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Improvement of Frequency Stability in the Power System Considering Wind Turbine and Time Delay

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ABSTRACT

In the power system, frequency stability is critical. The wind turbine oscillates (depending on the wind speed) and is of low inertia. Thus, wind turbines face the issue of power system frequency stability. Since the power system's resources are interconnected via communication networks, the presence of time delay also affects the frequency stability of the power system. When a disturbance occurs in the power system due to load or distributed generation sources (wind turbine), it leads to frequency deviations in the power system, exhibiting low damping speed. Although large conventional generators in the power system provide sufficient inertia and reduce frequency deviation, the damping speed of frequency fluctuations is slow, which may be due to time delays between power system resources. In this paper, virtual damping (a proposed method) is used to accelerate the damping of frequency deviations caused by load disturbances, distributed generation source disturbances, and the time delay between power system resources. The results of the proposed method are compared to those obtained using the conventional method in this field, demonstrating the superiority of the proposed method. The proposed method reduced frequency deviations in the power system caused by disturbances and time delays by 67 % (a 67 % improvement over existing methods in this field) and increased the damping speed of the frequency deviations by 62 % (a 62 % improvement over the methods used in this field).

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1. INTRODUCTION

The conventional energy generation system should be replaced by renewable energy sources since the uncontrolled use of fossil fuels is accompanied by global warming and environmental hazards, besides the danger of their depletion, and because much of the energy derived from these fuels is consumed by buildings [1]. Renewable energy systems impact the process of meeting domestic energy demands [2]. Due to the increased demand for electricity today, distributed generation sources such as wind turbines have made significant inroads into the power system [3, 4]. Wind turbine development has aided human progress throughout history [5, 6]. While incorporating a wind turbine into the power system has numerous benefits, the power system faces several challenges [7, 8]. The issue of frequency control is one of the primary challenges posed by the presence of turbines in the power system [9]. The power system is in a steady state when production and consumption are balanced, and if this equilibrium is lost to a disturbance, the frequency deviates from the nominal value [10]. If the system's frequency fluctuations are not controlled, they can cause significant damage, even up to the point where a production unit shuts down [11]. The primary control loop is the initial control loop responsible for limiting the frequency drop following a disturbance [12, 13]. This control loop is based on the generator's true frequency-power characteristic and is installed on the generator [13]. The primary control loop constrains the dropped frequency, but is unable to restore it to its nominal value, necessitating the use of another interactive loop termed as the secondary frequency control [14]. The load-frequency control loop can only respond to small-scale and slow changes in load and frequency and is, therefore, incapable of controlling emergencies and the resulting power imbalance. The control of systems during emergencies and rapid changes is investigated in terms of their transient stability and protection [15]. Active power primarily changes the system's frequency, whereas reactive power is insensitive to frequency and is primarily affected by changes in voltage magnitude [16]. As a result, active and reactive powers are managed separately. The loop regulates the Load-Frequency Control (LFC), the actual power, and frequency, and the reactive power and voltage magnitude are also regulated by the Automatic Voltage Regulator (AVR) [17]. The presence of a wind turbine in a power system reduces the system inertia, which later dampens frequency deviations [18]. Even in the presence of wind turbines, large synchronous generators provide sufficient inertia for the power system, but the problem of slow damping frequency deviations persists [19].

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Several methods have been developed to enhance the frequency stability of the power system in the presence of a wind turbine.

The sliding mode controller is used for Load-Frequency Control (LFC) in a wind turbine-powered power system [20]. Model Predictive Control (MPC) is used to control the load frequency in a power system with a wind turbine [21, 22]. In the presence of a wind turbine, the power system is controlled using a coordinated energy storage source and load-frequency control [23]. The power system and wind turbine controllers are highly complex [24, 25]. A neuro-fuzzy controller is used to coordinate the energy storage source and LFC in the power system in the presence of the wind turbine [26]. An optimized PID controller was used to coordinate the energy storage source and LFC in the power system in the presence of a wind turbine [27]. The methods for controlling the frequency in a power system with wind turbines perform well in the presence of disturbances and uncertainty in system parameters. They do, however, have challenges. These issues include the low damping speed of frequency deviations, the absence of wind turbine participation in the power system's frequency control, and the omission of time delays. Low damping speeds for frequency deviations may result in suboptimal performance of the frequency control system and frequency instability in the power system. The frequency deviation of the European power grid is greater than 0.1 Hz, and the wind turbine must participate in the issue of frequency control and compensate for the power grid's frequency deviations by changing its power [28]. Time delay in the power system is one of the issues that can cause numerous problems during frequency control system operation and result in frequency instability, which is why it is necessary to model time delay when controlling the power system's frequency. As a result, a method for frequency control in the power system is required to address the issues in this field.

The present study discusses the viablityof a method for frequency control in a power system with a wind turbine. The proposed method incorporates a virtual damping design on a wind turbine in the power system, thereby increasing the damping speed of power system frequency fluctuations. Among the other advantages of the proposed method are reduced power system frequency fluctuations and active wind turbine operation during control frequency. The proposed method is also designed to consider the effect of time delay. The results of the proposed method are compared to those of conventional methods, demonstrating the superiority of the proposed method in simulation. The proposed method reduced frequency deviations in the power system caused by disturbances and time delays by 67 % (a 67 % improvement over existing methods in this field) and increased the damping speed of the frequency deviations by 62 % (62 % improvement over the methods used in this field). This paper discusses the structure of a power system with a wind turbine, the proposed method, simulation, and results.

