DOI 10.2478/ama-2021-0026 acta mechanica et automatica, vol.15 no.4 (2021)

DESIGN OF DECOUPLED PI CONTROLLERS FOR TWO-INPUT TWO-OUTPUT NETWORKED CONTROL SYSTEMS WITH INTRINSIC AND NETWORK-INDUCED TIME DELAYS

Ould Mohamed MOHAMED VALL*

*Department of Computer Engineering and Networks, College of Computer and Information Sciences, Jouf University, Sakaka 72388, Kingdom of Saudi Arabia

medvall@ju.edu.sa

received 21 May 2021, revised 22 July 2021, accepted 27 July 2021

Abstract: Proportional integral controller design for two-input two-output (TITO) networked control systems (NCSs) with intrinsic and network-induced time delays is studied in this paper. The TITO NCS consists of two delayed sub-systems coupled in a 1-1/2-2 pairing mode. In order to simplify the controller design, a decoupling method is first applied to obtain a decoupled system. Then, the controllers are designed based on the transfer function matrix of the obtained decoupled system and using the boundary locus method for determining the stability region and the well-known Mikhailov criterion for the stability test. A comparative analysis of the designed controllers and other controllers proposed in previous literature works is thereafter carried out. To demonstrate the validity and efficacy of the proposed method and to show that it achieves better results than other methods proposed in earlier literature works, the implementation in simulation of Wood–Berry distillation column model (methanol–water separation), a well-known benchmark for TITO systems, is carried out.

Key words: pproportional integral controller, two-input two-output (TITO) systems, networked control systems, stability region boundary locus ,Wood–Berry distillation column model, time delay, Mikhailov criterion

1. INTRODUCTION

Several processes in industry, such as heat exchange, distillation process, and chemical reactions and so on, require the control of two or more output variables. In turn, the control of output variables requires the manipulation of two or more input variables(Ajayi and Oboh, 2012); such systems are known as multi-input multi-output (MIMO) systems. The most common form of MIMO system is a two-input two-output (TITO) system (Zhuang and Atherton, 1993). The problem of control of TITO systems has attracted the attention of many researchers (see: Hamdy et al.,2018;Baruah et al.,2018;Heris et al.,2019; Li et al.,2019; Ustoglu et al., 2016; Qian et al.,2017; Vargas et al.,2013; Maghade and Patre,2013; and references therein). In a TITO system, the interaction between loops makes analysis and design of the controller a very difficult task, and this task becomes more difficult and complex when the system to be controlled involves intrinsic time delays. Therefore, many of the methods dealing with TITO system control proposed in the literature have been interested in reducing the interaction loops by using a decoupling technique in a way that a change in each of the two loops does not affect the other (see: Tanaka et al., 2015; Hazarika and Chidambaram, 2014;Mahapatro and Subudhi, 2020;and references therein). Other research works existing in the literature have been interested on the control of TITO systems with time delays (see: Jeng and Jian, 2017; Jin et al., 2016; Liu et al., 2006; Khandekar and Patre, 2017; Hajare et al., 2017; and references therein).

On the other hand, networked control systems (NCSs), which are systems in which a band-limited network is used by the plant, sensor and controller to share control signals and information among them, have many advantages in terms of reduction of wiring, lower maintenance cost, increased system agility, ease of information sharing and so on (Hong et al., 2017), compared to traditional point to point control systems in which the components and devices are connected via wires. Due to their advantages, NCSs have found application in many fields, such as process control engineering (Sun and El-Farra, 2012; ElFarra and Mhaskar, 2008), teleportation (Liu, 2015), vehicle industry(Jin et al., 2014), power systems (Park, 2015; Yao et al., 2015), transportation systems (Park et al., 2014; Barrero et al., 2014) and so on. One of the major factors that make the control of NCSs a very challenging problem is the presence of inevitable time delay induced by the transmission of control signals and information over a network that may be used by others devices and systems. This justifies why many of research papers related to the control of NCSs with network-induced time delay have been published over the past few decades(see: Li et al., 2016; Zhang et al., 2006; Huang and Nguang, 2009; Liu and Liu, 2020; Mohamed Vall, 2020b; Pang et al., 2016; Mohamed Vall, 2020a; Elahi and Alfi, 2017). However, to the author's best knowledge, in the literature, there are few research works related to the control of TITO NCSs with intrinsic and network-induced time delay (Wang et al., 2000; Sharma and Padhy, 2017; Astrom et al., 2002). Moreover, most of the approaches dealing with this problem are very complex and very time consuming or even not applicable in real-world control problems.

Motivated by the above discussion, we propose, in this paper, a simple and practicable method for the control of TITO NCSs with intrinsic and network-induced time delays. The proposed method comprises two steps: first, a decoupler for the TITO NCS to be controlled is calculated; second, two decoupled proportional integral (PI) controllers for the augmented system, consisting of the obtained decoupler and the TITO NCS to be controlled, are separately designed using the boundary locus method for determining the stability region (Siljak, 1966; Chao and Han,1998; Wang,2011) and the Mikhailov criterion for stability test as presented by Barker (1979) and Mikhailov (1938).

In summary, the main objectives of this work are as follows:

- To design decoupled PI controllers that garantee robustness and good set point tracking, as well as good disturbance rejection, for TITO NCSs with intrinsic and network-induced time delays.
- To carry out a comparative analysis of the designed controllers with other controllers proposed in previous literature works (Hajare and Patre, 2015) and show the superiority of the method proposed in this paper.

The remainder of the paper is organized as follows. In Section 2, the structure of TITO NCSs with network-induced time delays is presented. The proposed method for the control of TITO NCSs with intrinsic and network-induced time delays is presented in Section 3. In Section 4, a simulation example is given to show the validity and effectiveness of the proposed method. Conclusions are given in Section 5.

2. PROBLEM FORMULATION

As mentioned above, this research work deals with the control of TITO-NCSs with intrinsic and network-induced time delays. Fig. 1 shows the structure of a TITO-NCS with network-induced delays. As one can notice in Fig. 1, there are three time delays affecting each sub-system of the whole system, which are as follows:

- delay sensor-to-controller $\tau^{(s_i c_i)}$ $(i = 1{,}2)$
- delay controller-to-actuator $\tau^{(c_i a_i)}$ $(i = 1{,}2)$
- controller computation delay $\tau^{(c_i)}$ $(i = 1{,}2)$

Although controller computation time delay always exists, it is usually small compared to network-induced time delays and can be neglected.

