Avrupa Bilim ve Teknoloji Dergisi
Özel Sayı, S. 172-180, Kasım 2020
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Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
Special Issue, pp. 172-180, November 2020
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Research Article

Analysis of Communication Time Delayed Automatic Generation Control via SMA with 2 DOF PI$^{\lambda}$D$^{\mu}$ Controller for Interconnected Power System

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(International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT) 2020 – 22-24 October 2020)

(**DOI:** 10.31590/ejosat.820449)

ATIF/REFERENCE: Saka M., Eke I., Taplamacioglu M.C. (2020). Analysis of Communication Time Delayed Automatic Generation Control via SMA with 2 DOF PI$^{\lambda}$D$^{\mu}$ Controller for Interconnected Power System. *European Journal of Science and Technology*, (Apecial Issue), 172-180.

Abstract

Automatic generation control (AGC) is a vital process for the design and operation of electrical power systems. Quality of electrical energy is generated with effective AGC and sent to the consumers. Interconnected power systems are large and complex systems since they consist of more than one control area and they are connected to each other. Therefore, it is very difficult to control these systems. In this study, two different interconnected power systems are considered for AGC. First, an AGC system having reheat without time delay is analyzed. Secondly, an AGC system with communication time delay (CTD) is examined in order to make control analysis closer to real system. These CTDs are observed the AGC systems because of communication networks, phasor measurement units (PMUs), wide - area measurement - monitoring systems (WAMSs), supervisory control and data acquisition (SCADA) units etc. AGC becomes much more complicate and complex with the addition of CTDs to the system. Because of high flexibility and capability ratio, two degree of freedom fractional order proportional – integral - derivative (2 DOF PI$^{\lambda}$D$^{\mu}$) controller has been used for both reheated and time delayed power systems. A new meta heuristic Slime Mold Algorithm (SMA) is used to set of the 2 DOF PI$^{\lambda}$D$^{\mu}$ controller parameters. SMA is based on nature of oscillation mode of slime mould and this algorithm is developed in 2020. System performances are examined in terms of settling time (for %0.005 band width), overshoot and undershoot for frequency deviation of each region and tie line power deviation. All results are expressed both numerically and graphically. It is clear that the results obtained with the proposed 2 DOF PI$^{\lambda}$D$^{\mu}$ and SMA are more successful than the defined as the more realistic AGC systems in literature and also improved the system performance.

Keywords: Automatic generation control, Slime mould algorithm, Communication time delay, Interconnected power systems.

Enterkonnekte Güç Sistemleri için Haberleşme Zaman Gecikmeli Otomatik Üretim Kontrolünün SMA Aracılığıyla 2 DOF PI$^{\lambda}$D$^{\mu}$ Kontrolör ile Analizi

Öz

Elektrik güç sistemlerinin tasarım ve işletimi için otomatik üretim kontrolü (AGC) hayati derecede önemli bir işlemdir. AGC ile kaliteli elektrik enerjisi üretilir ve tüketiciye gönderilir. Enterkonnekte sistemler birbirleriyle bağlantılı birden fazla kontrol bölgesinden oluştuğu için büyük ve karmaşık güç sistemleridir. Bu nedenle bu sistemlerin kontrolü oldukça zordur. Bu çalışmada

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AGC için iki farklı enterkonnekte güç sistemi dikkate alınmıştır. Öncelikle, ara ısıtmalı zaman gecikmesi dahil edilmeyen bir AGC sistemi analiz edilmiştir. Sonrasında, gerçeğe daha yakın kontrol analizleri yapmak amacıyla haberleşme zaman gecikmesine (CTD) sahip bir AGC sistemi incelenmiştir. Haberleşme ağları, fazör ölçüm üniteleri (PMUs), geniş alan ölçüm – izleme sistemleri (WAMSs), merkezi denetleme kontrol ve veri toplama (SCADA) gibi birimlerden dolayı AGC sistemlerinde CTDs gözlemlenir. CTD'nin sisteme eklenmesi ile birlikte, AGC sistemi çok daha karmaşık ve kompleks olmaktadır. Hem ara ısıtmalı hem de zaman gecikmeli güç sistemi için yüksek esneklik ve kabiliyet oranına sahip olduğundan dolayı iki serbestlik dereceli kesirli mertebeden oransal – integral - türev (2 DOF $PI^{\lambda}D^{\mu}$) kontrolör kullanılmıştır. 2 DOF $PI^{\lambda}D^{\mu}$ kontrolör parametrelerinin ayarlanmasında yeni sezgisel Balçık Küfü Algoritması (SMA) kullanılmıştır. SMA, balçık küflerinin salınım modunun doğasına dayanmaktadır ve bu algoritma 2020' de geliştirilmiştir. Sistem performansları, her bir bölge frekans değişimi ve ara bağlantı güç değişimi için oturma zamanı (%0.005 bant aralığı için), maksimum aşım ve minimum aşım açısından incelenmiştir. Elde edilen tüm sonuçlar hem sayısal olarak ifade edilmiş hem de grafiksel olarak gösterilmiştir. Önerilen 2 DOF $PI^{\lambda}D^{\mu}$ ve SMA ile elde edilen sonuçların, literatürde daha gerçekçi olduğu belirtilen AGC sistemlerinden daha başarılı olduğu ve sistem performanslarını güçlendirdiği görülmüştür.