2. POWER SYSTEM STRUCTURE WITH THE PRESENCE OF WIND TURBINE

Figure 1 shows the general structure of the power system considering the wind turbine. The studied power system includes several hydropower plants, several non-reheat power plants, some reheat power plants, a number of wind turbines, several Energy Storage Systems (ESS), and different loads. The total amount of power produced in the studied power system is 38000 MW, while the peak load is 29000 MW [27]. Figure 2 shows the dynamic model of the study power system in which different components are modeled using the reduced-order model, which suits the stability analysis of frequency [12].

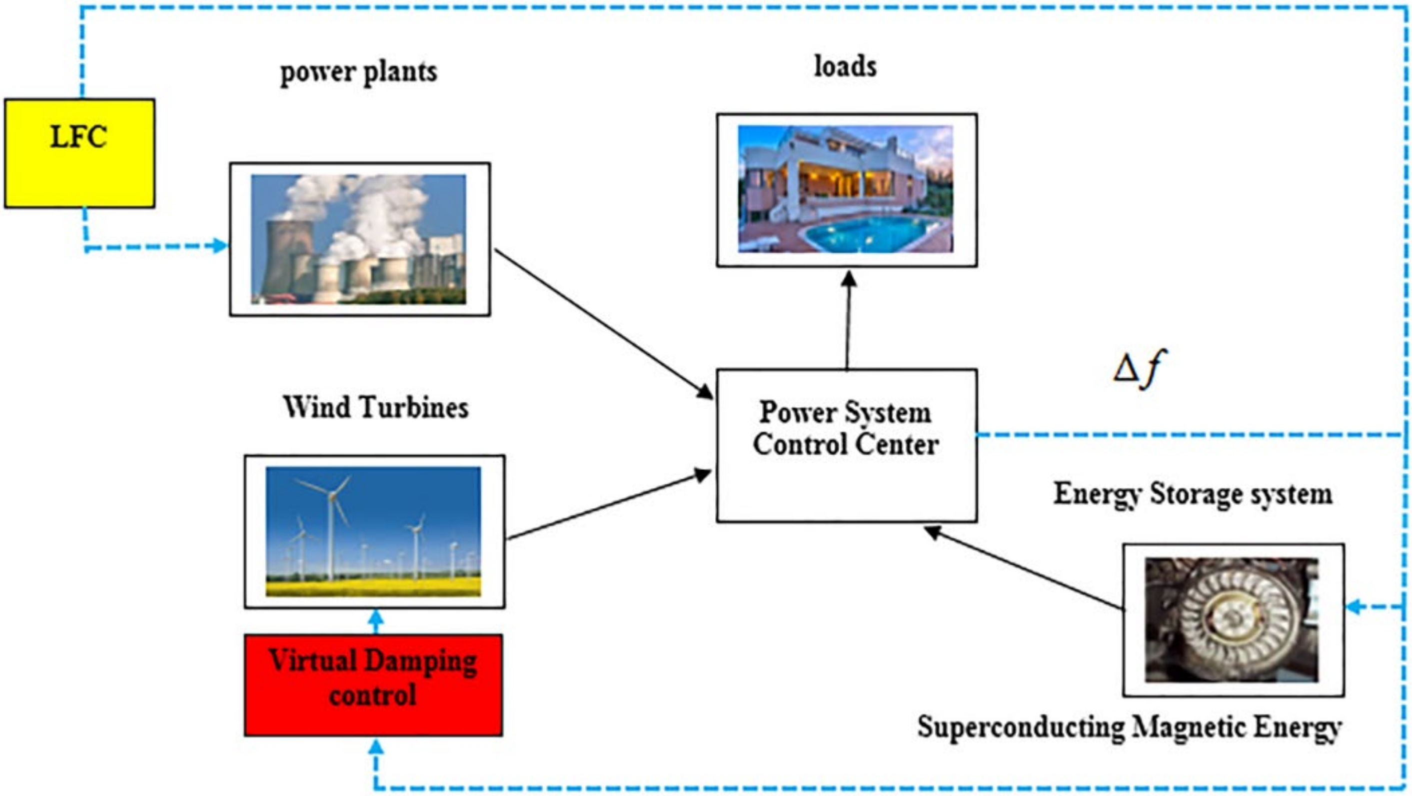

Figure 1. The general structure of the power system considering the wind turbine

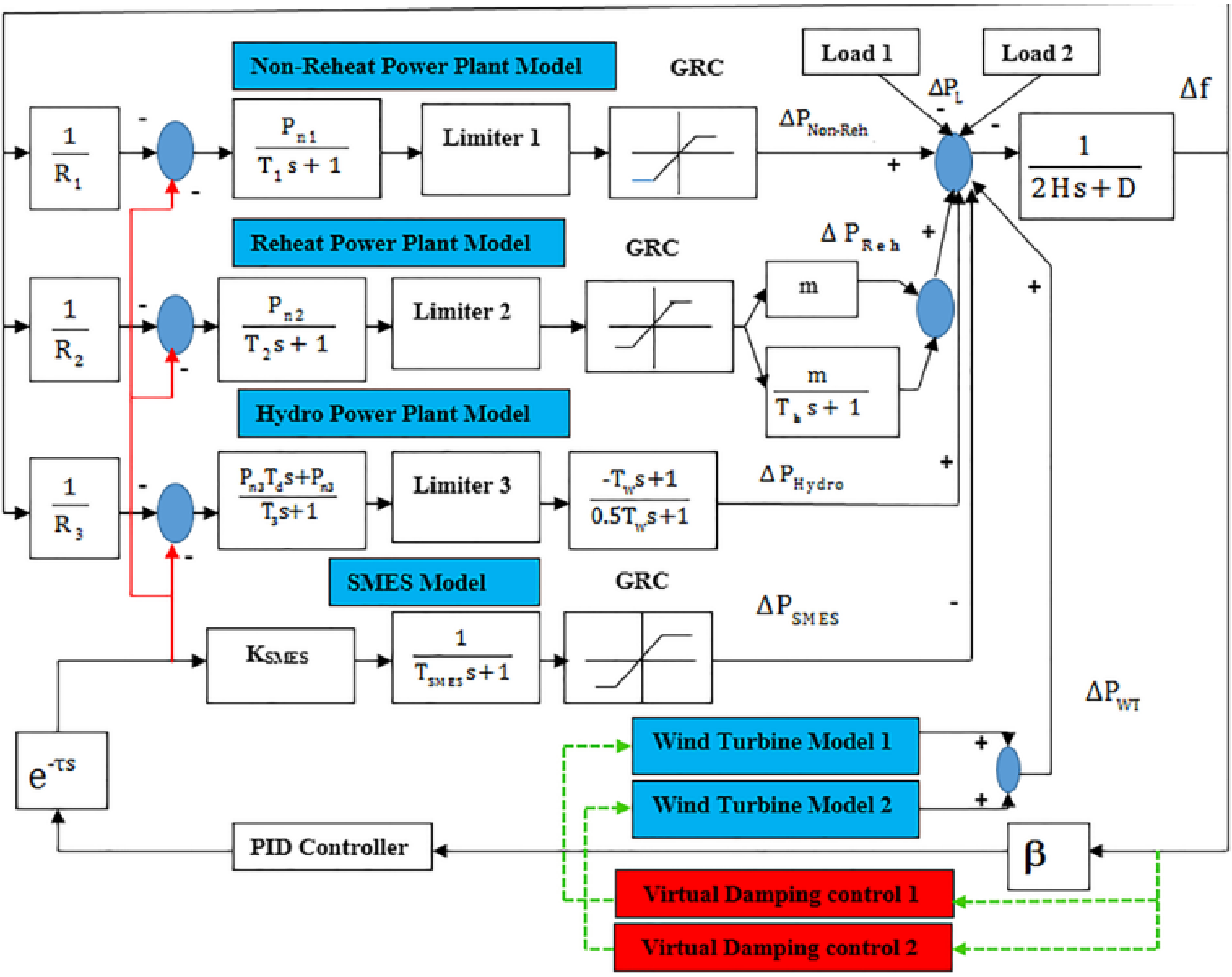

Figure 2. The dynamic model of the study power system

3. PROPOSED METHOD

3.1. The structure of the proposed method

The proposed method (virtual damping for wind turbines) is intended to mitigate frequency deviations caused by load disturbances and distributed generation source disturbances in the power system. It increases the frequency oscillations' damping speed. The proposed method activates the wind turbine during frequency control and also minimizes power system-related frequency deviations caused by disturbances. The dynamic model of the proposed method for wind turbines 1 and 2 is shown in Figure 3. When a disturbance occurs in the power system, feedback is obtained from the frequency deviation multiplied by the virtual Damping gain of wind turbine 1 (D_1) and the virtual Damping gain of wind turbine 2 (D_2). This signal is routed to the inverter of wind turbines 1 and 2. The coefficients D_1 and D_2, representing the virtual damping control gains for wind turbines 1 and 2, are proportional to the system and determined through system experiments. The proposed method bears no additional economical cost as it is merely a signal that increases the damping of frequency deviations in the power system when a wind turbine is present. During disturbances, the wind turbine operates passively under conventional control methods. To this end, the proposed method activates the wind turbine during disturbances. When a disturbance enters the power system, this method is used