In this paper, for simplicity and without losing generality, we neglect the controller computation time delay and assume that the network-induced delays affecting each sub-system are lumped together as one control time delay τ_i given by the following expression:

$$\tau_i = \tau^{(s_i c_i)} + \tau^{(c_i a_i)} \ (i = 1{,}2) \qquad (1)$$

'Depending on the medium access control (MAC) protocol of the control network, network-induced delay can be constant, time varying, or even random' (Zhang et al., 2001). Here, we are considering constant network-induced delay, 'which can be achieved by using an appropriate network protocol' (Zhang et al., 2001), and our objective is to design PI controllers to compensate for these time delays. The method proposed contains two steps. In the first step, the system is decoupled in order to simplify the controllers' design and to obtain controllers that can guarantee that changes in the reference signal of a sub-system do not affect the output of the other and vice versa. In the second step, for the decoupled system, PI controllers are designed utilizing the stability boundary locus method.

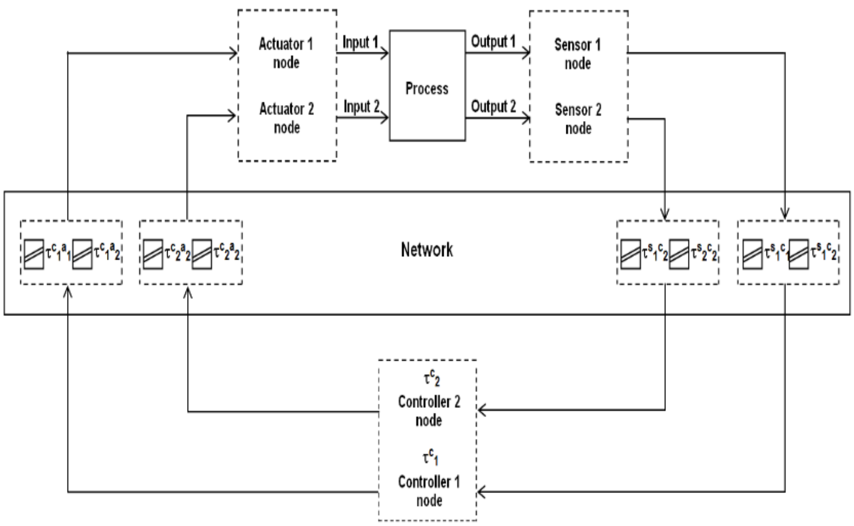

Fig. 1. Structure of TITO-NCS with Network-Induced Time Delays (NCS – networked control system; TITO – two-input two-output)

3. PROPOSED METHOD

3.1. Decoupling of the TITO system

Consider the closed-loop TITO system shown in Fig.2, where r_1 and r_2 are reference signals; $C_1(s)$ and $C_2(s)$ are two controllers to be designed; $G_{11}(s)$, $G_{12}(s)$, $G_{21}(s)$ and $G_{22}(s)$ are the transfer functions of the system; τ_1, τ_2, τ_3 and τ_4 are the time delays; and y_1 and y_2 are the outputs of the system.

The cross-interaction between the input–output pairs makes the design of the controllers very hard and may – in many control problems – lead to undesirable effects. Therefore, to simplify the controller design and eliminate the effects of loop interactions as much as possible, the following decoupling method is used.

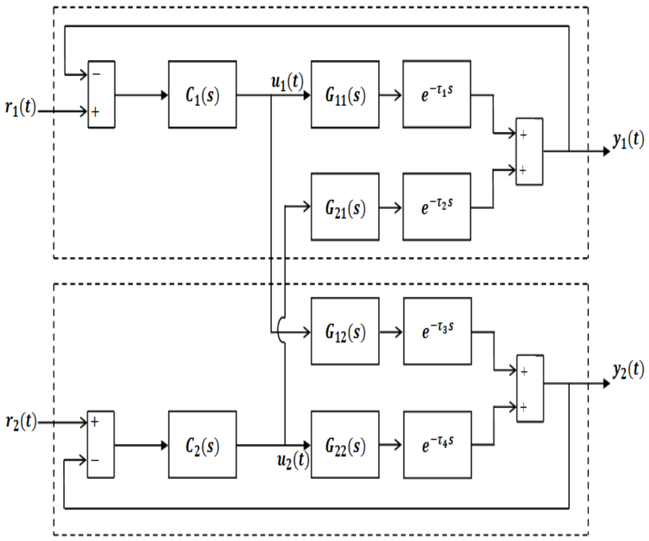

Fig. 2. 1-1/2-2 closed-loop TITO system with time delays (TITO – two-input two-output)

The transfer function matrix of the system shown in Fig.2 is

$$G(s) = \begin{bmatrix} G_{11}(s)e^{-\tau_1 s} & G_{12}(s)e^{-\tau_2 s} \\ G_{21}(s)e^{-\tau_3 s} & G_{22}(s)e^{-\tau_4 s} \end{bmatrix}. \quad (2)$$

Let the transfer function matrix of the decoupler be

$$D(s) = \begin{bmatrix} D_{11}(s) & D_{12}(s) \\ D_{21}(s) & D_{22}(s) \end{bmatrix}. \quad (3)$$

The matrix D(s) should be chosen so that the matrix

$$P(s) = G(s)D(s) \quad (4)$$

is diagonal.

As mentioned above, many decoupling methods for TITO systems have been proposed in the literature. In this paper, we propose to use the decoupler whose transfer function matrix is given in previous studies (Koo et al., 2017; de A. Aguiar and Barros, 2020; Naik et al., 2020).

$$D(s) = \begin{bmatrix} 1 & \frac{-G_{12}(s)e^{-(\tau_2-\tau_1)s}}{G_{11}(s)} \\ \frac{-G_{21}(s)e^{-(\tau_3-\tau_4)s}}{G_{22}(s)} & 1 \end{bmatrix} \quad (5)$$

Fig. 3 shows the structure of a TITO system with the proposed decoupler, where $W_{12}(s) = \frac{-G_{12}(s)e^{-(\tau_2-\tau_1)s}}{G_{11}(s)}$ and $W_{21}(s) = \frac{-G_{21}(s)e^{-(\tau_3-\tau_4)s}}{G_{22}(s)}$. Notice that the decoupler is not causal if $\tau_2 - \tau_1 < 0$ or/and $\tau_3 - \tau_4 < 0$ (Wanget al., 2000). However, even if the decoupler is not causal, one can introduce simple modifications in its structure so that it becomes causal without affecting the decoupled system's structure (Sharma and Padhy, 2017).

