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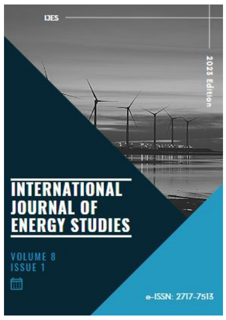

Research Article

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Ensuring energy balance for sudden demand changes in smart grids

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Highlights

- Supply-demand-price balance has been achieved in smart grids.
- Closed loop electrical power control system modeling is used.
- Load balance is provided by fuzzy logic PI controller.
- Applications were made for sudden demand increase and sudden demand decrease.

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ABSTRACT

With the increasing diversity in the use of electrical energy and the inclusion of renewable electricity power plants in the system, more efficient and more controllable electrical power systems are provided by smart grid technologies. Load balance based on pricing in electrical power systems; It is a strategy that takes into account customer demands, enables customers to use electrical energy at the most attractive price, and provides suppliers with the desired profit, that is, in summary, it coordinates the efficient operation of energy systems. In this study; While load balance is created with smart grid technology, demand-supply-price balance is achieved by using an optimum Fuzzy Logic PI controller within a closed-loop electric power control system model. Within the scope of the study, the simulation results obtained by applying 6 different demand scenarios to the power system model consisting of different types of generation resources were given graphically and analyzed. The different demand scenarios applied include difficult demand conditions such as possible sudden increase or decreases in demand in the electrical power system.

Keywords: Smart grids, load balancing, electric energy pricing, fuzzy logic PI controller

1. INTRODUCTION

With the continuous increase in the need for electrical energy, more electrical energy sources are needed, and today renewable energy power plants have started to replace conventional type of electrical power plants. Increasing diversity in electricity use and the inclusion of renewable electricity power plants in the system necessitate electrical power systems to be more efficient and more controllable. Today's electrical power system technologies, called smart grid technology, thanks to the advanced data communication network between generation resources and customers, it has a structure that coordinates all components in the network in a compatible, fast, flexible, cost-effective and environmentally friendly way. In general, smart grids can be defined as an automatic power distribution network consisting of a combination of advanced electrical and communication infrastructures, providing two-way electricity and information flow, controlling and monitoring each customer and node in the system [1, 2].

With smart grid technology, it is aimed both to use electrical energy at the most attractive price by customers and to operate power systems efficiently by achieving the desired profit of suppliers, taking into account the demands of customers. One of the most fundamental components of efficient operation is the provision of the customer-supplier coordination cycle, which includes load balance and pricing methods. An effective load balance management and dynamic pricing strategy creates an economical, robust and continuous power system as well as reducing electricity expenditures of customers and lowering the generation costs of suppliers.

In many scientific studies on pricing strategies and load balancing in smart grid electrical power systems, different applications and methods have been mentioned. Some of these studies can be summarized as follows:

Jianping He et al. used dynamic pricing to achieve the Generation Consumption Equilibrium in their study[3]. In the study reported by Sandeep Kakran and Saurabh Chanana published, it was emphasized that the balancing of demand and generation should also be with pricing [4]. Eissa developed a real-time demand response program in a smart grid power system consisting of different sources [5]. In the studies reported by B. Baykant Alagöz et al. [6] and B. Baykant Alagöz and A. Kaygusuz [7], electricity price control is provided by using a closed-loop PID/PI controller in order to balance energy demand and generation in smart grid electrical power systems. In the study of Thamer Alquthami et al., an incentive-based dynamic pricing method based on load shifting was introduced by using the genetic algorithm method in Smart Grids [8]. Fahad R. Albogamy et al. used the particle swarm optimization based super twisting sliding mode controller (PSO-STSMC) for closed-loop load balancing in smart grid power systems in their article [9]. Yu-Chung Tsao et al. performed the fuzzy logic programming approach in dynamic electricity pricing [10]. In the work reported by Amjed Al-Mousa and Ayman Faza published, a fuzzy logic based customer response prediction model was developed [11].

In this study, real-time electricity pricing and load balance in smart grids are examined. Within the scope of the study, while the load balance was created with smart grid technology, the demand-supply-price balance was achieved by using the optimum Fuzzy Logic PI controller within a closed-loop electric power control system model. In the present study, firstly, the structure of the proposed Fuzzy Logic PI controller and the modeling of the electrical power system using this controller are mentioned. Then, the generation responses and price responses of the system when using the proposed fuzzy logic PI controller for different demand scenarios were analyzed. When the different demand scenarios applied are examined, the performance of the system against possible sudden increases or decreases in demand is observed, and the difficult conditions that may be encountered in electrical power systems are evaluated. MATLAB/Simulink program was used for 6 different simulation applications including difficult demand conditions in the system model, and the results were analyzed.

In summary; In a distributed electrical power system consisting of different generation sources, to ensure the energy balance of the system by using a Fuzzy logic PI controller and by benefiting pricing in the face of possible difficult conditions that may occur in energy demands reveals the importance of the study.

2. THE USED SYSTEM MODEL AND THE STRUCTURE OF THE PROPOSED FUZZY LOGIC PI CONTROLLER

In line with the main purpose of making electrical power systems observable and manageable, smart grid applications are used to ensure that all components of electrical power systems, such as smart meters, etc. provide communication and coordination with applications. An electrical power system can be divided into components as power generation systems, transmission and distribution systems, consumers and the controller structures that enable management of them. In this context, the required representative smart grid technology cycle can be summarized as follows:

- Supply and demand information of energy generating and energy consuming units in the system is received by a price server unit through smart meters etc.
- The price server unit calculates the difference between supply and demand. This difference is also the load balance error of the system.
- Controller structures regulate the dynamic electrical energy price to bring the load balance error to zero.
- Dynamic price information is reported back to the price server and then to the suppliers and consumers.
- The cycle is completed by updating the supply and demand of energy generating and energy consuming units according to the new price information. Thus, the load balance is ensured by dynamic pricing.

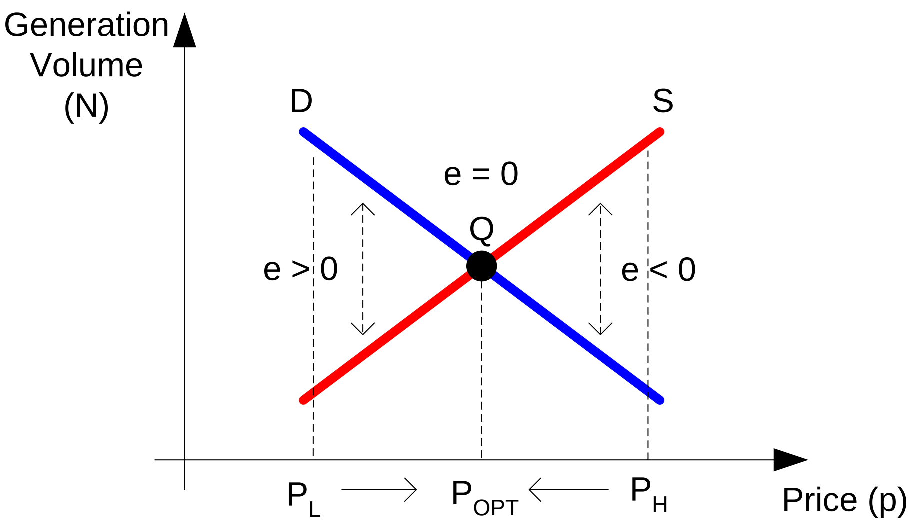


Figure 1. Energy supply-demand-optimal price point graph

The graphic describing the supply-demand-price relationship for a free electricity market is given in Figure 1 [6]. The *N* value represents the generation volume and varies between 10 - 100 GW in the literature. According to Figure 1, in a distributed electrical energy system market with a certain generation volume; As the price of electricity increases, demand decreases and generation (supply) increases. In Figure 1, energy demand is expressed as "*D*", energy supply as "*S*", low price as "P_L" and high price as "P_H". The difference between the energy demand and the energy supply ($e = D - S$) is defined as the load balance error *e(t)*. The load balance error *e(t)* is zero in P_{OPT} point, in other words, P_{OPT} expresses the optimal price point (*Q*), which is the price when supply and demand are equalized. According to this, by providing the load balance of the system at the price point *Q*, the equations "$D(p) = S(p)$" and "$e(t)=0$" are obtained.

In the case of $e > 0$, since $D > S$ in the system, increasing generation and decreasing demand can be achieved by increasing the price. Conversely, if $e < 0$, since $D < S$ in the system, reducing generation and increasing demand can be achieved by lowering the price. In other words, in both cases, what is desired is to keep demand and supply in balance by reaching $e = 0$, that is, the ideal price point.

A closed-loop control structure with asymptotic steady state error of zero takes the load balance error to zero ($\lim_{t \to \infty} e \to 0$), and this principle provides energy balancing with the help of an automatic control system [12]. In cases where $e > 0$ and $e < 0$, the specified closed-loop control places the error signal *e* to zero over time, bringing the system to the supply-demand-price equilibrium point [13]. For this structure, closed loop electrical power control system modeling is required.

