

Online conductivity monitoring is a valid, practical, and useful tool, with which one studies the pattern of sodium balance in patients on hemodialysis (Lambie, Taal, Fluck, & McIntyre, 2005,73). A small number of reaserch papers were found in the literature concerning the controlling process of conductivity. An FLC was used to adjust the parameters of a hemodialysis machine so that the patient's hemodynamic condition remained stable during hemodialysis treatment. This was achieved depending on heart rate, arterial blood pressure, and relative blood volume. The results showed that using FLC can reduce treatment time as well as stabilize the patient's condition (Vahid, Manouchehr, Mohammed, & Fatema, 2019, 37). To regulate conductivity by controlling pumping rates of the two concentrate components (acid and sodium bicarbonate), three controllers (PID, Linear Qauadratic Gausian (LQG), and Model Predictive Control (MPC)) were designed (Måns, 2016, 39). The results showed that LQG was the most suitable. A new Immune-LQI controller was designed for online regulation of dialysate conductivity (Jomana, & Sahar, 2022, 242), the new controller combines LQI and IC methods, IC gains were adjusted using FL and GA. For the purpose of comparison, a number of controllers (i.e., Proportional Integral Derivative (PID), LQI, LQI-PID) had been designed. The results showed that Immune-LQI controller was the best.

1.2 Research Gab and Motivation

There is a lack of investigations regarding control process of dialysate conductivity**.** The research conducted by Måns Fällman (Måns, 2016, 17), an LQG controller, a type of LQI, was designed, he take to account the delay time presented in the system, but the dialysate was prepared at two separate stages. The first relates to the acid pumping process and the second relates to the sodium bicarbonate process. This separation is different to what happens in reality, as the two concentrate components are pumped together at the same time and, hence, the conductivity is based on both.

The immune-LQI controller, that desigened to regulate the dialysate conductivity by simultaneous pumping of bicarbo controller when time dealy is precented, and to compare its response with PID, PID-Smith, and LQI**.**

1.3 Contribution and Paper Organization

Taking the importance of regulating dialysate conductivity in mind and due to the dialysate crucial role in the dialysis process, in this research the new Immune-LQI controller that combined the optimality of LQI, the accuracy and conversion speed of AIS, and the good adaptivity accomplished by FL and GA, was tested in the presence of time delay. The notable novelties of the Immune-LQI controller are specified as follows:

a) Improved the performance indices and regulating the conductivity faster and with minimal settling time compared with other controllers.

b) Regulating the conductivity with time delay (4.51 second for bicarbonate and 2.04 second for acid), which is consistent with what happens in the dialysis device in reality.

This paper is organized as follows: Section 2 introduces the mathematical model of the dialysis system with regard to conductivity with time delay, brief description of Smith predictor controller, LQI control method, Immune-LQI controller. Simulation results are presented and discussed in Section 3. The conclusion remarks on controller performance are presented in the last section.

2 .Materials and Methods

2.1 Conductivity Model

In this research, a mathematical model that describes the mechanism of preparing the dialysate in state space was adopted. This mathematical model has been evaluated, and its ability to accurately describe the process of dialysate preparation was verified by Måns Fällman (Måns, 2016, 15). It considers the preparation mechanism as a collection line (Figure 1). The process starts by adding treated (degasification, filtration, etc.) water (called RO-water), then a mixture of charges that are similar to those found in blood (called A-Concentrate) is added. The resulting mixture is pumped into the first chamber. Bicarbonate (called B-Concentrate) is, then, added and the resulting mixture is pumped into the second chamber. Finally, the conductivity is measured at the output of the second chamber. Each chamber is divided into two sections in order to reduce the effect of the disturbances resulting from the pumping action.

The well-known model describes the linear system in the state space as follows:

$$X^{\bullet} = AX + BU, Y = CX + DU \qquad (1)$$

where X is the system state vector, Y is the output vector, U is the input vector and A, B, C, D are state matrices.

The conductivity model used in our research contains four state variables that represent the conductivity in each chamber of the previously defined four chambers. The output of the model is the final conductivity, i.e., x_4 and the input vector U has two components: the pumping rate of A (Pu_a) and the pumping rate of B (Pu_b):

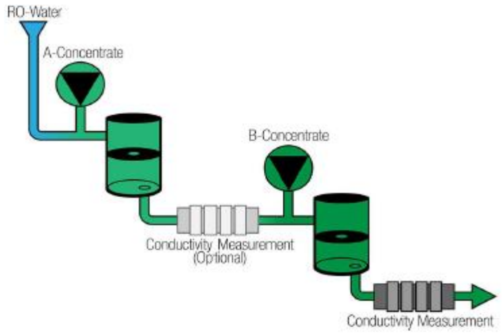

Figure (1) A schematic diagram of the dialysate preparation (Måns, 2016, 13).