Inserting Eqs. (2) and (5) in Eq. (4) gives the transfer function matrix of the decoupled system as

$$P(s) = \begin{bmatrix} P_{11}(s) & 0 \\ 0 & P_{22}(s) \end{bmatrix}, \quad (6)$$

where $P_{11}(s) = G_{11}(s)e^{-\tau_1 s} - \frac{G_{12}(s)e^{-\tau_2 s}G_{21}(s)e^{-(\tau_3-\tau_4)s}}{G_{22}(s)}$ and $P_{22}(s) = G_{22}(s)e^{-\tau_4 s} - \frac{G_{21}(s)e^{-\tau_3 s}G_{12}(s)e^{-(\tau_2-\tau_1)s}}{G_{11}(s)}$.

Based on the above decoupled system, PI controllers can be designed independently using the stability locus method, as presented in the following sub-sections.

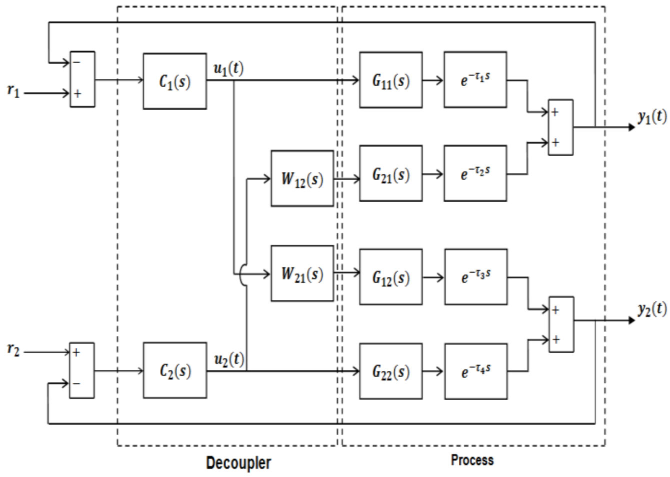

Fig. 3. Decoupling structure

3.2. Calculation of decoupled PI controllers

Suppose that network-induced time delays affect the decoupled system whose transfer function matrix is defined in Eq. (6). The closed-loop transfer functions of the sub-systems constituting the whole system are, thus, given by the following expressions:

$$T_1(s) = \frac{C_1(s)\{G_M(s)e^{(-\tau_1 s)} - G_D(s)e^{-(\tau_2+\tau_3-\tau_4)s}\}e^{-\tau_{N_i 11}s}}{G_{22}(s)+C_1(s)\{G_M(s)e^{(-\tau_1 s)} - G_D(s)e^{-(\tau_2+\tau_3-\tau_4)s}\}e^{-\tau_{N_i 11}s}} \quad (7)$$

$$T_2(s) = \frac{C_2(s)\{G_M(s)e^{(-\tau_4 s)} - G_D(s)e^{-(\tau_3+\tau_2-\tau_1)s}\}e^{-\tau_{N_i 22}s}}{G_{11}(s)+C_2(s)\{G_M(s)e^{(-\tau_4 s)} - G_D(s)e^{-(\tau_3+\tau_2-\tau_1)s}\}e^{-\tau_{N_i 22}s}} \quad (8)$$

where $G_M(s) = G_{11}(s)G_{22}(s)$, $G_D(s) = G_{12}(s)G_{21}(s)$, $C_1(s)$ and $C_2(s)$ are the two PI controllers to be designed and $\tau_{N_i 11}$ and $\tau_{N_i 22}$ are the network-induced time delays that affect Loops 1–1 and 2–2, respectively.

To determine the parameters of the controllers, the stability region locus method is used as follows.

3.2.1. Determination of the parameters of $C_1(s)$

Let:

$$C_1(s) = \alpha_1 + \frac{\beta_1}{s}; \quad (9)$$

$$\tau_{11} = \tau_{N_i 11} + \tau_1; \quad (10)$$

$$\tau_{12} = \tau_{N_i 11} + (\tau_2 + \tau_3 - \tau_4). \quad (11)$$

By inserting Eqs. (9), (10) and (11) in Eq. (7), we can express the transfer function $T_1(s)$ as follows:

$$T_1(s) = \frac{\left(\alpha_1 + \frac{\beta_1}{s}\right)\{G_M(s)e^{-\tau_{11}s} - G_D(s)e^{-\tau_{12}s}\}}{G_{22}(s) + \left(\alpha_1 + \frac{\beta_1}{s}\right)\{G_M(s)e^{-\tau_{11}s} - G_D(s)e^{-\tau_{12}s}\}}. \quad (12)$$

By substituting $s = j\omega$, decomposition of the numerators and denominators of $G_M(s)$, $G_D(s)$ and $G_{22}(s)$ into their even and odd parts and using Euler's identity, one can express the system characteristic equation as follows:

$$R_{Q_1}(\omega, \alpha_1, \beta_1) + jI_{Q_1}(\omega, \alpha_1, \beta_1) = 0. \quad (13)$$

where R_{Q_1} and I_{Q_1} are two functions in ω, α_1, β_1 with constant real coefficients.

Dropping ω for ease and equating $R_{Q_1}(\omega, \alpha_1, \beta_1)$ and $I_{Q_1}(\omega, \alpha_1, \beta_1)$ to zero result in the following system of equations:

$$\begin{cases} M_{11}\alpha_1 + M_{12}\beta_1 = X_1 \\ M_{21}\alpha_1 + M_{22}\beta_1 = X_2 \end{cases} \quad (14)$$

where M_{11}, M_{12}, M_{21}, M_{22}, X_1 and X_2 are functions in ω with constant real coefficients.

Solving the equation system (14) for α_1 and β_1 gives

$$\begin{cases} \alpha_1 = \frac{N_{\alpha_1}}{D_{\alpha_1}} \\ \beta_1 = \frac{N_{\beta_1}}{D_{\beta_1}} \end{cases}. \quad (15)$$

where N_{α_1}, D_{α_1}, N_{β_1} and D_{β_1} are functions in ω with constant real coefficients.

Plotting the dependency relation between α_1 and β_1 and the axis $\beta_1 = 0$ on the (α_1, β_1)-plane splits the plane into two regions. One of these regions is a stability region of the system. To determine which region is a stability region, the Mikhailov criterion for stability test is used. Next, once the stability region is determined, the values of the parameters of $C_1(s)$ that stabilise the system can be thus determined by choosing a point within the stability region(Chao and Han, 1998).