The equation given in Equation 1 states that the energy supply will increase as the increase in the energy price will increase the profitability [13]. According to this equation, the generation capacity for the unit energy price "*p*" is defined by the $S_d(p)$ function.

$$S_d(p) = \sum_{i=0}^{d} a_i p^i \tag{1}$$

$$S(s) = S_d(p).\frac{1}{\tau\, s + 1} \tag{2}$$

The "*S(s)*" transfer function with the "τ" time constant given in Equation 2, on the other hand, characterizes the energy generation response of the resource against the price [12]. According to this equation, It is assumed that after "5τ" time the generation capacity "$S_d(p)$" will be reached. In Equation 3, limitations related to system generation modeling are specified, while in Equation

4, a distributed system model consisting of different generation resources is expressed [7]. The expression "C_{max}" given in these equations indicates the maximum installed power of the generation system, the expression "p_0" indicates the average energy generation cost, and the expression "m" indicates the number of resource types.

$$G(s) = \begin{cases} 0 & p < p_0 \\ S(s) & p \geq p_0 \;\; and \;\; S(s) \leq C_{max} \\ C_{max} & S(s) > C_{max} \end{cases} \tag{3}$$

$$S_{Total}(S) = \sum_{j=1}^{m} G_j(s) \tag{4}$$

In Equation 5, the calculation of the "τ" time constant is given according to the "T" parameter, which indicates the average time required for the relevant generation resource to reach the maximum generation (C_{max}) from zero generation [6].

$$\tau_j = (1 - e^{-1}).T_j \tag{5}$$

According to the equations expressed, the block diagram of the Closed Loop Electric Power Control System Modeling used in this study is given in Figure 2.

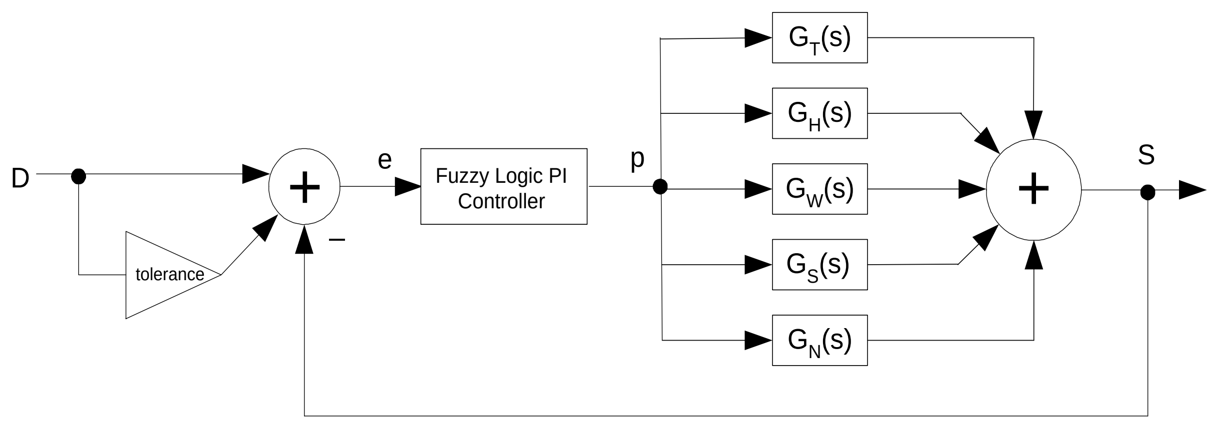


Figure 2. Closed loop electrical power control system block diagram

As can be seen in the block diagram illustrated in Figure 2, five different generation sources were used in the study. These are thermal, hydropower, wind, solar and nuclear generation sources. The closed loop electrical power control system is controlled by a fuzzy logic PI controller. Accordingly, the instantaneous error e of the system is calculated together with a certain tolerance generation amount and optimized by the controller. According to the *p* value obtained with the optimization, the generation resources provide the load balance of the system by adjusting the supply (generation) against the demand in proportion to their capacities.

The system parameters of the generation resources used in this study are given in Table 1. According to Table 1, the 24-hour status of a distributed system structure with different types of generation resources and a total installed power of 100000 MW was examined according to 6 different demand change scenarios and evaluations were made. As mentioned in the next sections of the article, the first of the demand change scenarios includes a stable demand change, while the others include possible difficult conditions such as sudden drastical demand increases and decreases. In all scenario applications in the present study, the tolerance generation value is taken as 20%. The single line diagram of the system is given in Figure 3.

Table 1. System parameters

Generation Source	C_{max} (MW)	T (min)	τ (hour)	Generation Model $G(s)$
Thermal	45000	25	0.263	$(0.014p^2 + 4p) / (0.263s + 1)$
Hydropower	30000	5	0.053	$(0.013p^2 + 4p) / (0.053s + 1)$
Wind	11000	8	0.084	$(0.011p^2 + 3p) / (0.084s + 1)$
Solar	9000	5	0.053	$(0.008p^2 + 2p) / (0.053s + 1)$
Nuclear	5000	5	0.053	$(0.015p^2 + 5p) / (0.053s + 1)$

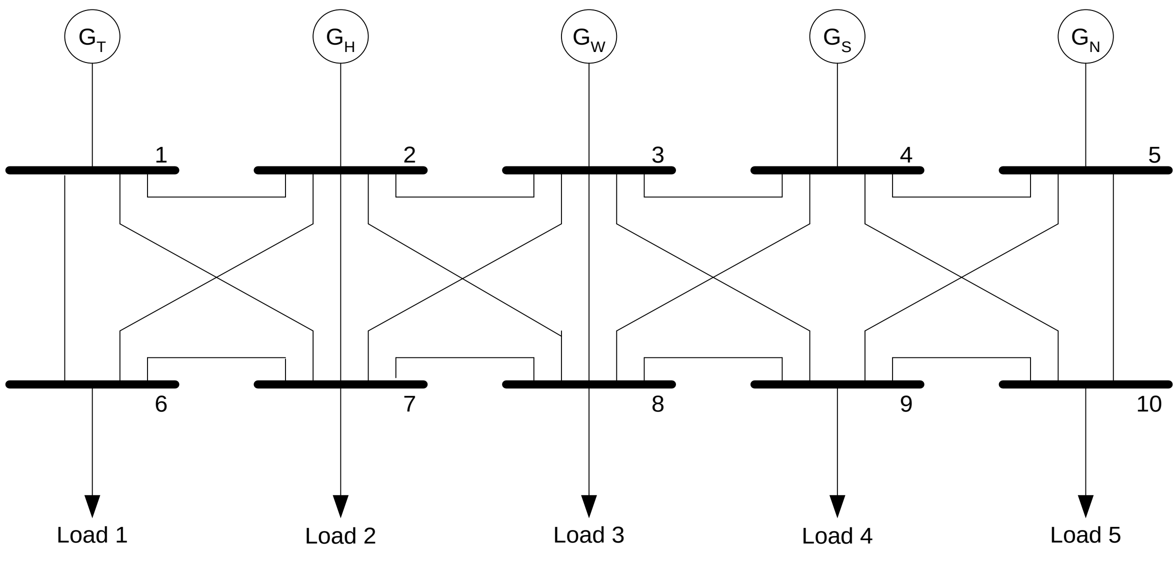


Figure 3. Single line diagram of the system

The structure and parameters of the Fuzzy logic PI controller used in the study are given in Figure 4, Figure 5, Figure 6, and Figure 7, respectively.

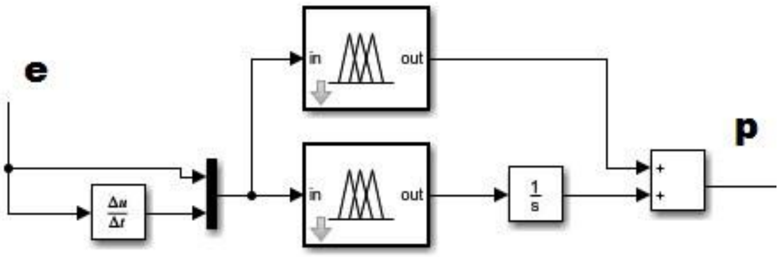
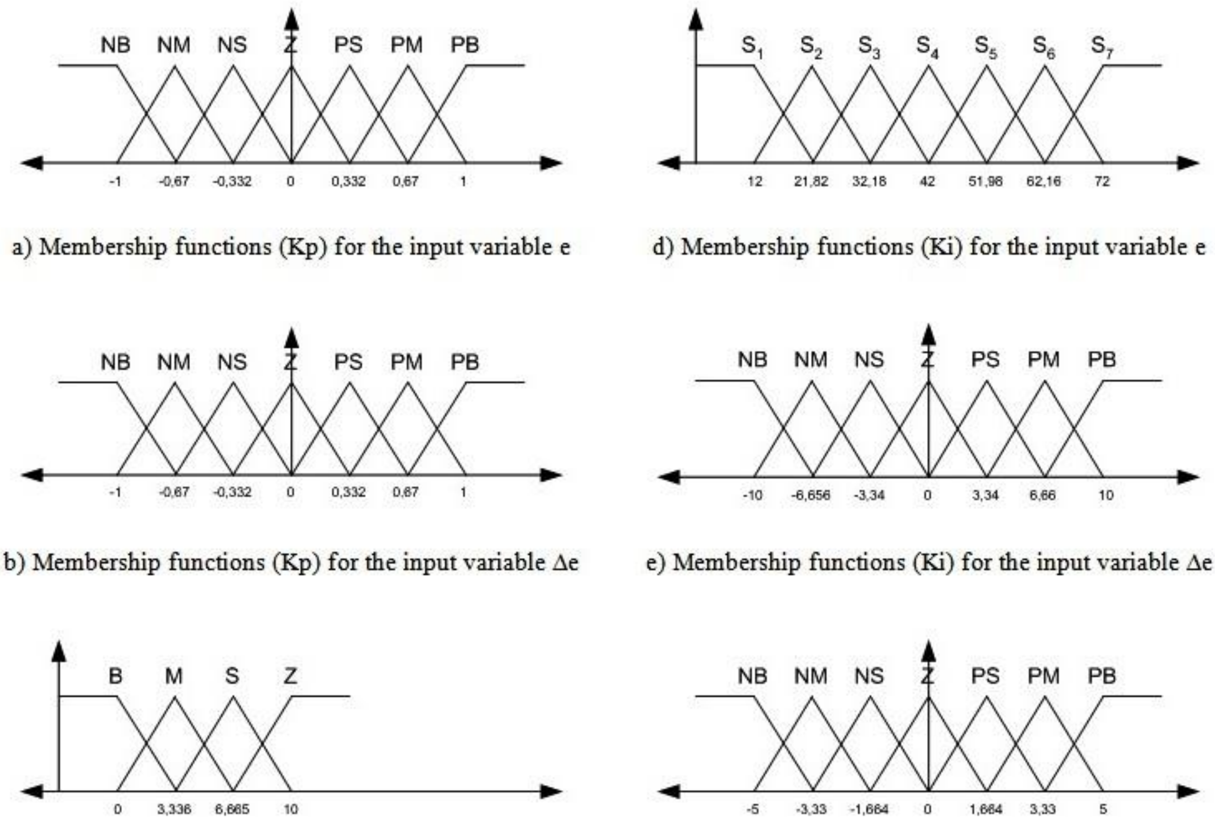