by the wind turbine to obtain feedback from the frequency deviations, reduce the frequency deviations, and enhance the frequency stability of the power system. In Figure 3, i = 1, 2, Δf denotes the power system's frequency deviation, Di is the virtual damping of wind turbines 1 and 2, ΔPwi denotes the output power of wind turbines 1 and 2, and ΔPwt is the output power of inverter wind turbines 1 and 2. The power system parameters in the presence of a wind turbine are listed in Table 1. Simulink MATLAB simulations were used to adjust the virtual damping associated with wind turbines 1 (D_1) and 2 (D_2). As illustrated in Figure 4, load disturbance is introduced into the power system to adjust the wind turbines' virtual damping gain. Additionally, the power system has a time delay ($\tau = 0.5$ sec.). Figure 5 illustrates the power system's frequency response to load disturbances. According to Figure 5, the trial-and-error method was used to determine the virtual damping gain of most turbines (D_1 and D_2). The maximum frequency deviation and settling time associated with the power system's frequency response are depicted in Figures 6 and 7, respectively. According to Figure 6, increasing the wind turbine's virtual damping gain reduces the power system's maximum frequency deviation. Thus, when tuning a wind turbine's virtual damping gain, the higher the gain, the lower the frequency deviation. According to Figure 7, as the virtual damping gain of a wind turbine increases, the settling time associated with the power system's frequency deviations decreases (higher damping speed). We can achieve a shorter settling time by selecting larger values for the wind turbine's virtual damping gain (higher damping speed). The virtual damping gains associated with wind turbines 1 and 2 are selected to be D_1=1.5 and D_2=1.5, respectively, based on the results obtained in the studied power system. A portion of the wind turbine's output must be considered as reserve power to implement the proposed method for frequency control purposes. It is possible to increase the amount of virtual damping gain to the extent that the wind turbine capacity is allowed. 5 % of each wind turbine's capacity is considered reserve power in this paper and the maximum virtual damping gain is selected accordingly.