3.2.2. Determination of the parameters of $C_2(s)$

The parameters of $C_2(s)$ can be determined in a way similar to that for $C_1(s)$.

Let:

$$C_2(s) = \alpha_2 + \frac{\beta_2}{s} \ ; \quad (16)$$

$$\tau_{22} = \tau_{N_i22} + \tau_4 \ ; \quad (17)$$

$$\tau_{21} = \tau_{N_i22} + (\tau_3 + \tau_2 - \tau_1). \quad (18)$$

By inserting Eqs. (16), (17) and (18) in Eq. (8), we can express the transfer function $T_2(s)$ as follows:

$$T_2(s) = \frac{\left(\alpha_2 + \frac{\beta_2}{s}\right)\{G_M(s)e^{-\tau_{22}s} - G_D(s)e^{-\tau_{21}s}\}}{G_{11}(s) + \left(\alpha_2 + \frac{\beta_2}{s}\right)\{G_M(s)e^{-\tau_{22}s} - G_D(s)e^{-\tau_{21}s}\}}. \quad (19)$$

By substituting $s = j\omega$, decomposition of the numerators and denominators of $G_M(s)$, $G_D(s)$ and $G_{11}(s)$ into their even and odd parts and using Euler's identity, one can express the system characteristic equation as follows:

$$R_{Q_2}(\omega, \alpha_2, \beta_2) + jI_{Q_2}(\omega, \alpha_2, \beta_2) = 0. \quad (20)$$

where R_{Q_2} and I_{Q_2} are two functions in ω, α_2, β_2 with constant real coefficients.

Dropping ω for ease and equating $R_{Q_2}(\omega, \alpha_2, \beta_2)$ and $I_{Q_2}(\omega, \alpha_2, \beta_2)$ to zero result in the following equation system:

$$\begin{cases} H_{11}\alpha_2 + H_{12}\beta_2 = Z_1 \\ H_{21}\alpha_2 + H_{22}\beta_2 = Z_2 \end{cases}. \quad (21)$$

where H_{11}, H_{12}, H_{21}, H_{22}, Z_1 and Z_2 are functions in ω with constant real coefficients.

Solving the equation system (21) for α_2 and β_2 gives

$$\begin{cases} \alpha_2 = \frac{N_{\alpha_2}}{D_{\alpha_2}} \\ \beta_2 = \frac{N_{\beta_2}}{D_{\beta_2}} \end{cases} \quad (22)$$

where N_{α_2}, D_{α_2}, N_{β_2} and D_{β_2} are functions in ω with constant real coefficients.

Plotting the dependency relation between α_2 and β_2; and the axis $\beta_2 = 0$ on the (α_2, β_2)-plane splits the plane into two regions. One of them is a stability region of the system. To determine which region is a stability region, the Mikhailov criterion for stability test is used. Then, the values of the parameters of $C_2(s)$ that stabilise the system can be thus determined by choosing a point within the stability region (Chao and Han, 1998).

4. SIMULATION EXAMPLE

In this section, a simulation example is given to show the validity and efficacy of the proposed method.

The simulation is carried out in Simulink and TrueTime in the environment of MatLab. The network communication mode is carrier-sense multiple access with collision detection(CSMA/CD; Ethernet), the transmission rate is 80 Kbit/s and the network-induced time delays that affect Loops 1–1 and 2–2 are $\tau_{N_i11} = 0.13$ secand $\tau_{N_i22} = 0.17$ sec, respectively. The sampling period is 0.02 sec. The process to be controlled is a Wood–Berry distillation column model (methanol–water separation), which has the following transfer function matrix (Astrom et al., 2002):

$$G(s) = \begin{bmatrix} \frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{-3s}}{21.0s+1} \\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \quad (23)$$

The transfer function matrix of the decoupler calculated according to Eq. (5) is

$$D(s) = \begin{bmatrix} 1 & \frac{1.48\,(16.7s+1)e^{-2s}}{21.0s+1} \\ \frac{0.34\,(14.4s+1)e^{-4s}}{10.9s+1} & 1 \end{bmatrix}. \quad (24)$$

The transfer function matrix of the decoupled system calculated according to Eq. (6) is

$$P(s) = \begin{bmatrix} P_{11}(s) & 0 \\ 0 & P_{22}(s) \end{bmatrix}, \quad (25)$$

where $P_{11}(s) = \frac{12.8e^{-s}}{16.7s+1} - \frac{6.43\,(14.4s+1)e^{-7s}}{(21.0s+1)(10.9s+1)}$ and $P_{22}(s) = \frac{-19.4e^{-3s}}{14.4s+1} + \frac{9.77\,(16.7s+1)e^{-9s}}{(10.9s+1)(21.0s+1)}$.

Consequently, based on the decoupled system in Eq. (25) and taking into account that Loops 1–1 and 2–2 are affected by the network-induced time delays $\tau_{N_i11} = 0.13$ sec and $\tau_{N_i22} = 0.17$ sec, respectively, and using Eqs (7) and (8), the closed-loop transfer functions of the sub-systems are obtained as follows:

$$T_1(s) = \frac{C_1(s)\left(A(s)e^{-s}+B(s)e^{-7s}\right)e^{-0.13s}}{\frac{-19.4}{14.4s+1}+C_1(s)\left(A(s)e^{-s}+B(s)e^{-7s}\right)e^{-0.13s}}; \quad (26)$$

$$T_2(s) = \frac{C_2(s)\left(A(s)e^{-3s}+B(s)e^{-9s}\right)e^{-0.17s}}{\frac{12.8}{16.7s+1}+C_2(s)\left(A(s)e^{-3s}+B(s)e^{-9s}\right)e^{-0.17s}}; \quad (27)$$

where $A(s) = \frac{-248.32}{(16.7s+1)(14.4s+1)}$, $B(s) = \frac{124.74}{(21.0s+1)(10.9s+1)}$, and $C_1(s) = \alpha_1 + \frac{\beta_1}{s}$ and $C_2(s) = \alpha_2 + \frac{\beta_2}{s}$ are the two PI controllers.

Let us determine the parameters of $C_1(s)$ and $C_2(s)$ based on the theory presented in Sub-section 3.2 of this paper.

By substituting Eq. (26) into Eq. (12), solving Eqs (13)–(14) for α_1 and β_1, and plotting the dependency between the obtained values of α_1 and β_1 and the axis $\beta_1 = 0$ on the (α_1, β_1)-plane, we obtain Fig. 4.