Figure 4. Proposed Fuzzy Logic PI controller model



a) Membership functions (Kp) for the input variable e

d) Membership functions (Ki) for the input variable e

b) Membership functions (Kp) for the input variable Δe

e) Membership functions (Ki) for the input variable Δe

c) Membership functions for the output signal Kp

f) Membership functions for the output signal Ki

Figure 5. Membership functions

		Δe						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
e	**NB**	B	B	B	M	M	S	Z
	NM	B	B	M	M	S	Z	S
	NS	B	M	M	S	Z	S	M
	Z	M	M	S	Z	S	M	M
	PS	M	S	Z	S	M	M	B
	PM	S	Z	S	M	M	B	B
	PB	Z	S	M	M	B	B	B

Figure 6. Fuzzy Logic Rules table of Kp output signal

		Δe						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
e	S_1	PB	PB	PM	PM	PS	PS	Z
	S_2	PB	PM	PM	PS	PS	Z	NS
	S_3	PM	PM	PS	PS	Z	NS	NS
	S_4	PM	PS	PS	Z	NS	NS	NM
	S_5	PS	PS	Z	NS	NS	NM	NM
	S_6	PS	Z	NS	NS	NM	NM	NB
	S_7	Z	NS	NS	NM	NM	NB	NB

Figure 7. Fuzzy Logic Rules table of Ki output signal

Due to the nature of wind and solar generation sources, it is not actually possible to reach the maximum power specified in Table 1 at all hours in a day. For this reason, the energy capacity changes of wind and solar generation sources are accepted as in Figure 8 [6]. In the simulation applications carried out in the study, the capacity changes given in Figure 8 were used.

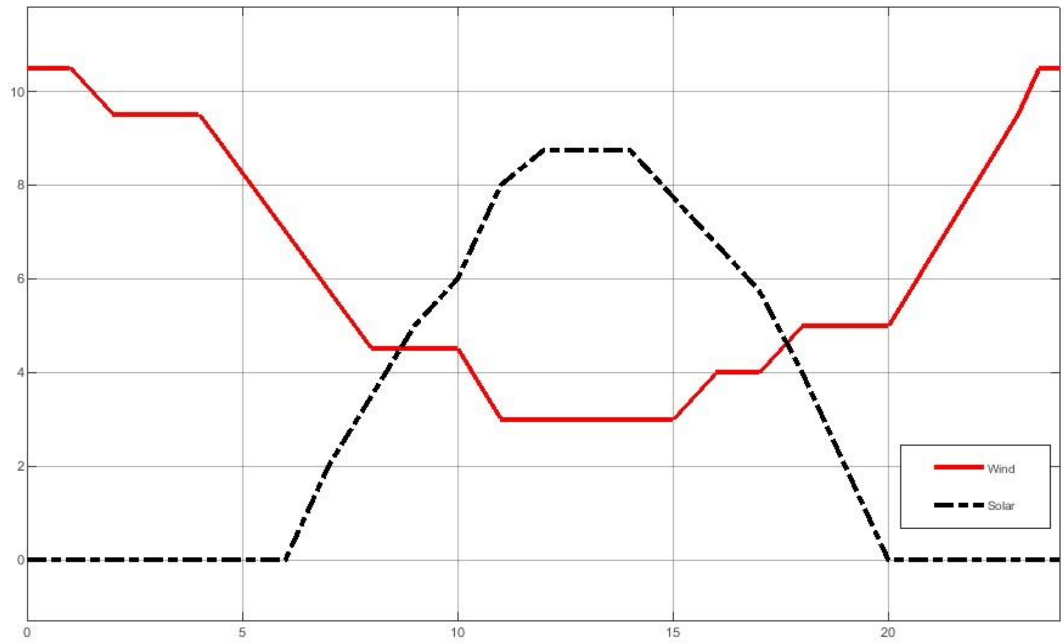


Figure 8. Changes in maximum energy capacity (GW) of wind and solar generation sources during a day

3. APPLICATIONS FOR DIFFERENT DEMAND CHANGE SCENARIOS

In this part of the study, the results obtained by performing 6 different simulation applications using the MATLAB/Simulink program are given. In each scenario application, the closed-loop electrical power control system block diagram given in Figure 2 is used. The performance of the Fuzzy Logic PI Controller, which is proposed in the face of stable demand conditions and possible difficult conditions such as sudden drastical demand increases and decreases for a distributed power system, is examined in applications. In the application called Scenario A, the situation in which the demand is stable in general despite small changes is analyzed, while in the applications called Scenario B and C, the situations where there are sudden drastical demand increases are analyzed. In Scenario D and E cases, where there are sudden drastical decreases in demand, and in Scenario F, both sudden drastical demand decrease and increases are examined.

3.1. Scenario A Application

In response to a generally stable demand change given in Figure 9, when using the fuzzy logic PI controller, whose structure and parameters are expressed in the second part of the study, as a controller in the closed-loop electric power control system in Figure 2, the obtained generation response, supply(generation)/demand ratio and price response are given in Figure 9, Figure 10 and Figure 11, respectively.

When Figure 9 is examined, it is seen that in a stable demand situation, the generation amount also changes stably by abiding by the 20% generation tolerance. It is observed in Figure 9 that although there are time delays in the self-adjustment of the generation response according to the demand, it reaches the desired level approximately after a while, the generation tends to decrease when the demand starts to decrease, and the generation tends to increase when the demand starts to increase.

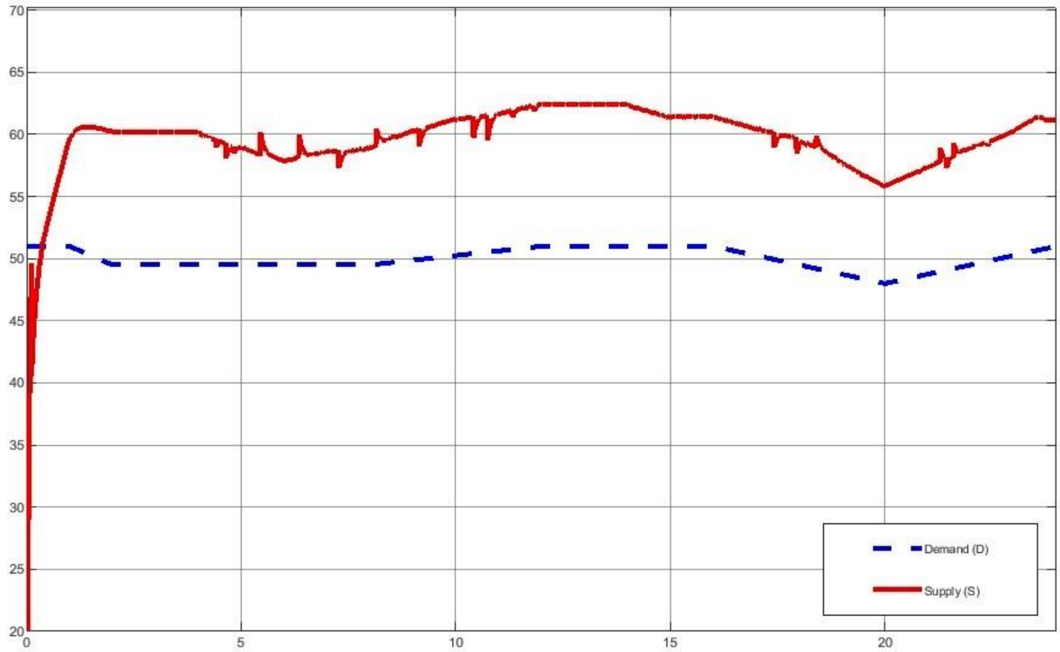


Figure 9. Change in demand applied to the system according to Scenario A and the generation response (GW) of the system against demand

If the Supply/Demand ratio of the system is less than 1, it means that less generation is made according to the demand, so there will be interruptions in the electrical power system. Of course, this situation is undesirable for an electrical power system. This is why 20% tolerance generation is already used in the applications made in this study. Because, depending on the change in demand, it is inevitable that oscillations will occur during the self-adjustment process of the generation, that is, in the delay time until the system stabilizes, and the tolerance value keeps the Supply/Demand ratio above 1 level. However, it is not appropriate for this value to be too large in terms of the economy of the system, as excessive tolerance will mean overgeneration. In Figure 10, the Supply/Demand ratio of the system is given for Scenario A. As a stable demand creates a stable generation response, the Supply/Demand ratio in this scenario is also seen as almost stable around 1.20 levels. In other scenarios in this study, the importance of keeping the

Supply/Demand ratio above 1 will be better understood. Figure 11 shows the price *(p)* response of the system. Similarly, although there are occasional oscillations, the price response remains stable at about 5.62.