Anahtar Kelimeler: Otomatik üretim kontrolü, Balçık küfü algoritması, Haberleşme zaman gecikmesi, Enterkonnekte güç sistemleri.

1. Introduction

Automatic generation control is one of the essential issues to operate power systems in stable. Especially for interconnected systems, AGC is a complex and complicate problem. When the communication time delay occurs in communication units such as RTUs, SCADA etc. is added to these systems, the power systems become both more realistic and more complex. CDTs reduce system dynamic performances, make the system more difficult to control and even make the unstabile system (Sonmez, Ayasun, & Nwankpa, 2016). Fundamental goal of AGC is to reduce the frequency deviation of each area and tie line power and make the steady state error zero (Kundur, 1994).

Different multi area power systems have been analyzed from past to present for automatic generation control. Various methods and different controllers are used in the analysis of these systems. Bacterial Foraging Optimization Algorithm (BFOA) (Ali & Abd-Elazim, 2013), Ecological Technique and Coefficient Diagram Method (CDM+ECO) (Mohamed, Shabib, & Ali, 2016), Cuckoo Search Algorithm (CSO) (Abdelaziz & Ali, 2015), Grey Wolf Optimization (GWO) (Guha, Roy, & Banerjee, 2016), Hybrid Differential Evolution Particle Swarm Optimization (DEPSO) (Sahu, Pati, & Panda, 2014) and Decentralized Sliding Mode Control (DSMC) (Mi, Fu, Wang, & Wang, 2013), Artificial Bee Colony (ABC) (Gark & Kaur) et. are the some of using techniques for AGC. When modeling power systems, communication time delay is included in the systems to create a more realistic model. For this reason, (Sonmez & Ayasun, 2016) and (Saxena & Hote, 2018) are studied single area having delay system for τ=2.28 sec. PI controller parameters are founded for both study for control of AGC.

Mentioned techniques and controllers may give good results. However, these may exhibit weakness performance capability for large and complicate systems. Therefore, 2 DOF $PI^{\lambda}D^{\mu}$ controller, which is more capable and flexible than PI/PID controller, is used for interconnected power systems in this study. Slime Mould Algorithm (Li, Chen, Wang, Heidari, & Mirjalili, 2020), which is new optimization technique developed in 2020, selected for better convergence behaviour and applied for tuning of 2 DOF $PI^{\lambda}D^{\mu}$ controller. In this study, two different interconnected power system (having reheater system and time delayed system) are considered to shown effectiveness proposed controller and technique. Main contributions of this work; (i) interconnected systems performances are enhanced, (ii) errors are minimized and (iii) peak to peak of frequency deviation is decreased.

The other sections of this paper: Interconnected power systems for AGC, 2 DOF $PI^{\lambda}D^{\mu}$ controller and SMA are defined in Section 2. Obtained numerical and graphical results are given in Section 3. Conclusions of the study are given in Section 4.