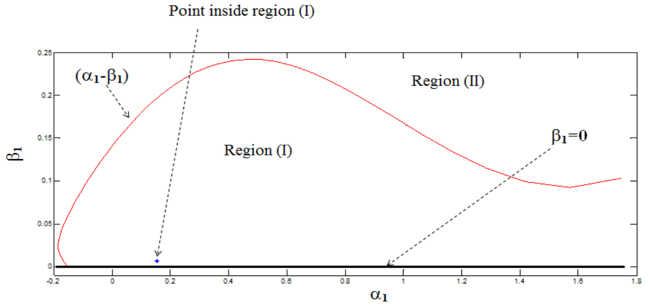

Fig. 4. α_1 versus β_1

As one can see from Fig. 4, the curve (α_1,β_1) and the axis $\beta_1 = 0$ split the (α_1, β_1)-plane into two regions: Region (I) and Region (II).

Now, let us choose the point (0.1532,0.0067) of Region (I) in Fig.4 and check whether the system in Eq. (26) is stable when one chooses the parameters of the controller $C_1(s)$ as $\alpha_1 = 0.1532$ and $\beta_1 = 0.0067$. To check the stability, the Mikhailov criterion for stability test can be used as mentioned earlier in this paper.

By determining the polynomial function $Q_1(j\omega)$ for the transfer function $T_1(s)$ given in Eq. (26) , $\alpha_1 = 0.1532$ and $\beta_1 = 0.0067$, as explained by Barker (1979) and Mikhailov (1938), we obtain the Mikhailov curve shown in Fig. 5. As one can see from Fig. 5, the system is stable since the Mikhailov stability criterion is fulfilled, as also reported by Barker (1979) and Mikhailov (1938).

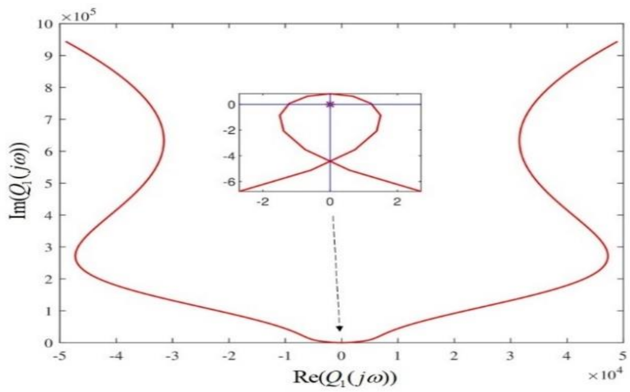

Fig. 5. Loop 1-1 Mikhailov curve for $\alpha_1 = 0.1532$, $\beta_1 = 0.0067$

In a similar way, one can determine the parameters of the controller $C_2(s)$ as those of the controller $C_1(s)$ were determined. By substituting (27) into (19), solving the equations (20)-(21) for α_2 and β_2, and plotting the dependency between the obtained values of α_2 and β_2 and the axis $\beta_2 = 0$ on the (α_2, β_2)- plan, we obtain Fig. 6.

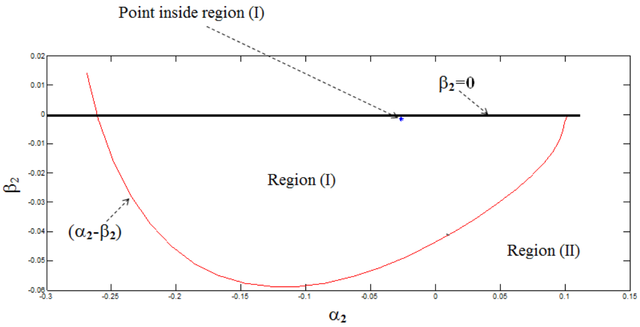

Fig. 6. α_2 versus β_2

As one can see, from Fig. 6., the curve (α_2,β_2) and the axis $\beta_2 = 0$ split the (α_2, β_2)- plan into two regions: Region (I) and Region (II). To determine which of them is a stability region of the system, let's choose the point (-0.0266,-0.0015) of the region (I) and use Mikhailov stability criterion to check whether the system is stable when one chooses the parameters of the controller $C_2(s)$ as $\alpha_2 = -0.0266, \beta_2 = -0.0015$.

By determining the polynomial function $Q_2(j\omega)$ for the transfer function $T_2(s)$ given in (27) , $\alpha_2 = -0.0266, \beta_2 = -0.0015$, as explained in in (Barker, 1979) and (Mikhailov, 1938), we obtain the Mikhailov curve shown in Fig. 7. As one can see, from Fig. 7., the Mikhailov stability criterion holds, as also reported in (Barker, 1979) and (Mikhailov, 1938), the system is, therefore stable.

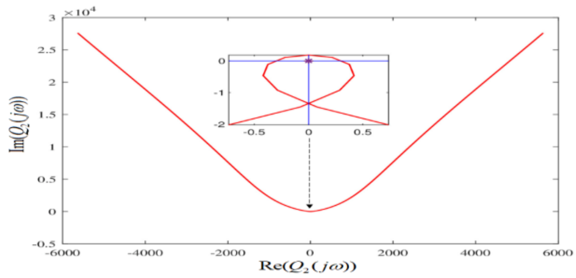

Fig. 7. Loop 2-2 Mikhailov curve for $\alpha_2 = -0.0266, \beta_2 = -0.0015$

To verify the validity and efficacy of the proposed method, the obtained PI controllers: $C_1(s) = 0.1532 + \frac{0.0067}{s}$, $C_2(s) = -0.0266 - \frac{0.0015}{s}$ are applied to the both loops of the decoupled system. In the simulation, a step change in the reference signal r_1 is made at $t = 50$ secand a step change in the reference signal r_2 is made at $t = 150$ sec, respectively. Furthermore, to show the disturbance rejection performance of the obtained controllers, steps disturbance $d_1(t) = 0.1$ at $t = 450$ sec and $d_2(t) = 9$ at $t = 450$ sec are introduced to loop 1 and loop 2, respectively. The simulation results of both set-point tracking and disturbance rejection are shown in Fig. 8 and Fig. 9, respectively. The performance metrics: Settling time (Ts) , Integral Absolute Error (IAE), RMS tracking error (RMSE) and Total Variance (TV) are reported in Tab. 1.