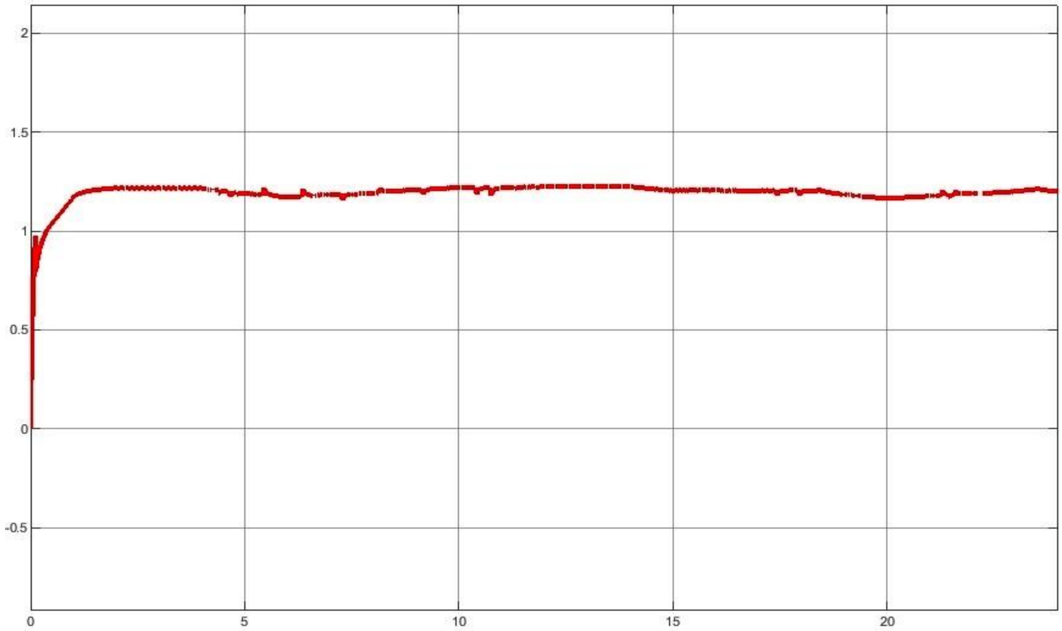


Figure 10. Supply(Generation)/Demand ratio of the system according to Scenario A

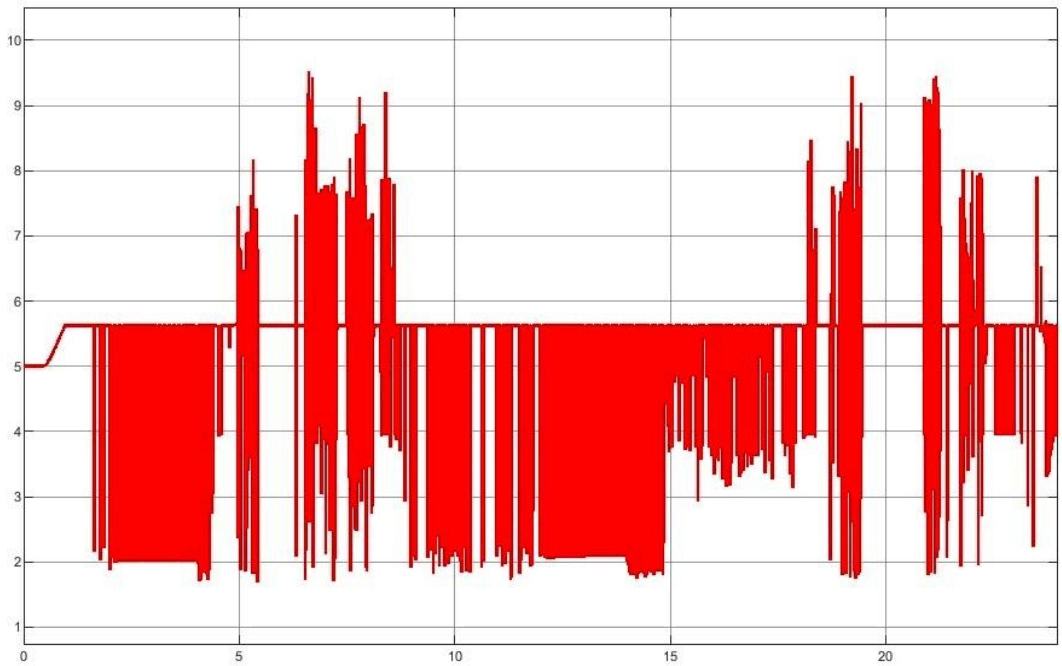


Figure 11. The price *(p)* response of the system according to Scenario A

3.2. Scenario B Application

In Figure 12, a sudden demand increase of 13.5 GW in the 8th hour and a generally stable demand change in the other hours are seen. In response to this demand change, when the fuzzy logic PI controller, which is suggested as the controller in the closed-loop electrical power control system in Figure 2, is used, the obtained generation response, supply(generation)/demand ratio and price response are given in Figure 12, Figure 13 and Figure 14, respectively.

When Figure 12 is analyzed, it is seen that in case of a sudden increase in demand at the 8th hour, generation tends to increase with a certain delay, and when the sudden increase in demand ends, it first shows a downward trend, and then settles to a new generation level. It is seen that the Supply/Demand ratio of the system given in Figure 13 approaches 1 due to the decrease in the Supply-Demand difference together with the time delay in the generation response in the time period when the sudden demand increase occurs. However, it did not fall below this level. In this application, the tolerance generation amount kept the Supply/Demand ratio above 1 level. It is observed that the price response given in Figure 14 also changed according to the new generation level after the sudden increase in demand and became stable at approximately 6.61 level.

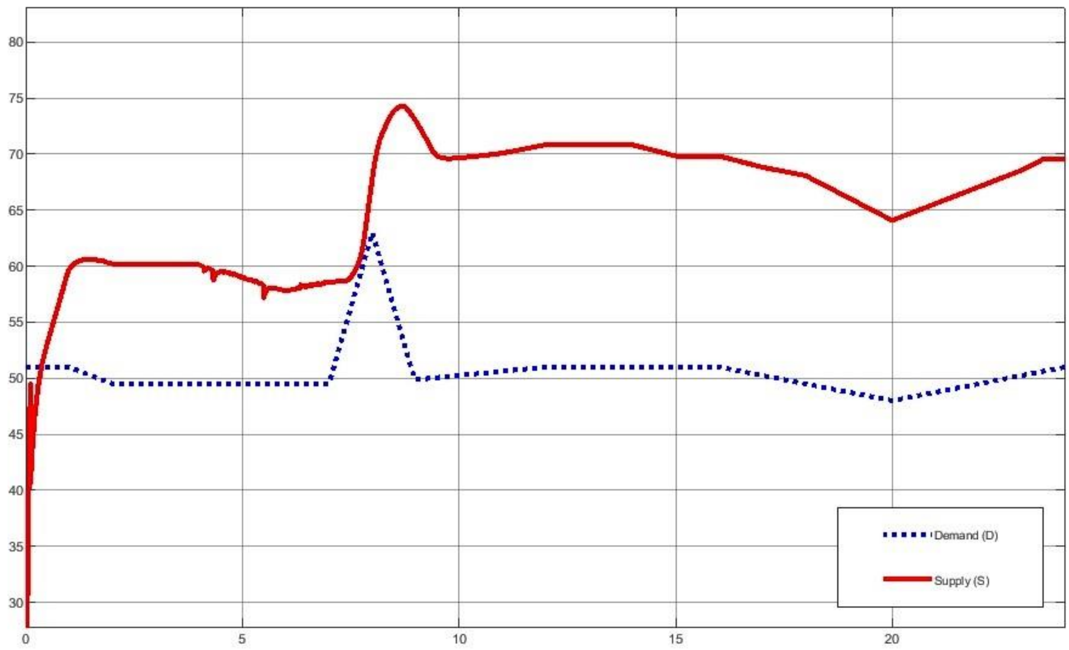


Figure 12. Change in demand applied to the system according to Scenario B and the generation response (GW) of the system in response to demand