2. Material and Method

2.1. Automatic Generation Control

Frequency control is necessary for quality energy in electrical power systems. Active power change in the system affects the frequency. Changes in frequency disrupt the stability of the system. Especially for interconnected systems, the frequency deviation of each region and the power deviation in the tie line should be examined. Changes in any region affects other regions as well. AGC minimizes the deviations that may occur in frequency and power of tie line and keeps it within a certain range (Kundur, 1994). A linear model of power systems can be used for AGC. The interconnected system considered in this study is shown as follows:

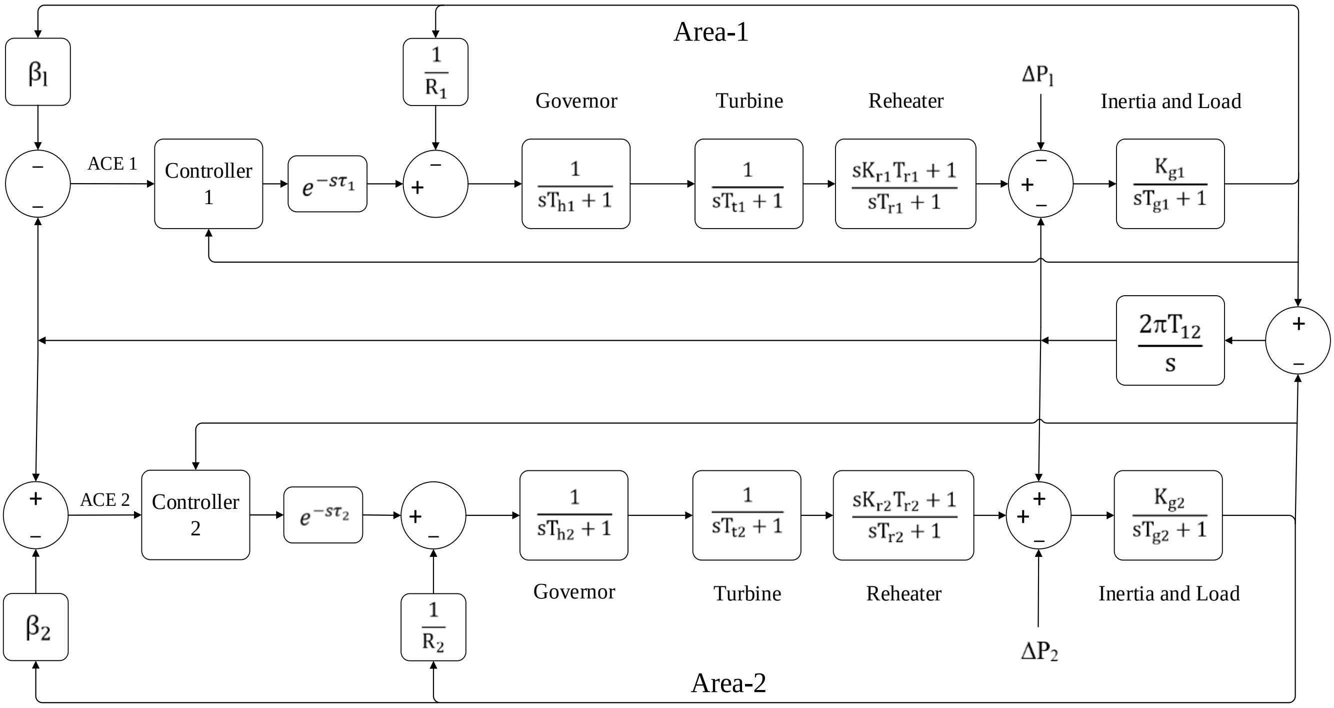

Figure 1. Linear model of the considered power system

This model is formed two regions and a tie line. Each area has governor, turbine, reheater, inertia and load blocks. In here, β is bias factor of frequency, R is droop characteristic and τ is communication time delay. Each controller is selected as 2 DOF $PI^{\lambda}D^{\mu}$ for this study.

Area control error (ACE) can be described as follows (Topno & Chanana, 2016):

$$ACE\ 1 = \beta_1 \Delta f_1 + \Delta P_{tie\ 1} \tag{1}$$

$$ACE\ 2 = \beta_2 \Delta f_2 - \Delta P_{tie\ 2} \tag{2}$$

where; Δf_1 and Δf_2 is frequency deviation of area 1 and area 2 respectively. ΔP_{tie} is tie line power deviation.

2.2. 2 DOF $PI^{\lambda}D^{\mu}$ Controller

PID is very useful and ability controller. However, sometimes this controller may not give desired system performance. For this reason, 2 DOF PID controller can be used. This controller has extra two parameters from PID. First is proportional set point coeeficient (P_c) and second is derivative set point coefficient (D_C). 2 DOF PID is used ACE signal and output of system signal as inputs (Mohapatra, Dey, & Sahu, 2019). For large systems this controller may exhibit insufficient performance. Thus, fractional terms are added to 2 DOF PID to improve effectiveness and capability. In this way, 2 DOF $PI^{\lambda}D^{\mu}$ controller may give better results according to the 2 DOF PID and PID controller.