DOI 10.2478/ama-2021-0026

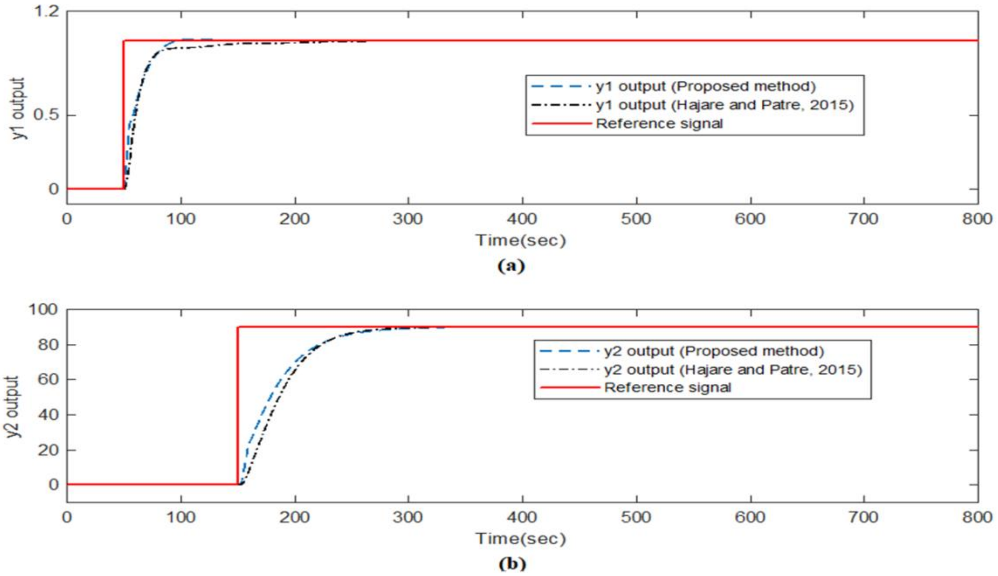

Fig. 8. System outputs: **(a)** Reference signal (red solid line), y_1 (loop1) output (blue dashed line) obtained using the proposed method and y_1 (loop1) output (black dot-dash lines) obtained using the method proposed in (Hajare and Patre, 2015) **(b)** refence signal (red solid line), y_2 (loop2) output (blue dashed line) obtained using the proposed method and y_2 (loop2) output (black dot-dash lines) obtained using the method proposed in (Hajare and Patre, 2015)

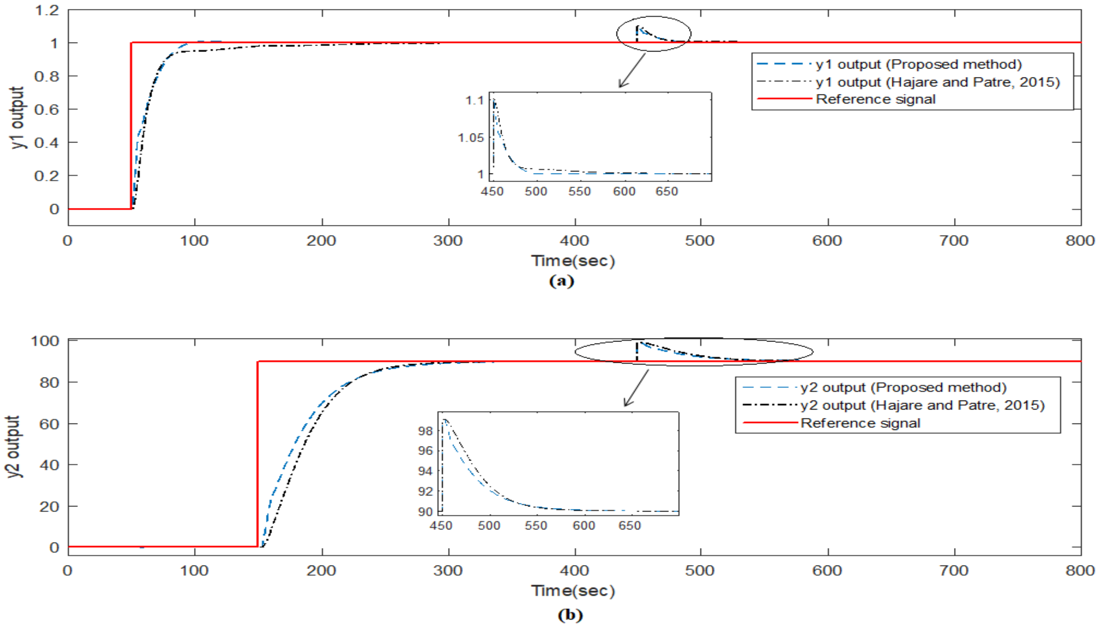

Fig. 9. System outputs with disturbance rejection: **(a)** Reference signal (red solid line), y_1 (loop1) output (blue dashed line) obtained using the proposed method and y_1 (loop1) output (black dot-dash lines) obtained using the method proposed in (Hajare and Patre, 2015) **(b)** refence signal (red solid line), y_2 (loop2) output (blue dashed line) obtained using the proposed method and y_2 (loop2) output (black dot-dash lines) obtained using the method proposed in (Hajare and Patre, 2015)

Tab.1. Performance metrics

Controllers	Input-output	T_s (sec)	RMSE	IAE	TV
Proposed decoupled PI controllers	u_1-y_1 u_2-y_2	41 130	0.09 13.81	12.1131091	0.008174.6
(PID) controllers proposed in Hajare and Patre (2015)	u_1-y_1 u_2-y_2	103.2 119.2	0.12 16.1	17.553586	0.011236.7

IAE – integral absolute error; PI – proportional–integral; PID – proportional–integral–derivative;
RMSE – root mean square tracking error; TV – total variance.

From Fig. 8, it can be seen that the proposed controllers guarantee excellent tracking of the system outputs to the set points and maintain the system stable in both loops. It can be also noticed that the change in the set point of Loop 1 does not affect the response output in the Loop 2 and vice-versa, the change in the set point of the Loop 2 does not affect the response output in the Loop 1. Additionally, the simulation results in Fig. 9 show that the obtained controllers also offer excellent disturbance rejection performance. Moreover, it is evident from the simulation results (shown in Figs. 8 and 9) and the performance metrics (reported in Tab. 1) that the proposed controllers achieve better results than the proportional–integral–derivative (PID) controllers proposed in a previous paper (Hajare and Patre, 2015). For example, it can be seen from Fig. 9 that the proposed controllers take less time and control action to achieve the steady state and zero steady-state error in case of load disturbance.