$$U=\begin{bmatrix} Pu_a \\ Pu_b \end{bmatrix} \qquad (2)$$

The state matrices are (Måns, 2016, 15):

$$A=\begin{bmatrix} -\frac{Q}{V1} & 0 & 0 & 0 \\ \frac{Q}{V2} & -\frac{Q}{V2} & 0 & 0 \\ 0 & \frac{Q}{V3} & -\frac{Q}{V3} & 0 \\ 0 & 0 & \frac{Q}{V4} & -\frac{Q}{V4} \end{bmatrix},$$

$$B=\begin{bmatrix} \frac{Q}{V1}KA & 0 \\ 0 & 0 \\ 0 & \frac{Q}{V3}KB \\ 0 & 0 \end{bmatrix},$$

$$C=\begin{bmatrix}0 & 0 & 0 & 1\end{bmatrix}, D=\begin{bmatrix}0 & 0\end{bmatrix} \qquad (3)$$

The symbols used in the model are described in (Table 1).

Due to the physical distance between the concentrate injection points and conductivity measurements a time delay is present. This time delay is due to the flow of water and thereby also inversely proportional to the flow. The time delay is present due to both the tubing and the fact that the mixing chambers do not have a stirrer. Excluding the fact that the concentration in each chamber is non homogeneous. The time delay could be estimated by measuring the length L and area of the tubing A

Table (1) The parameters of the conductivity model

Symbol	**description**	**Unit**
K_A	Acid conductivity	ms/cm
K_B	Bicarbonate conductivity	ms/cm
Q	The main flow of distilled and sterilized water	L/Sec
V_1	The largest volume of the first container	L
V_2	The smallest size of the first container	L
V_3	The largest volume of the second container	L
V_4	The smallest size of the second container	L
Pu_a	Acid pump flow	mL/min
Pu_b	Flow of bicarbonate pump	mL/min

$$\tau=\frac{L.A}{Q} \qquad (4)$$

Where Q is the main flow rate and τ is the time delay from the measuring point. Time delay was estimated from the delayed step response on the actual system (Måns, 2016, 18). Time delay of A (τ_a) and of B (τ_b) are:

$$\tau=\begin{bmatrix}\tau_a \\ \tau_b\end{bmatrix}=\begin{bmatrix}4.51 \\ 2.04\end{bmatrix} \qquad (5)$$

2.2 Immune-LQI Controller

Immune-LQI controller (Jomana, & Sahar, 2022, 246), controller combines LQI and IC methods, IC gains were adjusted using FL and GA, (figure 2). The two control signals $U_A \, and \, U_B$ of Immune-LQI controller are obtained by multiplying LQI controller output $U_a \, and \, U_b$ (equation 6), by k_{m1}, k_{m2} the Immune gains (equation 8).

LQI control law is $U=-KZ$ (figure 3), where $Z=[X \int e]^T$, X is the system state vector, ∫e is the integral of the error which is the difference between the reference conductivity (r=14 mS/cm) and the output of the system (y) which represents the instantaneous conductivity during the preparation of the dialysate. The conductivity value should remain in the range of 12-16 mS/cm and it is usually maintained at 14 mS/cm in order to obtain a good dialysis process. K is the feedback control matrix:

$$K=\begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_{15} \\ k_{21} & k_{22} & k_{23} & k_{24} & k_{25} \end{bmatrix}$$

$$\begin{bmatrix}U_a \\ U_b\end{bmatrix}=\begin{bmatrix} k_{11}z_1+k_{12}z_2+k_{13}z_3+k_{14}z_4+k_{15}z_5 \\ k_{21}z_1+k_{22}z_2+k_{23}z_3+k_{24}z_4+k_{25}z_5 \end{bmatrix} (6)$$

The immune controller is described by Equation 7.

$$u(t)=k(1-\mu f)e(t) \quad (7)$$

where $k(1-\mu f)$ represents the immune controller gain (Xin-hua et al.,2014), and are described in equation (8)

$$km_1 = k_1(1-\mu_1 f_1)$$
$$km_2 = k_2(1-\mu_2 f_2) \quad (8)$$

The functions f_1 and f_2 were computed online using FL, and the parameters k_1, k_2, μ_1 and μ_2 were obtained using the GA.