PID can be described as follows:

$$u = K_{p_i} ACE_i + K_{i_i} \int ACE_i + K_{d_i} \frac{d}{dt}[ACE_i] \tag{3}$$

2 DOF PID can be described as follows:

$$u = K_{p_i}[ACE_i P_{c_i} - \Delta f_i] + K_{i_i} \int [ACE_i - \Delta f_i] + K_{d_i} \frac{d}{dt}[ACE_i D_{c_i} - \Delta f_i] \tag{4}$$

2 DOF $PI^{\lambda}D^{\mu}$ can be described as follows:

$$u = K_{p_i}[ACE_i P_{c_i} - \Delta f_i] + K_{i_i} \frac{d^{-\lambda}}{dt^{-\lambda}}[ACE_i - \Delta f_i] + K_{d_i} \frac{d^{\mu}}{dt^{\mu}}[ACE_i D_{c_i} - \Delta f_i] \tag{5}$$

In here; i is ith control area; u is output signal, K_p is proportional, K_i is integral and K_d is derivative gain of controller.

2.3. Slime Mould Algorithm

Slime mould algorithm is recently developed meta heuristic algorithm. It's based on slime mould behavior for food seek in the nature. If the initial found food has lower quality, slime mould seek higher quality food in their surroundings (Li et al., 2020). Slime mould's behavior towards food is described as follows:

$$X(t+1) = \begin{cases} X_b(t) + vb \cdot \left(W \cdot X_A(t) - X_B(t)\right) & ; \quad r < p \\ vc \cdot X(t) \quad ; & r \geq p \end{cases} \tag{6}$$

In here; X_A and X_B are random chosen two slime mould, X is location. vb can be decribed as follows:

$$vb = [-a, a] \tag{7}$$

In here, a can be represented as follows:

$$a = \operatorname{arctanh}(-\left(\frac{t}{\max\_t}\right) + 1) \tag{8}$$

p is given as follows:

$$p = \tanh|S(i) - DF| \tag{9}$$

W is weight of slime mould and it can be expressed as follows:

$$W\left(SmellIndex(i)\right) = \begin{cases} 1 + r \cdot \log\left(\frac{bF - S(i)}{bF - wF}\right) + 1 & ; \quad condition \\ 1 - r \cdot \log\left(\frac{bF - S(i)}{bF - wF}\right) + 1 & ; \quad others \end{cases} \tag{10}$$

$$SmellIndex) = sort(S) \tag{11}$$

In here; bF is best fitness, wF is worst fitness, r is random number, S(i) is fitness of X and condition is S(i) ranks first half of the population.

Slime mould updates the position as following equation:

$$X^* = \begin{cases} rand \cdot (UB - LB) + LB & ; \quad rand < z \\ X_b(t) + vb \cdot \left(W \cdot X_A(t) - X_B(t)\right) & ; \quad r < p \\ vc \cdot X(t) & ; \quad r \geq p \end{cases} \tag{12}$$

In here; LB is represents lower bound and UB is represents upper bound.

Detail information about SMA and expression of mathematical equations of this method can be found out from (Li et al., 2020).

In this paper, integral time absolute error (ITAE) function is selected as objective function. ITAE can be described as follows:

$$ITAE = \int (time|error|)dt \tag{13}$$

The main objective function used in this study is given as follows:

$$J = \int w_1(t|\Delta f_1|) + w_2(t|\Delta f_2|) + w_3(t|\Delta P_{tie}|)dt \tag{14}$$

In here; w_1, w_2 and w_3 are weight coefficients.

3. Results and Discussions

In this section, two different multi area system are analyzed. All results are examined in terms of settling time for %0.005 band width, overshoot and undershoot values of the signal.

3.1. AGC for Reheater System

Reheater turbine power system is considered for AGC. System parameters are given in (Gozde, Cengiz Taplamacioglu, & Kocaarslan, 2012). τ_1 and τ_2 are equaled to 0 for this system. Obtained control parameters are given in Table 1.