5. CONCLUSIONS

This paper proposes an approach for the design of decoupled PI controllers for TITO NCSs with intrinsic and network-induced time delays. A decoupler that can reduce interaction between loops and simplify the design of controllers is defined. Moreover, a method based on stability region locus and the Mikhailov criterion for stability test is proposed to determine the parameters of PI controllers to control a TITO NCS with intrinsic and network-induced time delays. A comparative analysis of the designed controllers with other controllers proposed in previous research works has been carried out. The validity and efficacy of the proposed approach are shown through a simulation example, in which the well-known benchmark for TITO systems – the Wood–Berry distillation column model (methanol–water separation) – is built in Simulink and TrueTime in the environment of MatLab; network-induced time delays are included and PI controllers are designed based on the approach proposed. The simulation results show that the designed PI controllers guarantee very good tracking of the system outputs to the set points and maintain the system stable in both loops with excellent disturbance rejection performance. Moreover, the simulation results show that the proposed method achieves better results than other methods proposed in earlier literature works.

REFERENCES

1. **Ajayi T., Oboh I.** (2012), Determination Of Control Pairing for Higher Order Multi-Variable Systems by the Use of Multiple Ratios. *Int, J, Eng&ScientificRes*, 3(3),1–5.
2. **Astrom K.J., Johansson K.H., Wang, Q.G.** (2002), Design of Decoupled PI Controllers for Two-By-Two Systems. In *IEE Proceedings-Control Theory and Applications*, 149, 74–81.
3. **Barker L.K.** (1979), *Mikhailov Stability Criterion for Time-Delayed Systems*. Washington, DC.USA: NASA.
4. **Barrero F., Guevara J., Vargas E., Toral S., Vargas, M.** (2014), Networked Transducers in Intelligent Transportation Systems Based on The IEEE 1451 Standard. *Computer Standards Interfaces*, 36(2), 300–311. doi:10.1016/j.csi.2012.05.004.
5. **Baruah G., Majhi S., Mahanta C.** (2018), Auto-Tuning of PI Controllers for TITO Processes with Experimental Validation. *International Journal of Automation and Computing*, 16. doi:10.1007/s11633-018-1140-0.
6. **Chao G.-L., Han K.W.** (1998), Robust Stability Analysis of Time-Delay Systems Using Parameter-Plane and Parameter-Space Methods. Journal of the Franklin Institute, 335(7), 1249–1262.
7. **de Aguiar A.P.V., Barros P. (**2020), Evaluation and Redesign of The Inverted Decoupler : Open and Closed-Loop Approaches. *Int .J. Control Autom.Syst.*,18, 1435–1444. doi:0.1007/s12555-019-0371-3.
8. **Elahi A., Alfi A.** (2017), Finite-Time H Control of Uncertain Networked Control Systems with Randomly Varying Communication Delays. *ISA transactions*, 69,65–88.
9. **El-Farra N., Mhaskar P.** (2008), Special issue on 'Control of Networked and Complex Process Systems'. *Comput. Chem. Eng.*, 32(9), 1963–1963.
10. **Hajare V., Khandekar A., Patre B.** (2017), Discrete Sliding Mode Controller with Reaching Phase Elimination for TITO Systems. *ISA Transactions*, 66, 32–45. doi:10.1016/j.isatra.2016.10.010.
11. **Hajare V., Patre B. (**2015), Decentralized PID Controller for TITO Systems Using Characteristic Ratio Assignment with An Experimental Application. *ISA transactions*, 59, 385–97.
12. **Hamdy M., Ramadan A., Abozalam B.** (2018), Comparative Study Of Different Decoupling Schemes for TITO Binary Distillation Column via PI Controller. IEEE/CAA Journal of Automatica Sinica, 5(4), 869–877. doi:10.1109/JAS.2016.7510040.
13. **Hazarika S., Chidambaram M. (**2014), Design of Proportional Integral Controllers with Decouplers for Unstable Two Input Two Output Systems. *Industrial & Engineering Chemistry Research*, 53(15), 6467–6476. doi:10.1021/ie403791q.
14. **Heris P.C., Saadatizadeh Z., Babaei E.** (2019), A New Two Input-Single Output High Voltage Gain Converter with Ripple-Free Input Currents and Reduced Voltage on Semiconductors. *IEEE Transactions on Power Electronics*, 34(8), 7693–7702. doi:10.1109/TPEL.2018.2880493.
15. **Hong L., Hongye S., Peng S., Zhan S., Zheng-Guang W.** (2017), *Estimation and Control for Networked Systems with Packet Losses without Acknowledgement*. Springer, Cham. Switzerland. doi:10.1007/978-3-319-44212-9.
16. **Huang D., Nguang S.** (2009), Dynamic Output Feed-Back Control for Uncertain Networked Control Systems with Random Network-Induced Delays. *Int. J. Control Autom. Syst.*, 7(841), doi:10.1007/s12555-009-0517-9.
17. **Jeng J., Jian Y.** (2017), Model-Free Simultaneous Design of Multiloop PID Controllers for TITO Interactive Processes with Time Delays. In *2017 56th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*, 1033–1038. doi:10.23919/SICE.2017.8105580.
18. **Jin Q., Zhu L., Wang Q., Jiang, B.** (2016), PI Controller Design for A TITO System Based on Delay Compensated Structure and Direct Synthesis. *Canadian Journal of Chemical Engineering*, 94(9), 1740–1754. doi:10.1002/cjce.22551.
19. **Jin Y., Kwak D., Kim K.J., Kwak K.S.** (2014), Cyclic Prefixed Single Carrier Transmission in Intra-Vehicle Wireless Sensor Networked Control Systems.In*2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*,1–5.
20. **Khandekar A., Patre B.** (2017), Decentralized Discrete Sliding Mode Controller for TITO Processes with Time Delay with Experimental Application. *International Journal of Dynamics and Control*, 5, 614—-628. doi:10.1007/s40435-015-0202-1.
21. **Koo J., Ha D., Park D., Roh H.J., Ryu S., Kim G.H., Baek K.H., Han C.** (2017), Design of Optical Emission Spectroscopy Based Plasma Parameter Controller for Real-Time Advanced Equipment Control. *Computers Chemical Engineering*, 100, 38–47. doi:10.1016/j.compchemeng.2017.02.009.
22. **Li B., Wu J., Huang L.** (2016), Improved H∞ Control for Networked Control Systems with Network-Induced Delay and Packet Dropout. *J. Cent. South Univ.*, 23(5), 1215–1223.