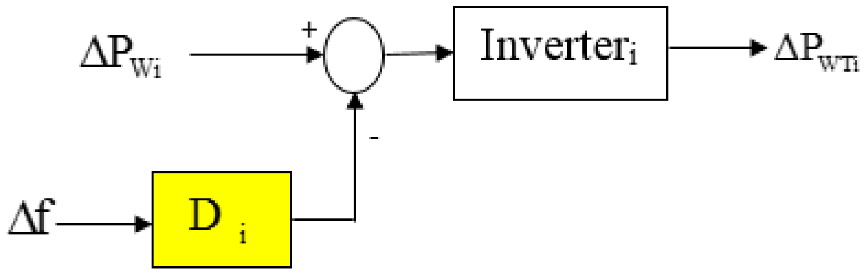

Figure 3. The dynamic model of the proposed method

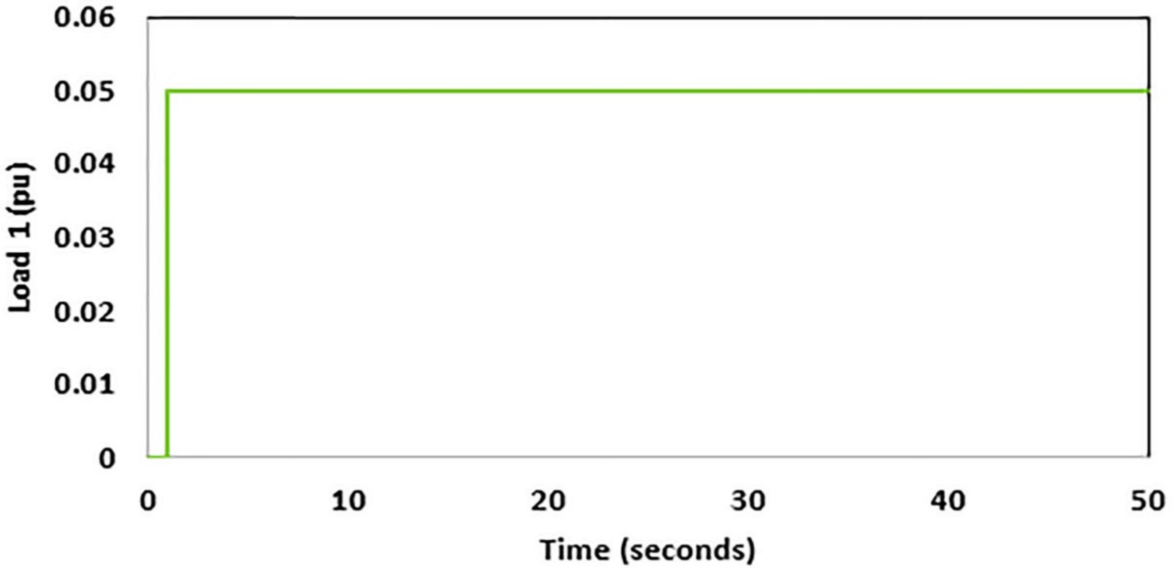

Figure 4. The load disturbance

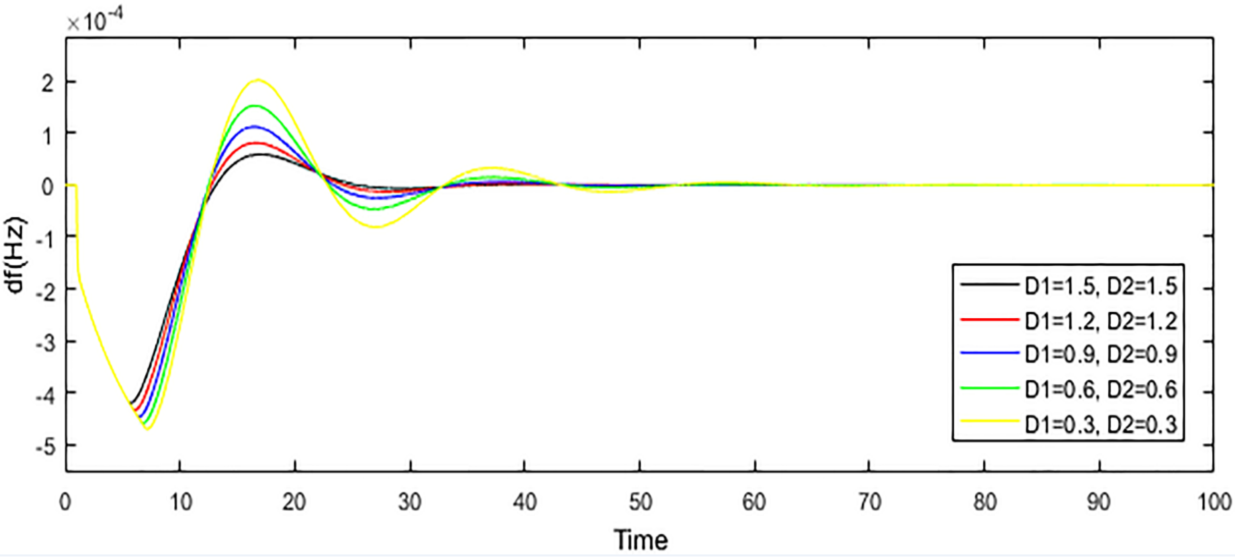

Figure 5. The frequency response of power system