Table 1. Controller parameters

			Area 1				
Reference	K_{p_1}	K_{i_1}	K_{d_1}	λ_1	μ_1	P_{c_1}	D_{c_1}
Proposed	5.000	5.000	1.8536	0.9387	1.2615	5.000	0.4076
(Abdel-Magid & Abido, 2003)	-0.0360	0.4900	---	---	---	---	---
(Gozde et al., 2012)	1.9660	9.5902	3.9320	---	---	---	---
			Area 2				
Reference	K_{p_2}	K_{i_2}	K_{d_2}	λ_2	μ_2	P_{c_2}	D_{c_2}
Proposed	4.5542	4.2583	1.4700	1.1420	0.9734	1.6920	0.1547
(Abdel-Magid & Abido, 2003)	-0.0360	0.4900	---	---	---	---	---
(Gozde et al., 2012)	0.7100	0.6827	0.7420	---	---	---	---

Comparative frequency deviations of each are shown in Figure 2 and Figure 3 respectively.

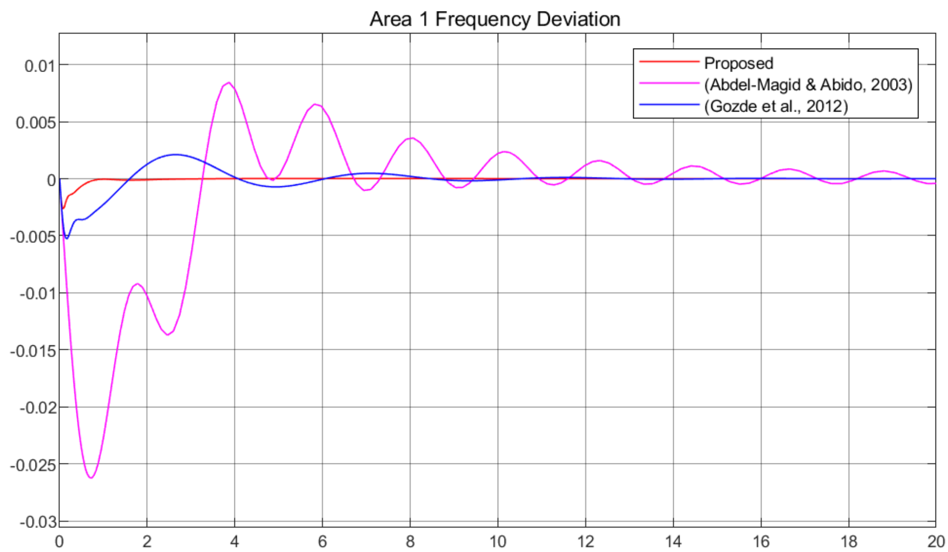

Figure 2. Comparative frequency deviations for Area 1

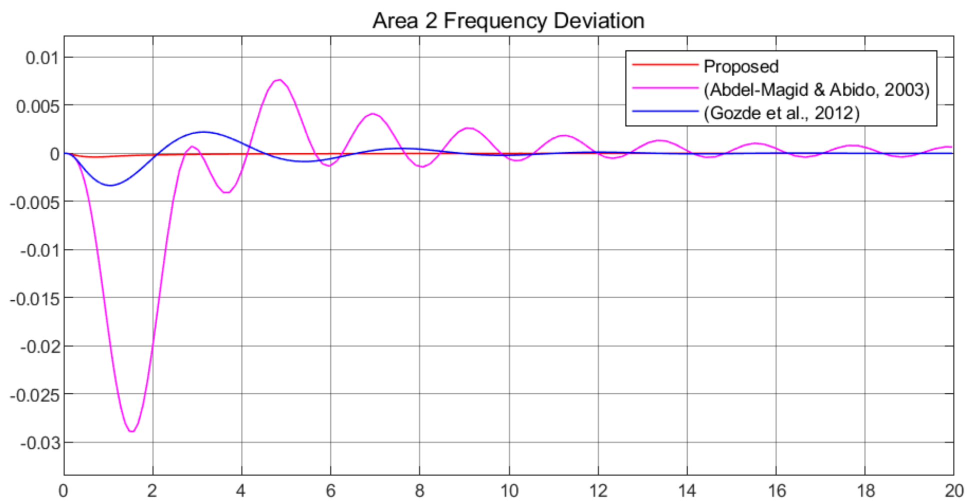

Figure 3. Comparative frequency deviations for Area 2

Comparative tie line power deviations are shown in Figure 4.