2.3 Smith predector control

A classic Smith Predictor control is a feedback control strategy which has a minor loop. The plant model is considered in the minor feedback loop with a virtual time delay to compensate time delay in the system. The outer feedback loop contains an actual plant as well feedback delay induced in that. Using the available information of the plant model and time delay, controller is designed using Smith predictor (figure 4). To understand the working of Smith predictor let G(s) be the plant, C(s) be the controller, and τ is the total time delay. Then transfer function of the system $G_c(s)$ in closed loop without any time delay, and without Smith predictor is,

$$G_C(s)=\frac{G(s)C(s)}{1+G(s)C(s)} \quad (9)$$

Transfer function of the system $T_d(s)$ when the plant has a delay of τ second without Smith predictor is,

$$T_d(s)=\frac{G(s)C(s)e^{-\tau s}}{1+G(s)C(s)e^{-\tau s}} \quad (10)$$

This delay will make the controller act on the wrong way. if the controller takes the delay out of the plant, a stable system with desired output can be designed. Let $C_c(s)$ be the new controller to fulfill this requirement. Equation defining this new controller can be obtained as given,

$$\frac{C_c(s)G(s)e^{-\tau s}}{1+C_c(s)G(s)e^{-\tau s}}=\frac{G(s)C(s)e^{-\tau s}}{1+G(s)C(s)}$$

$$\Rightarrow C_c(s)=\frac{C(s)}{1+G(s)C(s)(1-e^{-\tau s})} \quad (11)$$

From the above derived equation (equation 11) for the control structure, Smith predictor well be as given in (Figure 4). In this $G_s(s)$ represents the predicted model of the plant.

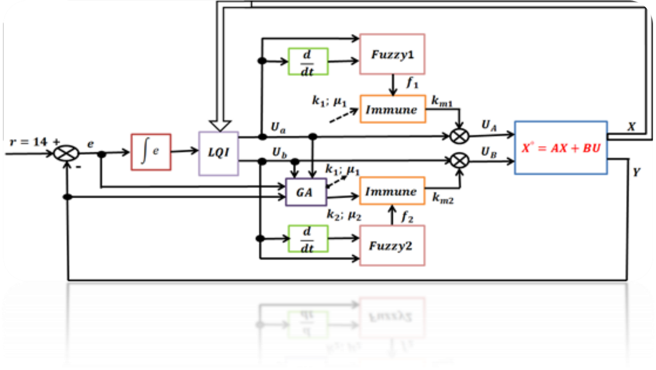

Figure (2) A block diagram of the closed loop Immune-LQI controlled system (Jomana, & Sahar, 2022, 246).

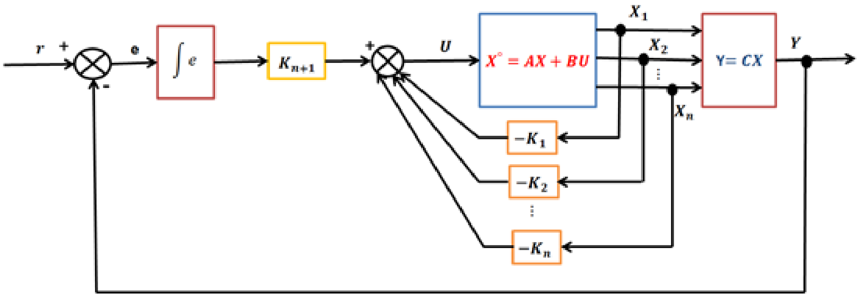

Figure (3) A block diagram of the LQI method (Jomana, & Sahar, 2022, 255).

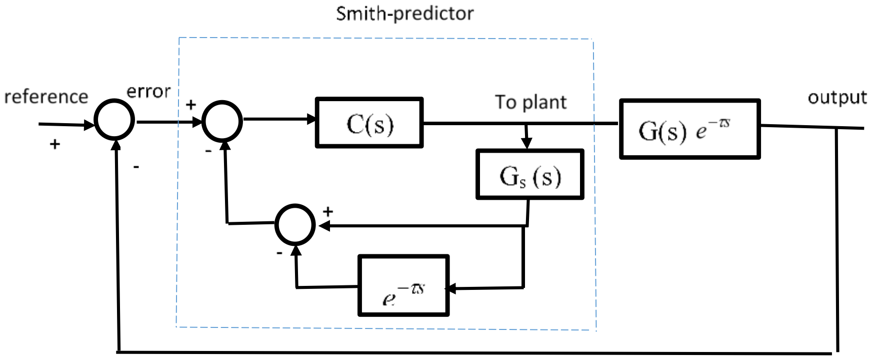

Figure (4) Smith predictor in closed loop

One point to be noted in this scenario that efficiency of a Smith predictor depends on the accuracy of the model used in the controller part to represent the plant (Shubhasree, & Vijay, 2015, 2728).

3 .Results and Discussion

The plant, PID, LQI, PID-Smith and Immune-LQI controllers were modeled and simulated using Matlab-Simulation Tool. The responses of the closed loop when using all controller are shown in (Figure 5), and the control signals U_A (Acid pumping rate) and U_B (Bicarbonate pumping rate) from LQI, PID-Smith, and Immune-LQI controllers are shown in Figure 6 & figure 7 respectively. The closed loop response specifications (Rise time, Overshoot%, and Settling time) obtained from all designed controllers are shown in (Table 2).