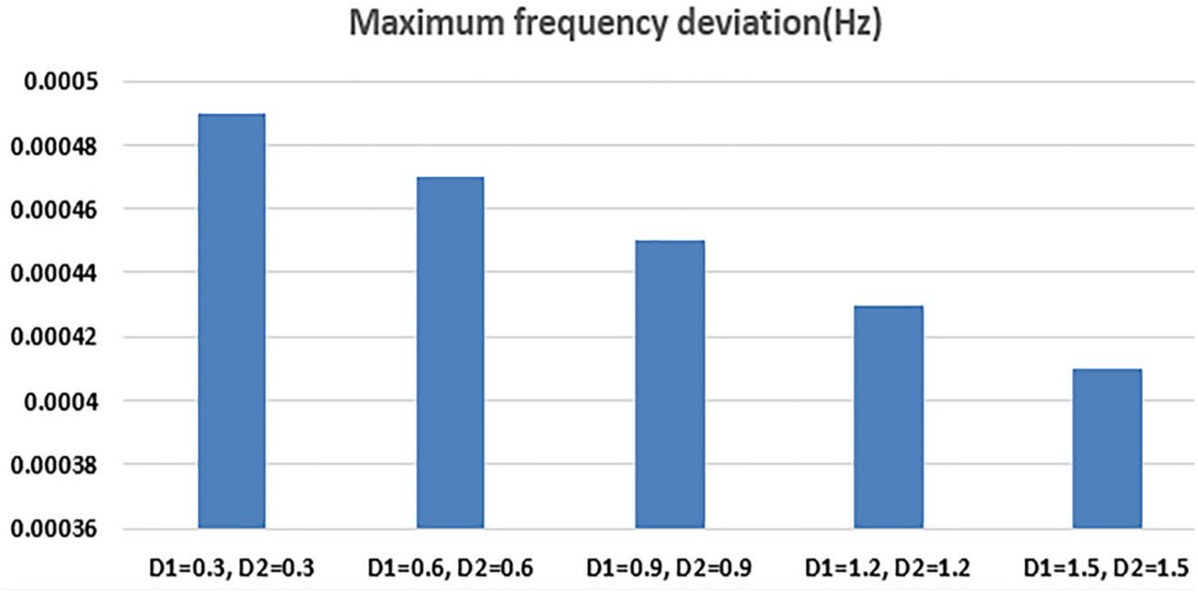

Figure 6. The maximum frequency deviation related to the frequency response of the power system

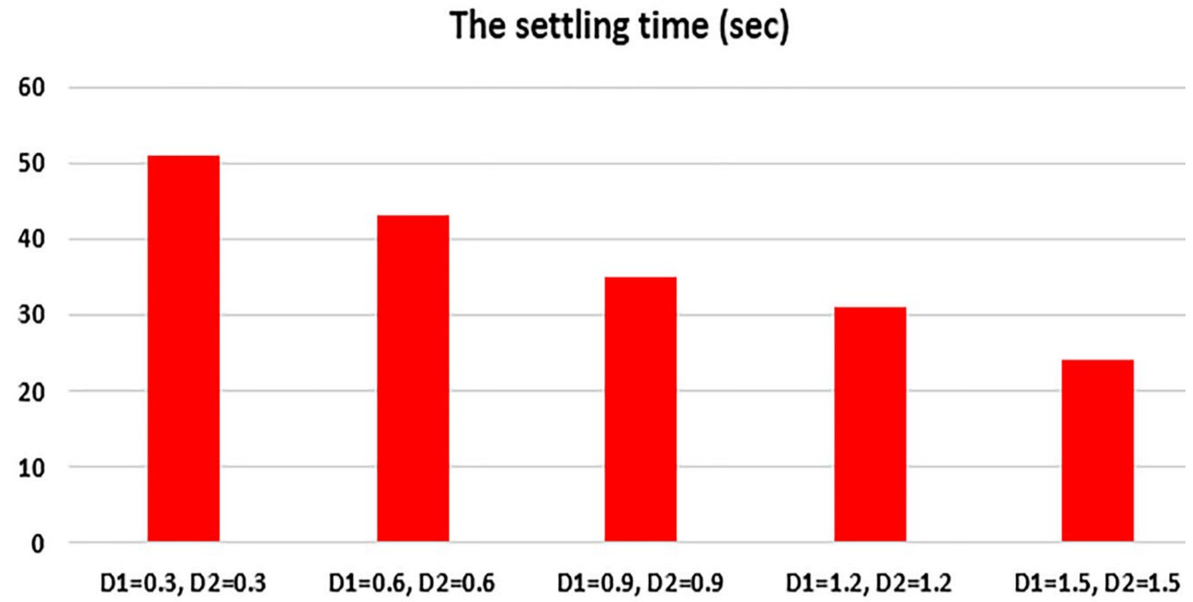

Figure 7. The settling time related to the frequency response of the power system