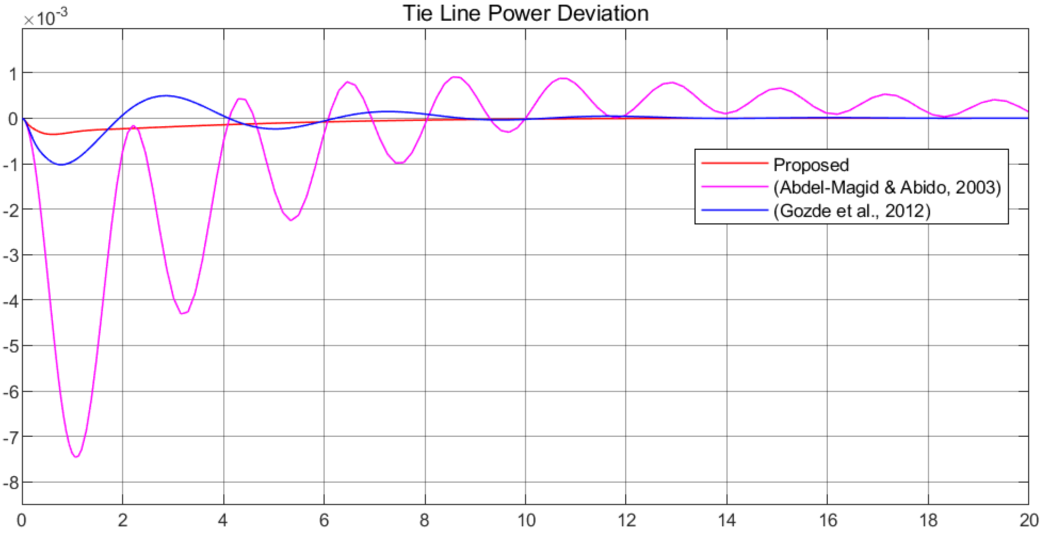

Figure 4. Comparative power deviations for Tie line

Obtained numerical results are given for this system in Table 2.

Table 2. Comparative results of reheater system

		Area 1		
Reference	**Method**	**Settling Time**	**Overshoot**	**Undershoot**
Proposed	SMA	2.435	1.411e-5	-2.625e-3
(Abdel-Magid & Abido, 2003)	PSO	---	8.443e-3	-2.623e-2
(Gozde et al., 2012)	ABC	12.368	2.109e-3	-5.256e-3
		Area 2		
Reference	**Method**	**Settling Time**	**Overshoot**	**Undershoot**
Proposed	SMA	4.759	8.524e-7	-3.806e-4
(Abdel-Magid & Abido, 2003)	PSO	---	7.661e-3	-2.889e-2
(Gozde et al., 2012)	ABC	12.928	2.216e-3	3.343e-3
		Tie Line		
Reference	**Method**	**Settling Time**	**Overshoot**	**Undershoot**
Proposed	SMA	7.346	2.873e-6	-3.536e-4
(Abdel-Magid & Abido, 2003)	PSO	---	9.095e-4	-7.460e-3
(Gozde et al., 2012)	ABC	8.332	4.963e-4	-1.023e-3

When obtained results are analysed, PSO is not settled to %0.005 band width. Settling time is improved 5.08 times for Area 1 and 2.71 times for Area 2. overshoot is; 314.88 times lower than PSO and 149.47 times lower than ABC for Area 1, 8987 times lower than PSO and 2599 times lower than ABC for Area 2, 316.56 times lower than PSO and 172.74 times lower than ABC for tie line. % undershoot is; 9.99 times lower than PSO and 2.0 times lower than ABC for Area 1, 75.9 times lower than PSO and 8.78 times lower than ABC for Area 2, 21.09 times lower than PSO and 2.89 times lower than ABC for tie line.

3.2. AGC for Delayed System

Non-reheat turbine having communication time delayed power system is considered for AGC. System parameters are given in (Sönmez, 2019). Because of non-reheat turbine system is considered, K_{r_1}, K_{r_2}, T_{r_1}, and T_{r_2} are equaled to zero. Obtained control parameters are given in Table 3.