23. **Li D.Z., He X., Song T.H., Jin, Q.** (2019), Fractional Order IMC Controller Design for Two-Input-Two-Output Fractional Order System. *International Journal of Control, Automation and Systems*, 17. doi:10.1007/s12555-018-0129-3.
24. **Liu B., Liu Y.** (2020), Mixed Event-Triggered Mechanism Modeling and Controlling for Networked Control Systems with Time-Varying Delays and Uncertainties. *ASIAN JOURNAL OF CONTROL*, 22(2), 803–817.
25. **Liu T., Zhang W., Gu, D. (**2006), Analytical Design of Decoupling Internal Model Control (IMC) Scheme for Two-Input Two-Output (TITO) Processes with Time Delays. *Industrial Engineering Chemistry Research*, 45, 3149–3160. doi:10.1021/ie051129q.
26. **Liu Y.C.** (2015), Robust Synchronization of Networked Lagrangian Systems and its Applications to Multi-robot Teleoperation. *IET Control Theory & Applications*, 9(1),129–139.
27. **Maghade D. Patre B.M.** (2013), Pole Placement by PID Controllers to Achieve Time Domain Specifications for TITO Systems. *Transactions of the Institute of Measurement and Control*, 36, 506–522. doi:10.1177/0142331213508803.
28. **Mahapatro S.R. Subudhi B.** (2020), A Robust Decentralized PID Controller Based on Complementary Sensitivity Function for a Multivariable System. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 67(10), 2024–2028. doi:10.1109/TCSII.2019.2943382.
29. **Mikhailov A. (**1938), Method of Harmonic Analysis in Control Theory. (in russian), A Vlomatiku 2., i Telemechllnika, 3, 27-81.
30. **Mohamed Vall O.M** (2020a), Artificial Neural Network-Based Smith Predictor for Compensating Random Time Delays Acting in Networked Control Systems. *International Journal of Control and Automation*, 13(1), 36–44.
31. **Mohamed Vall O.M** (2020b), PI Controller Design for Networked Control Systems with Random Time Delay. *International Journal of Emerging Trends in Engineering Research*,8(1),114–118. doi:10.30534/ijeter/2020/15812020.
32. **Naik R.H., Kumar D., Sujatha P. (**2020), Independent Controller Design for MIMO Processes Based on Extended Simplified Decoupler and Equivalent Transfer Function. *Ain Shams EngineeringJournal*, 11, 343–350.
33. **Pang Z., Liu G., Zhou D., Sun D. (**2016), Data-Based Predictive Control for Networked Nonlinear Systems with Network-Induced Delay and Packet Dropout. *IEEE Transactions on Industrial Electronics*, 63(2), 1249–1257.doi:10.1109/TIE.2015.2497206.
34. **Park P. (2015),** Power Controlled Fair Access Protocol for Wireless Networked Control Systems. *Wireless Networks*, 21, 1499–1516.
35. **Park P., Khadilkar H., Balakrishnan H., Tomlin C.J.** (2014), High Confidence Networked Control for Next Generation Air Transportation Systems. *IEEE Transactions on Automatic Control*, 59(12), 3357–3372. doi:10.1109/TAC.2014.2352011.
36. **Qian G., Wei P., Ruan Z., Lu J.Q.** (2017), A Low-Complexity Modulation Classification Algorithm for MIMO–OSTBC System. *Circuits, Systems, and Signal Processing*, 36. doi:10.1007/s00034-016-0428-y.
37. **Sharma A., Padhy P.** (2017), Design and Implementation of PID Controller for The Decoupled Two In-Put Two Output Control Process. In *2017 4th International Conference on Power, Control Embedded Systems (ICPCES)*, 1–6. doi:10.1109/ICPCES.2017.8117666.
38. **Siljak D.** (1966), Generalization of the Parameter Plane Method. IEEE Transactions on Automatic Control, 11(1), 63–70. doi:10.1109/TAC.1966.1098230.
39. **Sun Y., El-Farra N.** (2012), Resource Aware Quasi-Decentralized Control of Networked Process Systems over Wireless Sensor Networks. *Chemical Engineering Science*, 69(1),93–106. doi: https://doi.org/10.1016/j.ces.2011.10.010.
40. **Tanaka Y., Ogata T., Imagawa, S.** (2015), Decoupled Direct Tracking Control System Based on Use of A Virtual Track for Multilayer Disk with A Separate Guide Layer. *Japan Society of Applied Physics*, 54(9), 09MB03.
41. **Ustoglu I., Eren Y., Soylemez, M.** (2016), Stabilizing Constant Controllers for Two-Input, Two-Output Systems with Reducible and Irreducible Characteristic Equations. *Transactions of the Institute of Measurement and Control*, 39. doi:10.1177/0142331216645649.
42. **Vargas F., Silva E., Chen J.** (2013), Stabilization of Two-Input Two-Output Systems over SNR-Constrained Channels. *Automatica*, 49, 3133–3140. doi:10.1016/j.automatica.2013.07.031.
43. **Wang Q., Huang B., Guo X.** (2000), Auto-Tuning of TITO Decoupling Controllers from Step Tests. *ISA Transactions*, 39(4), 407–418.
44. **Wang Y.J. (**2011), Graphical Computation of Gain and Phase Margin Specifications-Oriented Robust PID Controllers for Uncertain Systems With Time-Varying Delay. Journal of Process Control, 21(4), 475–488.
45. **Yao W., Jiang L., Wu J.W.Q., Cheng S.** (2015), Wide-Area Damping Controller for Power System Inter-Area Oscillations: A Networked Predictive Control Approach. *IEEE Transactions on Control Systems Technology*, 23(1), 27–36. doi:10.1109/TCST.2014.2311852.
46. **Zhang W., Branicky M., Phillips S.** (2001), Stability of Networked Control Systems. *IEEE Control Systems Magazine*, 21(1), 84–99. doi:10.1109/37.898794.
47. **Zhang X., Zheng Y., Lu G.** (2006), Stochastic Stability of Networked Control Systems with Network-Induced Delay and Data Dropout. In *Proceedings of the45th IEEE Conference on Decision and Control*, 5006–5011. doi:10.1109/CDC.2006.376970.
48. **Zhuang M., Atherton D.P. (**1993), PID Controller Design for A TITO System. In *1993 American Control Conference*, 3176–3177. doi:10.23919/ACC.1993.4793493.

Ould Mohamed Mohamed Vall: https://orcid.org/0000-0002-2701-0140