3.2. State space of the studied power system

Eq. (1) shows the power system's frequency deviation model. Eq. (2) shows the generated power model from the non-reheat power plant. Eqs. (3) and (4) exhibit the generated power model from the reheat power plant. Eqs. (5) and (6) show the hydropower plants' generated power model. Eq. (7) demonstrates the power model of wind turbines. Eq. (8) exhibits the generated power model from superconducting magnetic energy. The system state-space is shown in Eqs. (9) and (10), respectively, for the purpose of designing the proposed method for power systems in the studied power system [27].

$$\Delta f = \frac{1}{2Hs + D}\left[\Delta P_{Reh} + \Delta P_{WT} + \Delta P_{Non\text{-}Reh} + \Delta P_{Hydro} - \Delta P_{SMES} - \Delta P_{L}\right] \quad (1)$$

$$\Delta P_{Non\text{-}Reh} = \frac{P_{n1}}{T_1 s + 1} \times \left[\frac{-1}{R_1}\Delta f - \Delta P_c\right] \quad (2)$$

$$\Delta P_{g2} = \frac{P_{n2}}{T_2 s + 1} \times \left[\frac{-1}{R_2}\Delta f - \Delta P_c\right] \quad (3)$$

$$\Delta P_{Reh} = \left[m + \frac{m}{T_h s + 1}\right] \times \Delta P_{g2} \quad (4)$$

$$\Delta P_{g3} = \frac{P_{n3} T_d s + P_{n3}}{T_3 s + 1} \times \left[\frac{-1}{R_3}\Delta f - \Delta P_c\right] \quad (5)$$

$$\Delta P_{Hydro} = \left[\frac{-T_W s + 1}{0.5 T_W s + 1}\right] \times \Delta P_{g3} \quad (6)$$

$$\Delta P_{WT} = \frac{1}{T_{WT} s + 1} \times \Delta P_{wind} \quad (7)$$

$$\Delta P_{SMES} = \frac{K_{SMES}}{T_{SMES} s + 1} \times \Delta f \quad (8)$$

$$\begin{bmatrix} \dot{\Delta f} \\ \dot{\Delta P}_{Non-Reh} \\ \dot{\Delta P}_{Reh} \\ \dot{\Delta P}_{g2} \\ \dot{\Delta P}_{Hydro} \\ \dot{\Delta P}_{g3} \\ \dot{\Delta P}_{WT} \\ \dot{\Delta P}_{SMES} \end{bmatrix} = \frac{2m}{T_h} \begin{bmatrix} \frac{-D}{2H} & \frac{1}{2H} & \frac{1}{2H} & 0 & \frac{1}{2H} & 0 & \frac{1}{2H} & \frac{1}{2H} \\ \frac{-P_{n1}}{T_1R_1} & \frac{-1}{T_1} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-mP_{n2}}{T_2R_2} & 0 & \frac{-1}{T_h} & (\frac{2m}{T_h}-\frac{m}{T_2}) & 0 & 0 & 0 & 0 \\ \frac{-P_{n2}}{T_2R_2} & 0 & 0 & \frac{-1}{T_2} & 0 & 0 & 0 & 0 \\ (\frac{-T_dP_{n3}D}{T_3R_3H}+\frac{2P_{n3}}{T_3R_3}) & (\frac{T_dP_{n3}}{T_3R_3H}) & (\frac{T_dP_{n3}}{T_3R_3H}) & 0 & (\frac{T_dP_{n3}}{T_3R_3H}-\frac{2}{Tw}) & (\frac{2}{Tw}+\frac{2}{T3}) & 0 & 0 \\ (\frac{T_dP_{n3}D}{2T_3R_3H}-\frac{P_{n3}}{T_3R_3}) & (\frac{-T_dP_{n3}}{2T_3R_3H}) & (\frac{-T_dP_{n3}}{2T_3R_3H}) & 0 & (\frac{-T_dP_{n3}}{2T_3R_3H}) & \frac{-1}{T_3} & 0 & 0 \\ \frac{-D_i}{T_{SMES}} & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{WT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{SMES}} \end{bmatrix} \begin{bmatrix} \Delta f \\ \Delta P_{Non-Reh} \\ \Delta P_{Reh} \\ \Delta P_{g2} \\ \Delta P_{Hydro} \\ \Delta P_{g3} \\ \Delta P_{WT} \\ \Delta P_{SMES} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{-P_{n1}}{T_1} \\ \frac{-mP_{n2}}{T_2} \\ \frac{-P_{n2}}{T_2} \\ \frac{2P_{n3}}{T_3} \\ \frac{-P_{n3}}{T_3} \\ 0 \\ \frac{-K_{SMES}}{T_{SMES}} \end{bmatrix} [u]$$

$$+\begin{bmatrix} 0 & -\frac{1}{2H} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{-T_dP_{n3}}{T_3R_3H} \\ 0 & \frac{T_dP_{n3}}{2T_3R_3H} \\ \frac{-1}{T_{WT}} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta P_{wi} \\ \Delta P_L \end{bmatrix} \tag{9}$$

$$y = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0] \begin{bmatrix} \Delta f \\ \Delta P_{Non-reh} \\ \Delta P_{Reh} \\ \Delta P_{g2} \\ \Delta P_{Hydro} \\ \Delta P_{g3} \\ \Delta P_{WT} \\ \Delta P_{SMES} \end{bmatrix} \tag{10}$$

4. SIMULATION

This paper considers various implementation scenarios for the proposed method. In Scenario (1), the proposed method's performance against load disturbances is evaluated by considering the time delay between the power system's sources. In Scenario (2), the performance of the proposed method against load disturbances and parameter uncertainty is evaluated by considering the time delay between power system resources. In Scenario (3), the performance of the proposed method against power system disturbances (load and wind turbine) is evaluated. Scenario (4) evaluates the performance of the proposed method in the presence of disturbances and uncertainty in system parameters.