Table 3. Controller parameters

Area 1							
Reference	K_{p_1}	K_{i_1}	K_{d_1}	λ_1	μ_1	P_{c_1}	D_{c_1}
Proposed	0.6369	0.4711	0.5606	1.0278	0.9884	0.7698	0.3971
(Sönmez, 2019)	0.5000	0.6190	---	---	---	---	---
Area 2							
Reference	K_{p_2}	K_{i_2}	K_{d_2}	λ_2	μ_2	P_{c_2}	D_{c_2}
Proposed	0.4716	0.4887	0.7762	1.0254	0.6092	0.6926	0.2155
(Sönmez, 2019)	0.5000	0.6190	---	---	---	---	---

Comparative frequency deviations of each area shown in Figure 5 and Figure 6 respectively.

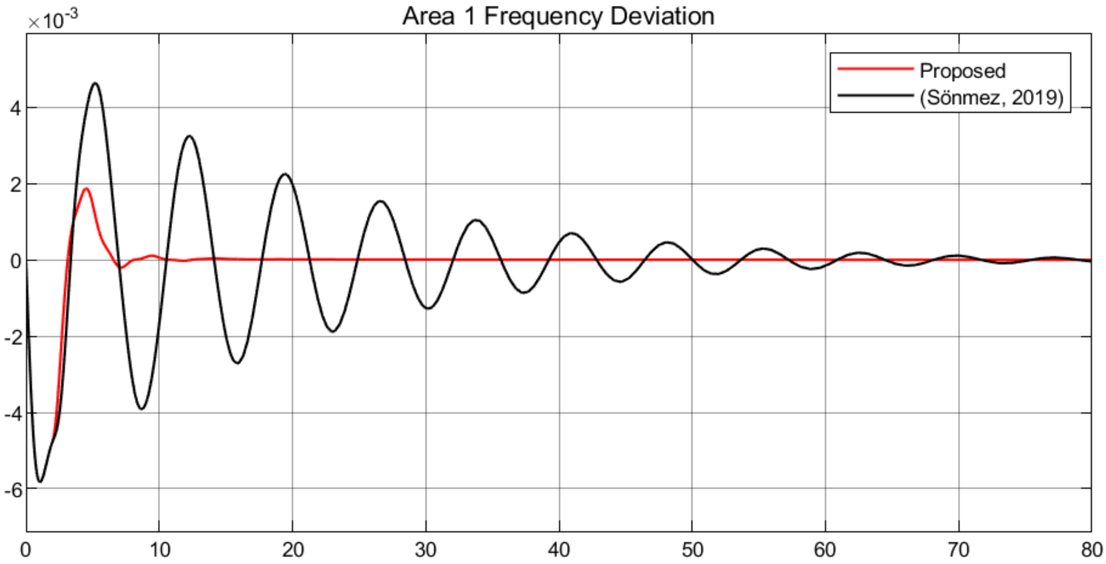

Figure 5. Comparative frequency deviations for Area 1

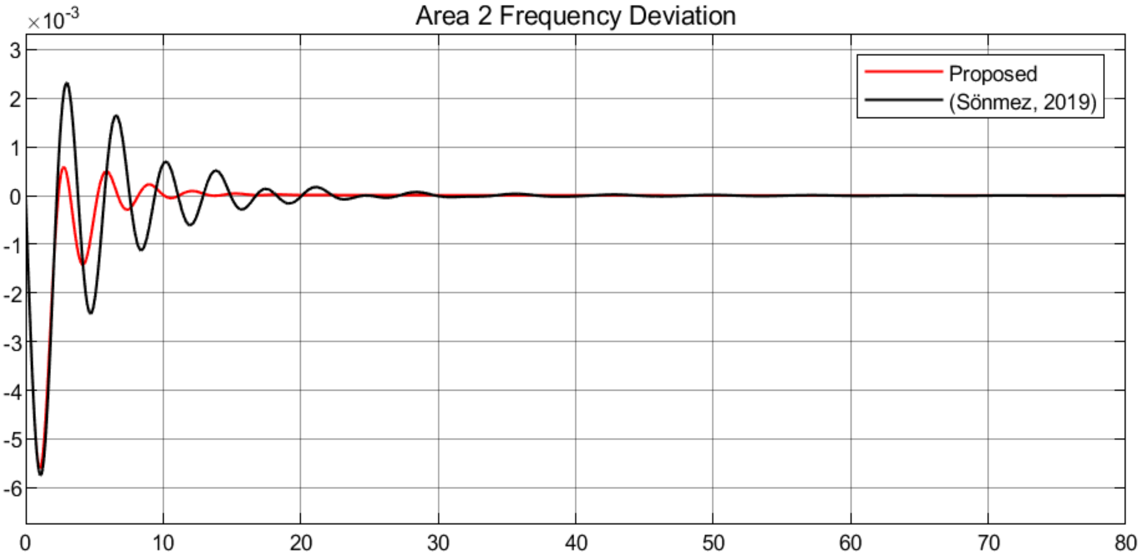

Figure 6. Comparative frequency deviations for Area 2

Comparative tie line power deviations are shown in Figure 7.