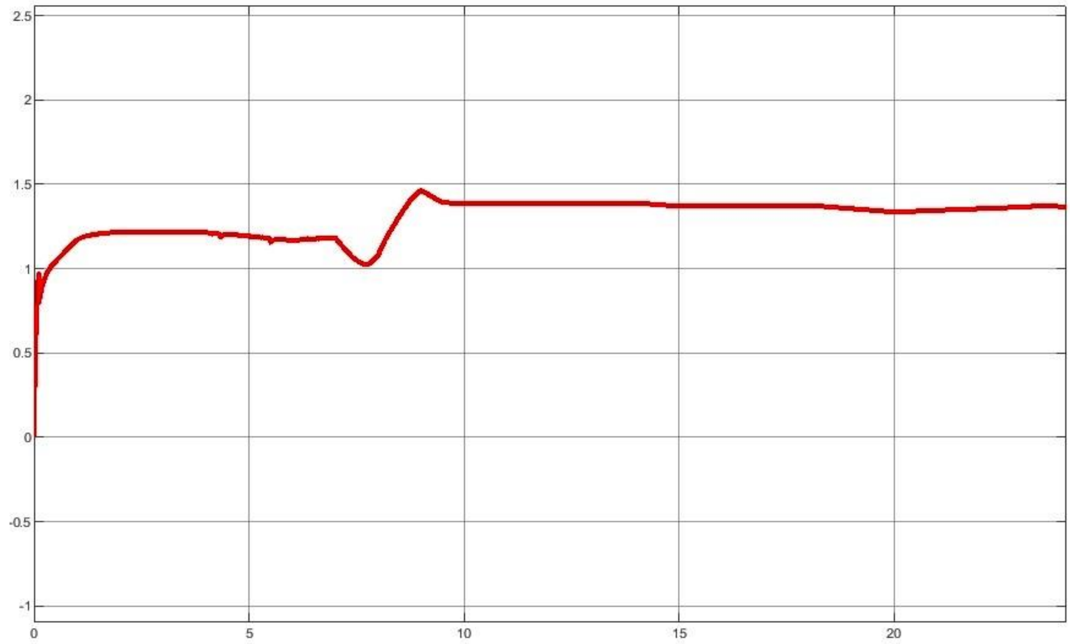


Figure 13. Supply(Generation)/Demand ratio of the system according to Scenario B

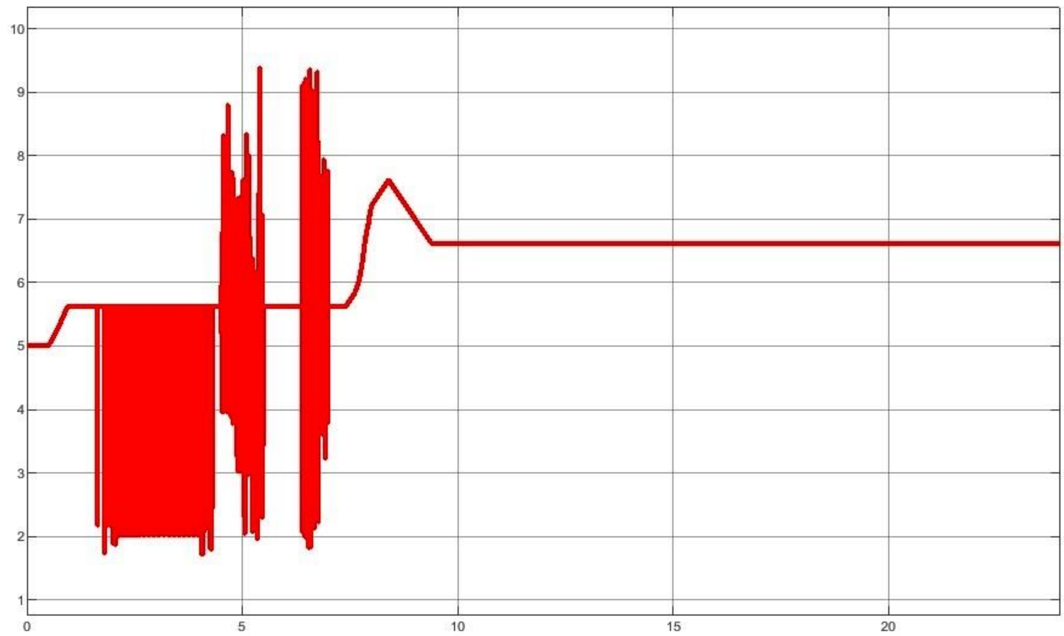


Figure 14. The price (*p*) response of the system according to scenario B

3.3. Scenario C Application

In Figure 15, both a sudden demand increase of 13.5 GW at the 8th hour and also 16 GW at the 20th hour, and a generally stable demand change at the other hours are seen. In response to this demand change, the generation response, supply(generation)/demand ratio and price response obtained when fuzzy logic PI controller is used as the controller in the the closed-loop electric power control system in Figure 2, are given in Figure 15, Figure 16 and Figure 17, respectively.

When Figure 15 is analyzed, it is seen that in the case of a sudden increase in demand at the 8th hour, generation tends to increase with a certain delay and when the sudden increase in demand ends, it first shows a downward trend and then settles to a new generation level. In the 20th hour, with a sudden increase in demand with a higher intensity, the generation amount increased with a certain time delay again and it was positioned at a new generation level. It is seen that the Supply/Demand ratio of the system given in Figure 16 approaches 1, but does not fall below this level, depending on the reasons explained in the previous applications, during the time intervals when sudden demand increases occur. It is observed that the price response given in Figure 17 changed according to the new generation level after both two sudden demand increases and finally stabilized at approximately 9.30 level. Of course, in this scenario example, a serious forced case has been tested. Therefore, it is not possible to talk about economics. It is considered as a positive result that the system does not reduce the Supply/Demand ratio below 1 level by adjusting the generation according to the new demand.

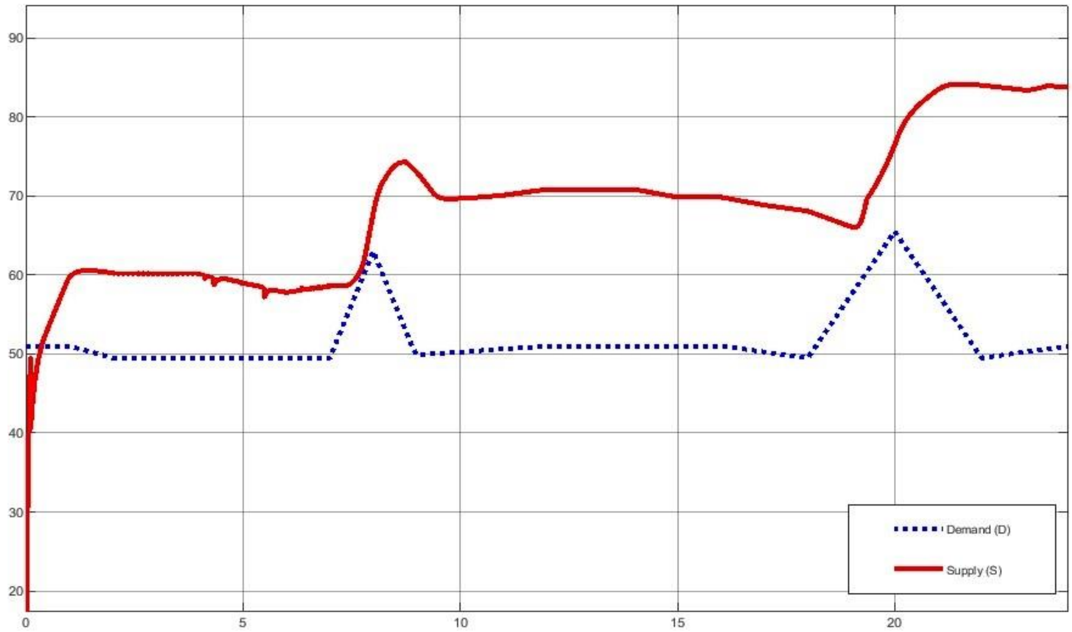


Figure 15. Change in demand applied to the system according to Scenario C and the generation response (GW) of the system against demand

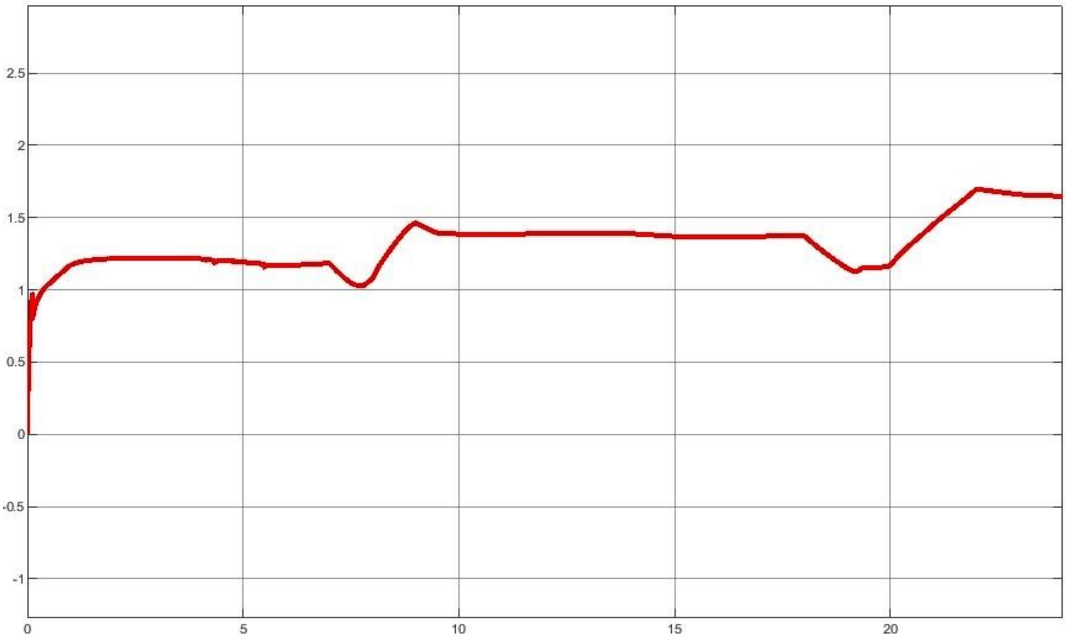


Figure 16. Supply (Generation)/Demand ratio of the system according to Scenario C