Table 1. Power system parameters with the presence of wind turbine [23]

Parameter	Value	Parameter	Value
R_1	2.5	m	0.5
R_2	2.5	T_d	5
R_3	1	T_1	0.4
β	1	T_2	0.4
T_w	1	T_3	90
T_h	6	H	5.7096
P_{n1}	0.2529	P_{n3}	0.1364
P_{n2}	0.6107	$P_{w,1}$	750KW
$P_{w,2}$	3000kW	D	0.028
D_1	1.5	D_2	1.5

Scenario (1): In this scenario, the performance of the proposed method against load disturbance is investigated by considering the time delay between power system resources. First, the load disturbance according to Figure 8 is applied to the power system considering the time delay (τ = 0.5 sec.). Figure 9 shows the frequency response of the power system to disturbances. According to Figure 9, the maximum frequency deviation using the proposed method is 0.0008 Hz. The maximum frequency deviation using conventional methods (without virtual damping) is 0.0024 Hz. The settling time of frequency deviations using the proposed method is 12 sec. The settling time of frequency deviations using conventional methods (without virtual damping) is 45 sec. The proposed method has reduced the frequency deviations due to disturbances and time delays of the power system by 67 % and has increased the damping speed of the frequency deviations by 73 % (73 % improvement over the methods used in this field). According to the results of this scenario, the proposed method has a better performance against load disturbance and system time delay.

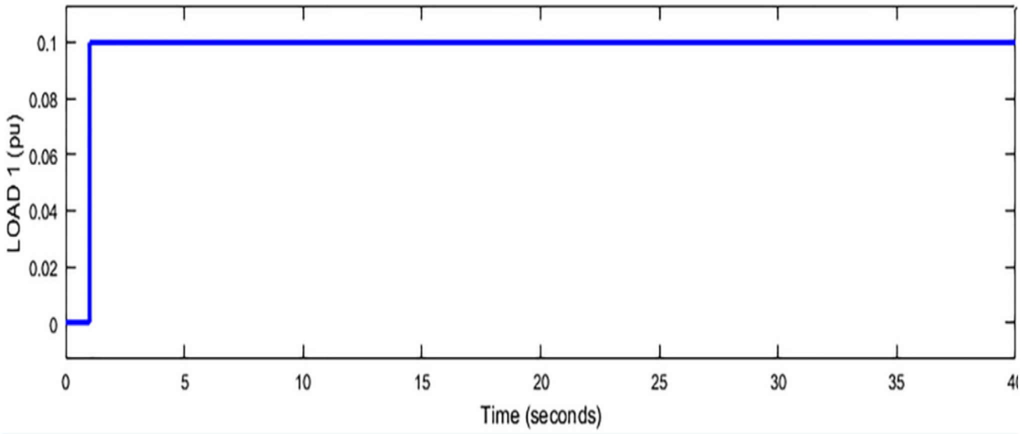

Figure 8. The load disturbance

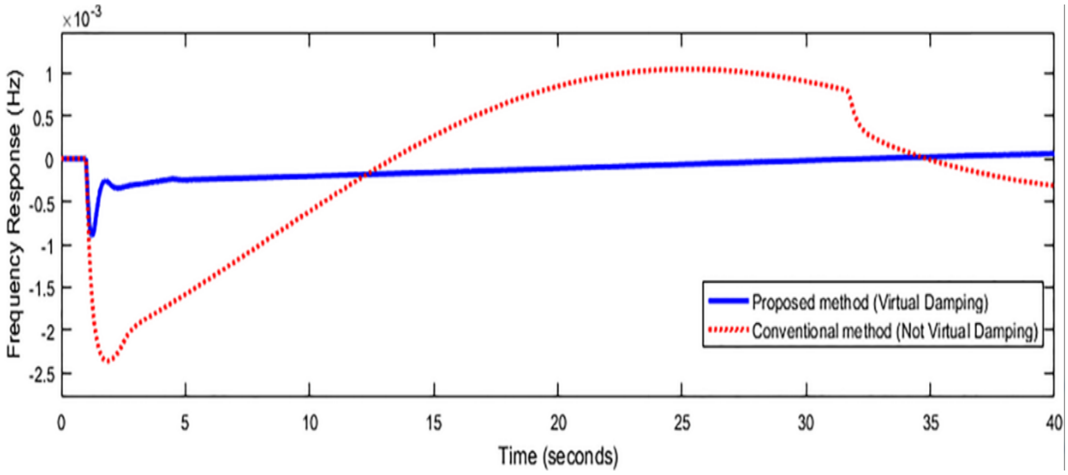

Figure 9. The frequency response of power system, scenario (1)