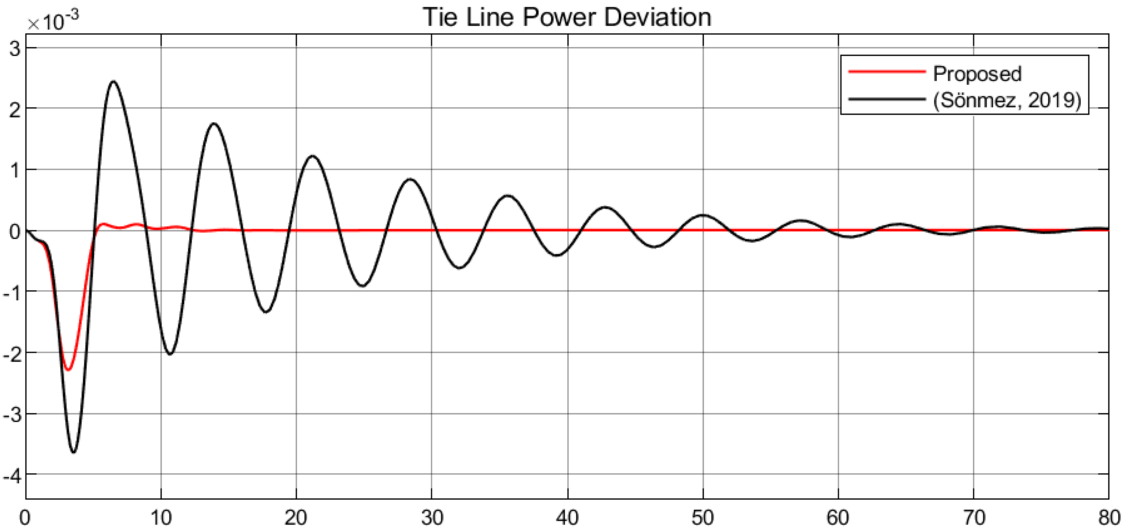

Figure 7. Comparative power deviations for Tie line

Obtained numerical results are given for time delayed system in Table 4.

Table 4. Comparative results of delayed system

		Area 1		
Reference	**Method**	**Settling Time**	**Overshoot**	**Undershoot**
Proposed	SMA	10.071	1.875e-3	-5.831e-3
(Sönmez, 2019)	SBL	77.759	4.641e-3	-5.831e-3
		Area 2		
Reference	**Method**	**Settling Time**	**Overshoot**	**Undershoot**
Proposed	SMA	12.821	5.922e-4	-5.604e-3
(Sönmez, 2019)	SBL	29.078	2.318e-3	-5.746e-3
		Tie Line		
Reference	**Method**	**Settling Time**	**Overshoot**	**Undershoot**
Proposed	SMA	11.476	1.051e-4	-2.296e-3
(Sönmez, 2019)	SBL	72.324	2.446e-3	-3.651e-3

When Area 1 results are analysed, the frequency signal is settled to %0.005 band width 7.72 times faster. Overshoot is decreased approximately 2.5 times but undershoot is not change. When Area 2 results are analysed, frequency signal is settled to %0.005 band width 2.27 times faster. Overshoot is decreased approximately 3.91 times and % undershoot is obtained at lower value. When tie line results are analysed, signal is settled to %0.005 band width 6,3 times faster. Overshoot and undershoot are decreased approximately 23.27 times and 1.6 times respectively.

4. Conclusions

In this study two different type AGC systems are analyzed via SMA with 2 DOF $PI^{\lambda}D^{\mu}$. Reheater system AGC is performed for first case and time delayed AGC system is performed for second case. When all obtained results are analysed, lower settling time, overshoot and undershoot values are found (except for Area 1 of delayed system) against the compared studies. It is explicitly understood that, system performances highly improved for both cases with proposed method and controller. Based on these results, proposed controller and technique can be used for much larger and also hybrid systems for future studies.

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