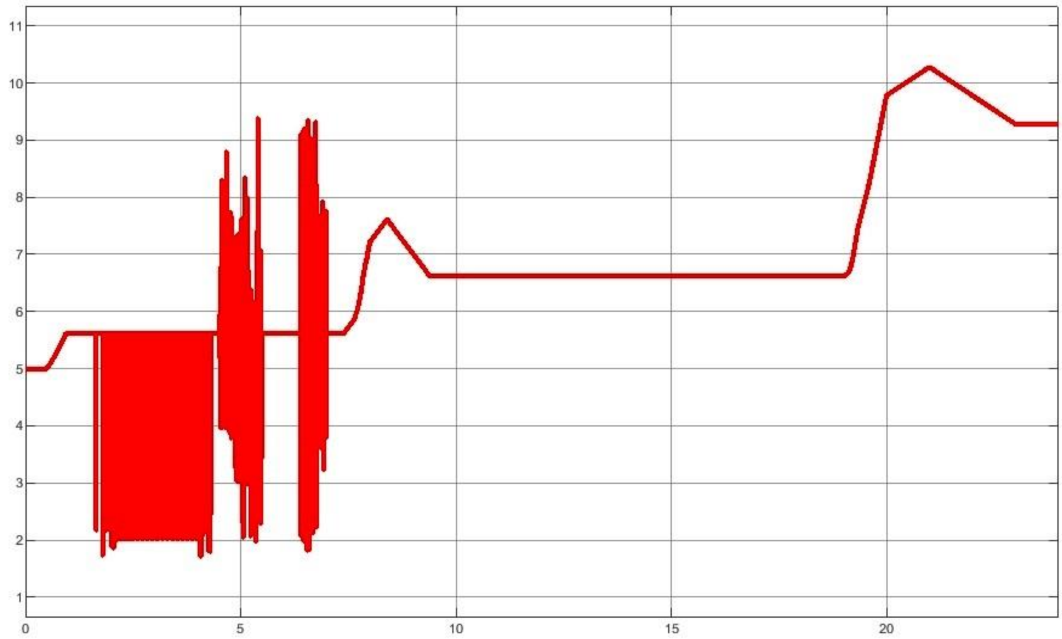


Figure 17. The price (*p*) response of the system according to scenario C

3.4. Scenario D Application

In Figure 18, a sudden decrease in demand of 15 GW at the 20th hour and a demand change that is generally stable in other hours are seen. In response to this demand change, when the fuzzy logic PI controller is used as a controller in the closed loop electric power control system in

Figure 2, the obtained generation response, supply(generation)/demand ratio and price response are given in Figure 18, Figure 19 and Figure 20, respectively.

When Figure 18 is analyzed, it is seen that in case of a sudden decrease in demand at the 20th hour, generation also enters a downward trend with a certain time delay, and when the sudden decrease in demand ends, it increases again and is positioned at a new generation level. It is seen that the Supply/Demand ratio of the system given in Figure 19 increased to higher levels due to the increase in the Supply-Demand difference together with the time delay in the generation response in the time period when the sudden decrease in demand occurred. It is observed that the price response given in Figure 20 also changed according to the new generation level after the sudden decrease in demand and became stable at the level of approximately 6.1.

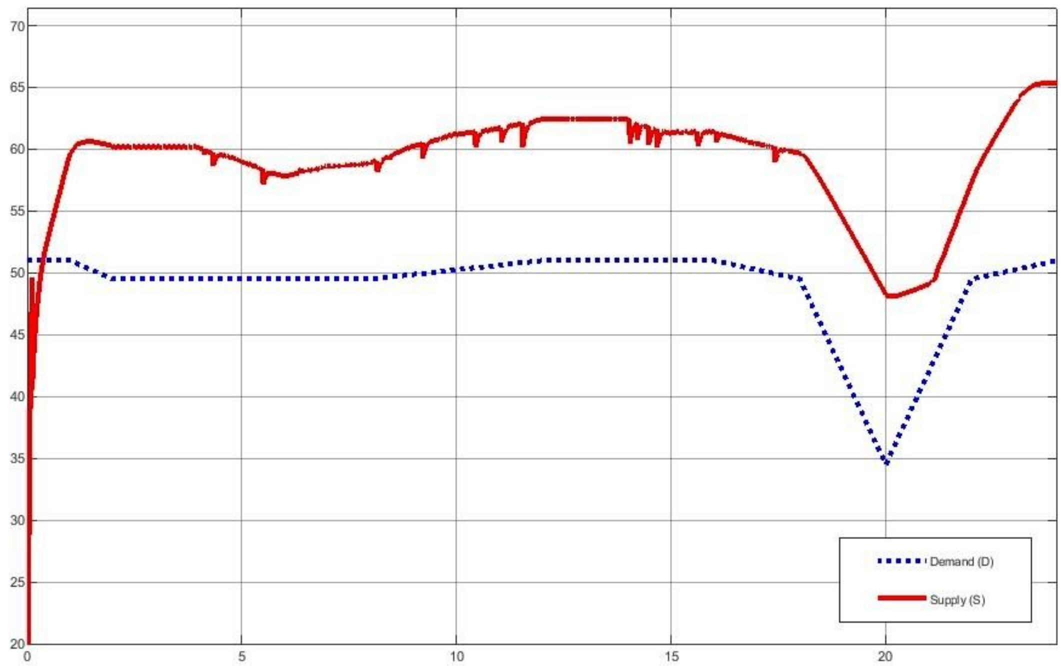


Figure 18. Change in demand applied to the system according to Scenario D and the generation response (GW) of the system against demand

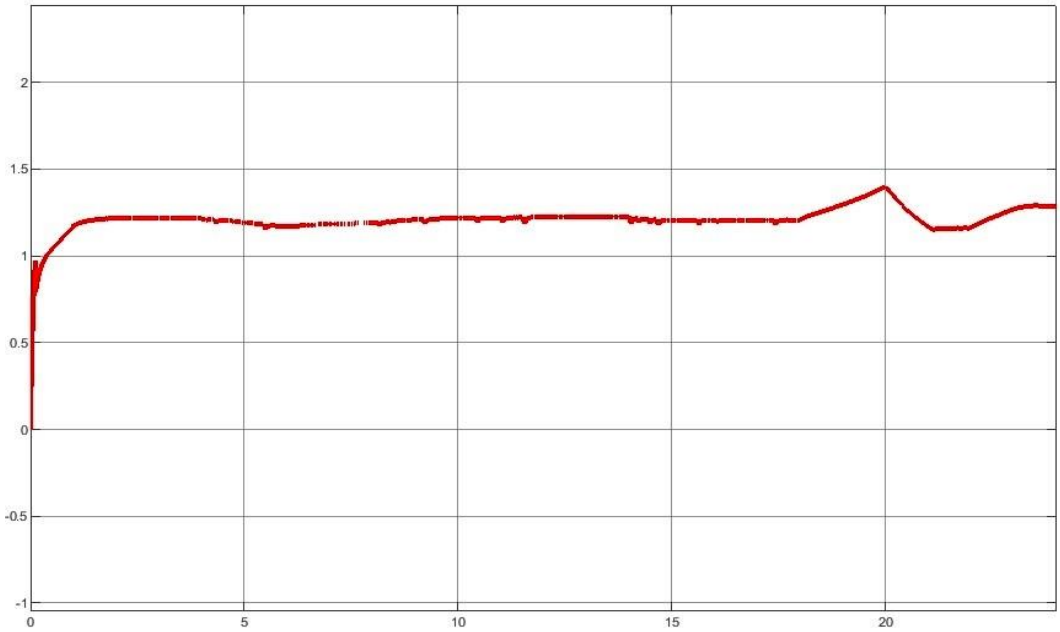


Figure 19. Supply (Generation)/Demand ratio of the system according to Scenario D