3.1 PID Controller

The control signal provided by the standard PID is given by Equation 12

$$U_{PID}(t) = k_p(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt} \quad (12)$$

where, k_p, T_i, and T_d are the controller parameters that represent the proportional gain, integration time, and differential time respectively.

In this research, a PID controller was designed using Matlab PID controller tuning tool. The simulated system response in the closed loop is not good with a large overshoot, and setlling time (Table 2), and the conductivity does not reach the set point (figure 5). However, the two signals U_A and U_B have extremely large initial value.

3.2 LQI Controller

The LQI controller was designed as in (Jomana, & Sahar, 2022, 245). The closed loop response resulting from the LQI controller (Figure 5) was slow and had relatively large overshoot (Table 2). The resulting control signals U_A and U_B are within the permissible limits, but have initial delay time (Figure 6, figure 7).

3.3 PID-Smith Controller

Smith predictor with first orded filter was added to the previously designed PID. The closed loop response has no overshoot (figure 5), however, the rise time and sitlling time were high (Table 3). The resulting control signals U_A and U_B are good, but they do not start at zero initial value (Figure 6, figure 7).

3.4 Immune-LQI Controller

Immune-LQI was designed as in (Jomana, & Sahar, 2022, 246). The Immune-LQI controller improved the response (Figure 5), and the control signals (Figure 6, Figure 7) using all controller are shown in (Figure 5), and the control signals U_A were good**.** The conductivity regulation was better when using Immune-LQI controller than that when LQI and PID-Smith were used (Figure 5). The response was faster and with less overshoot (Table 2).

Table (2) The closed Loop Response specifications of all designed controllers

controller	Rise Time	Over shoot%	Settling Time
Immune- LQI	11.7696	1.1231	20.4374
LQI	11.9741	5.0591	36.1417
PID-smith	17.2782	0	31.6257
PID	14.2870	17.6629	58.7584

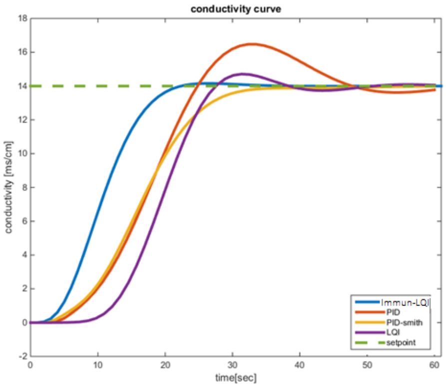

Figure (5) The closed loop response using PID, PID-Smith, LQI , and Immune- LQI controller.

Immune-LQI controller has provided better response specifications when compared with the LQI controller (Table 2). The percentage of improvement was 1.70 % in rise time, 77.80 % in overshoot, and 43.47 % in settling time.

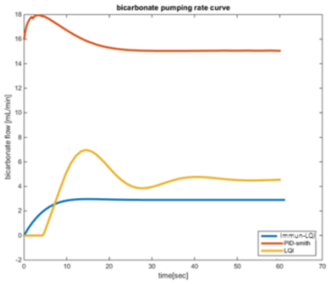

Figure (6) The acid pumping rate (UA) using PID-Smith, LQI, and Immune-LQI controllers

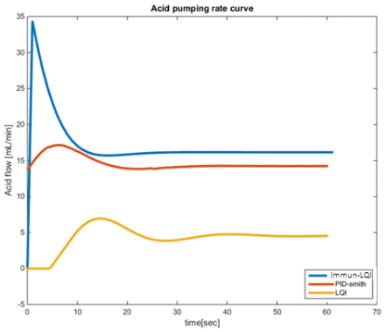

Figure (7) The bicarbonate pumping rate (UB) using PID-Smith, LQI, and Immune-LQI controllers

4 .Conclusions

In this work the immune-LQI controller that was designed by Jomana & sahar (Jomana, & Sahar, 2022, 245) was tested to regulate dialysate conductivity in the presence of time delay. Three intelligent techniques (AIS, FL, and GA) were used to improve LQI method. The following conclusions can be drawn from the presented work:

1) The immune-LQI controller succeeded in regulating global conductivity of dialysate with time delay without the need for retuning the parameters k_1, k_2, μ_1 *and* μ_2 , and the response was fast and accurate,

2) The immune-LQI controller was superior to PID, LQI, and PID-Smith as it provided faster rise time, and settling time.

3) Fuzzy logic succeeded in online tuning the functions f_1 and f_2 to compensate time delay in the system.

As a future work, the Immune-LQI controller can be tested on systems with uncertainty and time-variant model or nonlinear models.

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