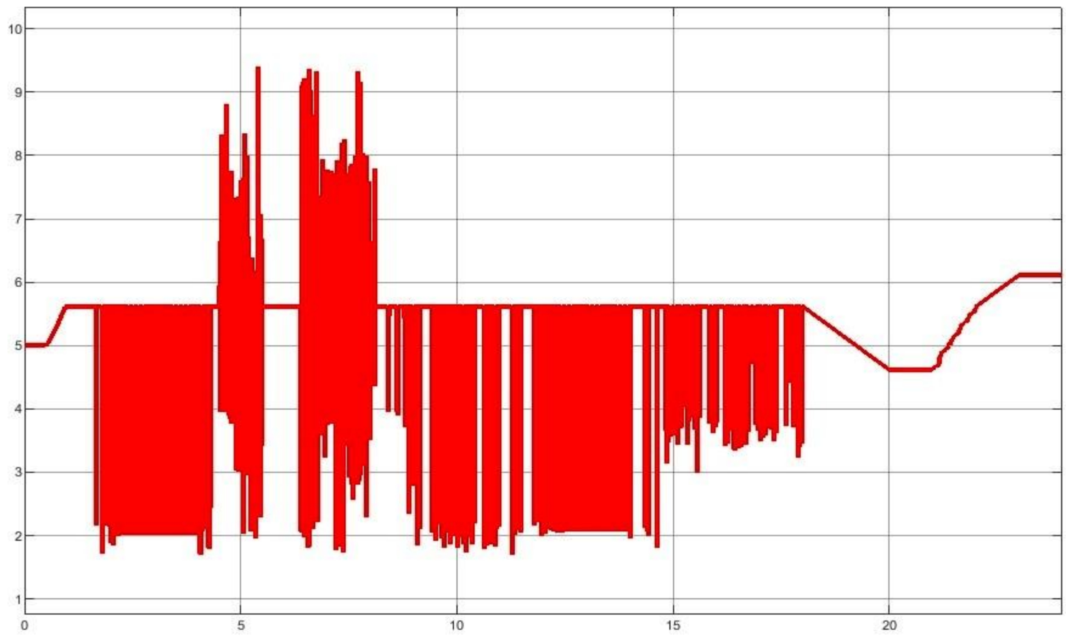


Figure 20. The price (*p*) response of the system according to scenario D

3.5. Scenario E Application

In Figure 21, both a sudden demand decrease of 9.5 GW at the 4th hour and also 15 GW at the 20th hour, and a generally stable demand change at the other hours are seen. In response to this demand change, the generation response, supply(generation)/demand ratio and price response obtained when fuzzy logic PI controller is used as the controller in the the closed-loop electric power control system in Figure 2, are given in Figure 21, Figure 22 and Figure 23, respectively.

When Figure 21 is analyzed, it is seen that in case of a sudden decrease in demand at the 4th hour, generation also enters a downward trend with a delay for a certain period of time, and when the sudden decrease in demand ends, it increases again and is positioned at a new generation level. At the 20th hour, however, with a sudden decrease in demand with a higher intensity, and again with a delay in time, the generation amount first started to decline. Then, when the sudden decrease in demand ended, it increased again and positioned itself to a new generation level. In Figure 22, the Supply/Demand ratio of the system is seen. It is observed that the price response given in Figure 23 changed according to the new generation level after both two sudden demand decreases and finally stabilized at about 6.21 levels.

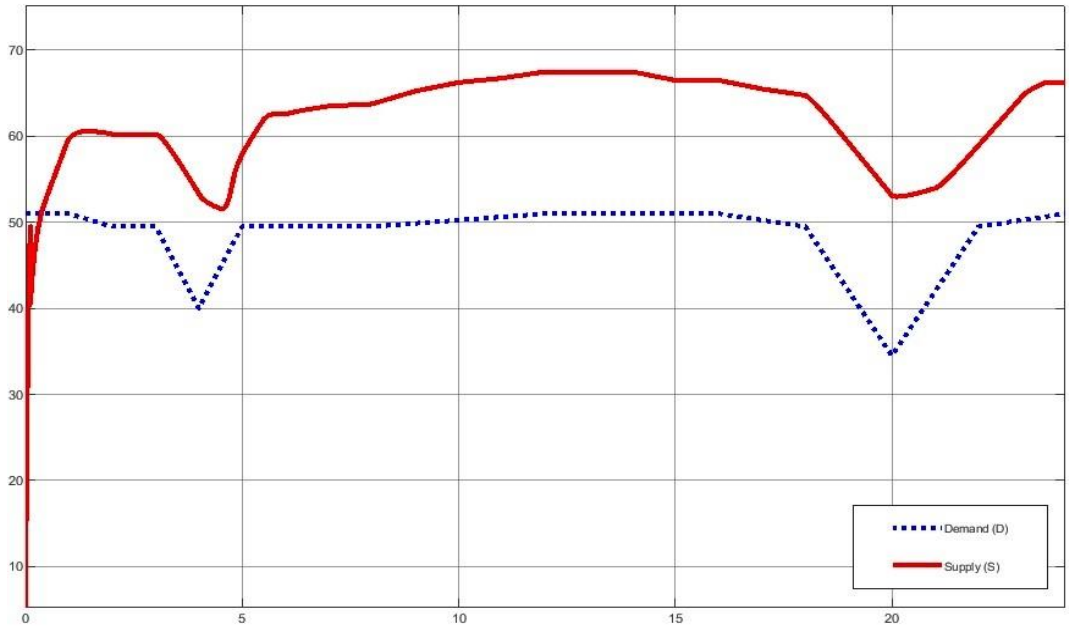


Figure 21. Change in demand applied to the system according to Scenario E and the generation response (GW) of the system against demand

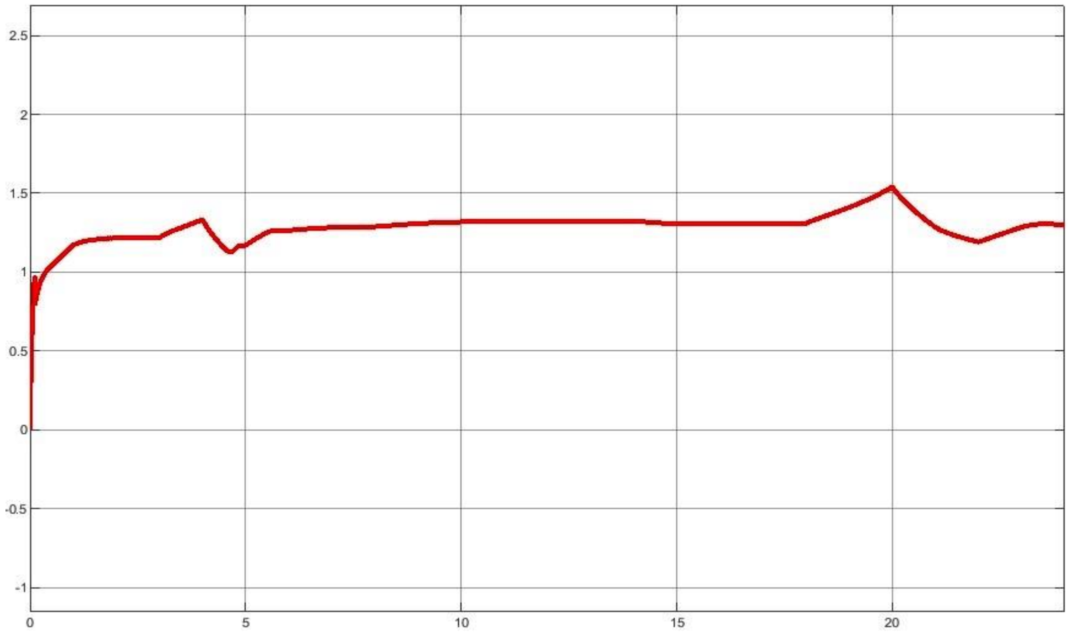


Figure 22. Supply (Generation)/Demand ratio of the system according to Scenario E

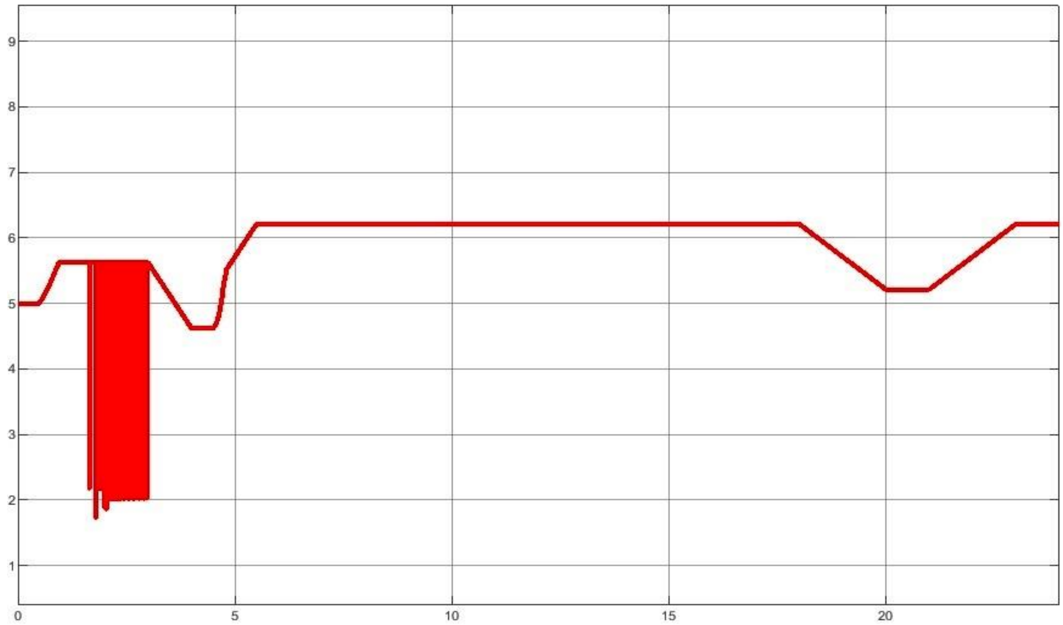


Figure 23. The price (*p*) response of the system according to scenario E

3.6. Scenario F Application

In Figure 24, both a sudden demand decrease of 9.5 GW at the 4th hour and also a sudden demand increase of 13.5 GW at the 8th hour, and a generally stable demand change in the other hours are seen. In response to this demand change, the generation response, supply(generation)/demand ratio and price response obtained when fuzzy logic PI controller is used as the controller in the closed-loop electric power control system in Figure 2, are given in Figure 24, Figure 25 and Figure 26, respectively. The system responses obtained in the sudden decrease in demand and sudden increase in demand in the previous scenarios are similarly encountered in this scenario.

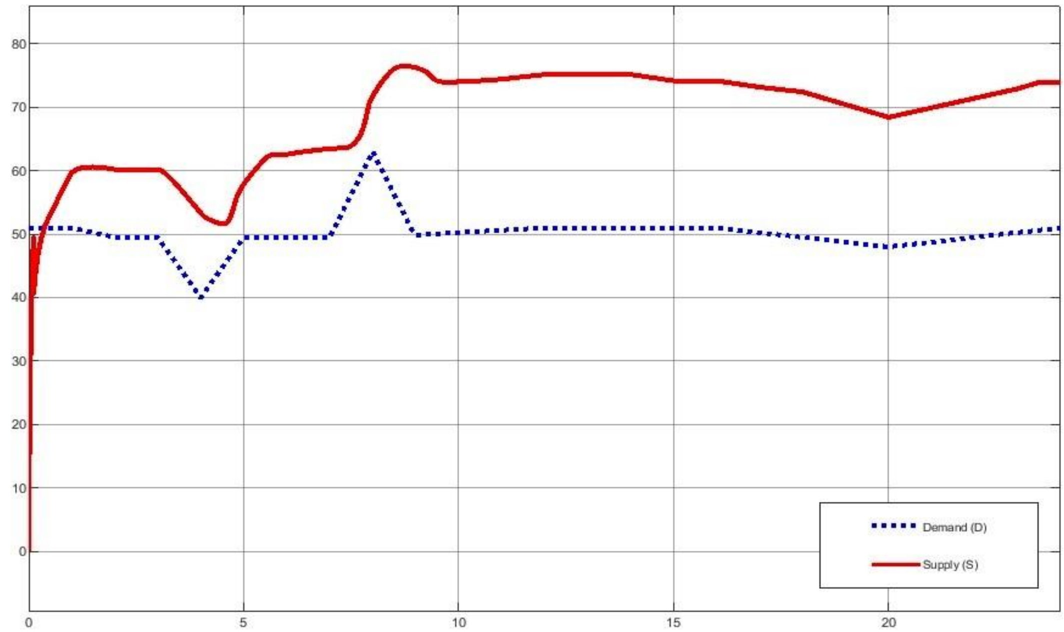


Figure 24. Change in demand applied to the system according to Scenario F and the generation response (GW) of the system in response to demand

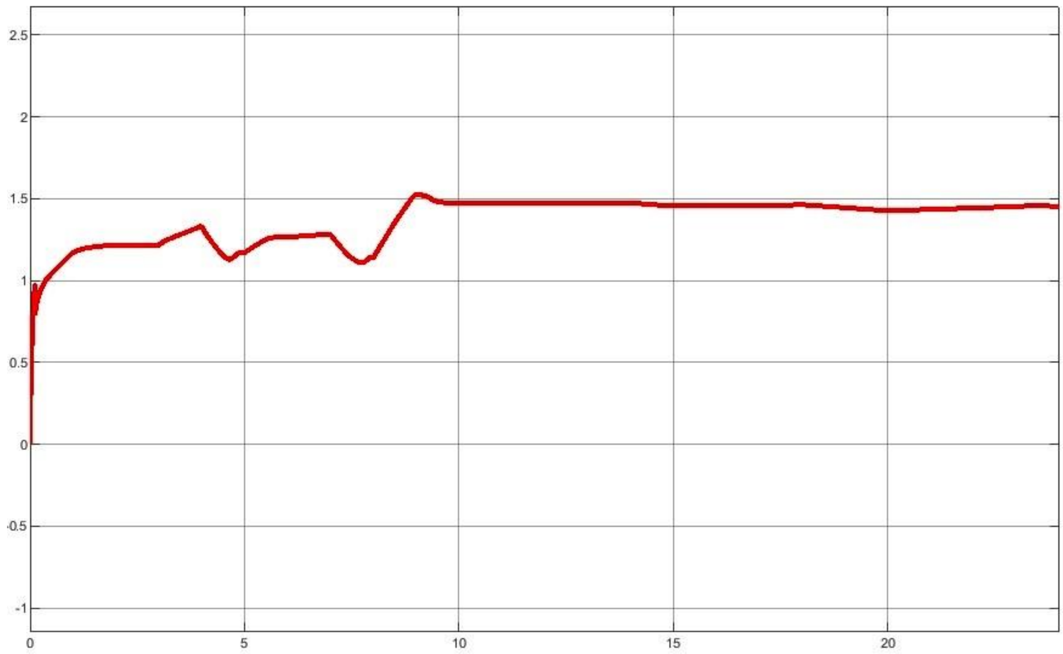


Figure 25. Supply (Generation)/Demand ratio of the system according to Scenario F

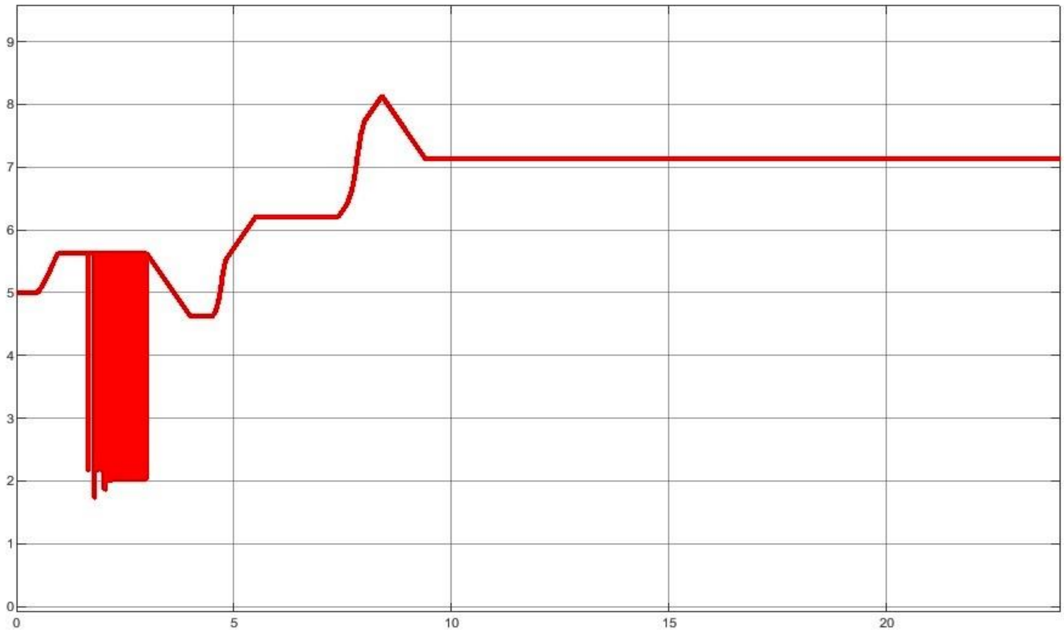


Figure 26. The price (*p*) response of the system according to scenario F

4. CONCLUSION

In this study, load balance in electrical power systems is investigated by adjusting the generation of energy generation sources in a closed loop electrical power control system model using fuzzy logic PI controller according to change in customer demands in smart grids, depending on electrical energy pricing. The power system model used represents a distributed system structure consisting of different types of generation resources. A fuzzy logic PI controller is used as the controller in the closed loop electrical power control system.

Fuzzy logic applications are one of the methods used for optimization and give better results than many methods. Especially in this study, it is preferred to use a fuzzy logic PI controller to provide load balance, since it is suitable for smart grid technology logic. Because a fuzzy logic PI controller can adjust itself according to changing system parameters and demand conditions.

When the demand change scenarios used in the study are examined, the main purpose of the study is to provide energy balance in the face of difficult conditions such as sudden sharp demand increases and instantaneous sharp demand decreases, which are always possible in an electrical power system. In line with this main purpose, different scenarios such as consecutive sudden demand increases and decreases are examined. It has been observed that the performance of the fuzzy logic PI controller used is positive.

In conclusion; It has been suggested to use a fuzzy logic PI controller, which is an smart system suitable for smart grid technology, in energy balance management applications based on dynamic pricing, which has an important place in the formation of system stability and price stability in electrical power systems.

NOMENCLATURE

$e(t)$: Load balance error

p : Price

D : Energy demand

S : Energy supply

N : Generation volume

Q : Optimal price point

P_L : Low price

P_H : High price

P_{OPT} : Optimal price

$S_d(p)$: Function of generation capacity for the unit energy price

$S(s)$: Transfer function of the energy generation response of the resource against the price

τ : Time constant

C_{max} : Maximum installed power of the generation system

p_0 : Average energy generation cost

$G(s)$: Generation model

T : Average time required for the relevant generation resource to reach the maximum generation from zero generation

$G_T(s)$: Generation model for thermal generation source

$G_H(s)$: Generation model for hydropower generation source

$G_W(s)$: Generation model for wind generation source

$G_S(s)$: Generation model for solar generation source

$G_N(s)$: Generation model for nuclear generation source

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Ahmet Karyeyen: Performed the applications, analyse the results, and wrote the manuscript.

Nurettin Cetinkaya: Analyse the results, and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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