Scenario (2): In this scenario, the proposed method's performance against load disturbances and uncertainty of system parameters is evaluated by considering the time delay between power system resources. First, the load disturbance is applied to the power system according to Figure 8, considering time delay (τ = 0.5 sec.). The uncertainty of system parameters is considered for power system inertia and power system damping (D = -30 %, H = -30 %). The frequency response of the power system to disturbances is depicted in Figure 10. According to Figure 10, the proposed method produces a maximum frequency deviation of 0.0011 Hz. The maximum frequency deviation when using conventional methods (without virtual damping) is 0.0031 Hz. The settling time of frequency deviations using the proposed method is 31 sec. The settling time of frequency deviations using conventional methods (without virtual damping) is 78 sec. The proposed method reduced frequency deviations in the power system caused by disturbances and time delays by 65 % and increased the damping speed of the frequency deviations by 61 % (61 % improvement over the methods used in this field). According to the outcomes of this scenario, the proposed method outperforms existing methods in terms of load disturbance and system time delay.

Scenario (3): The performance of the proposed method against power system disturbances is examined in this scenario. According to Figure 11, the power system is subjected to load disturbances and disturbances from distributed generation sources. Figure 12 illustrates the frequency response of the power system to disturbances. As per Figure 12, the maximum frequency deviation for the proposed method is 0.005 Hz. The maximum frequency deviation when using conventional methods (without virtual damping) is 0.017 Hz. According to the results of this scenario, the proposed method (virtual damping) performed better than conventional methods (without virtual damping) in damping power system frequency fluctuations and was able to dampen the fluctuations more.

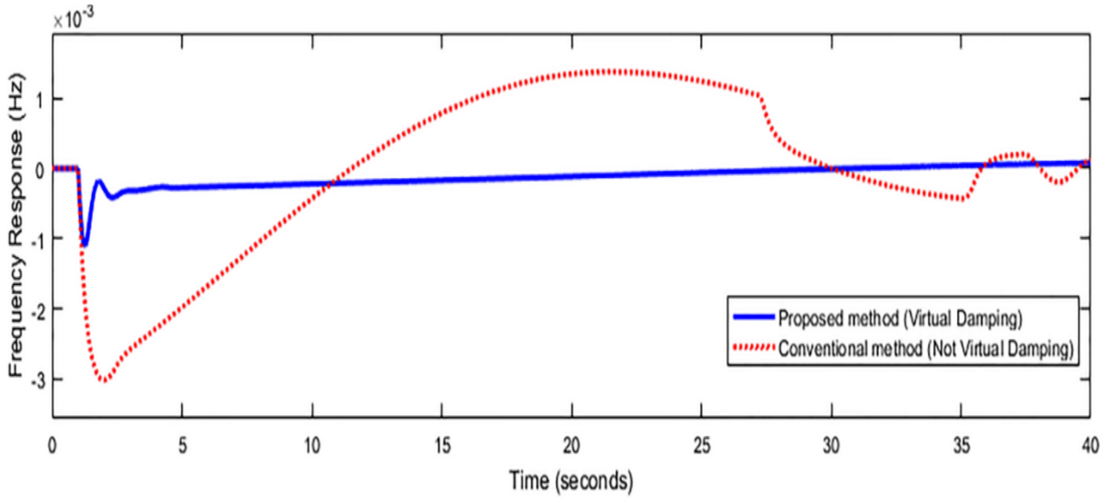

Figure 10. The frequency response of the power system, Scenario (2)

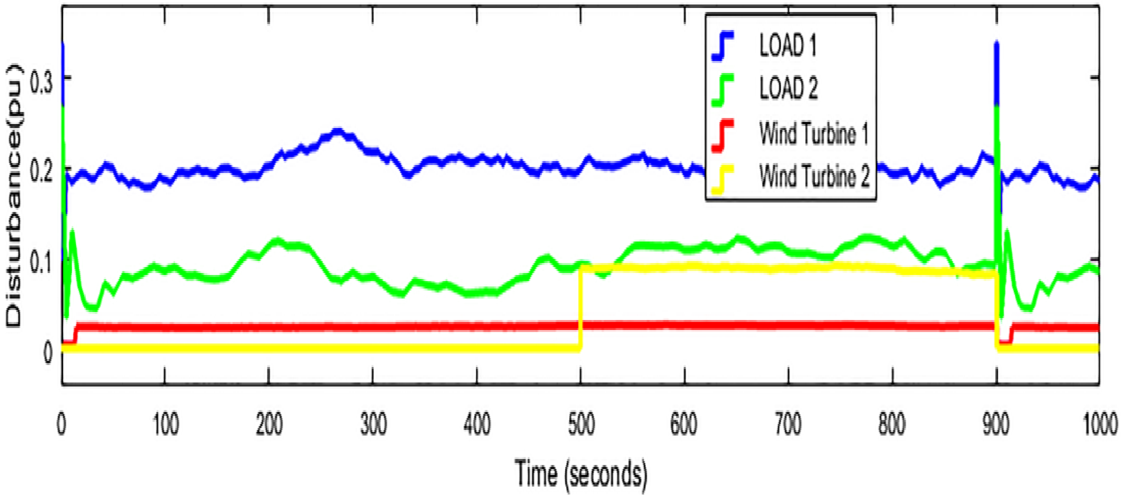

Figure 11. The disturbances in the power system

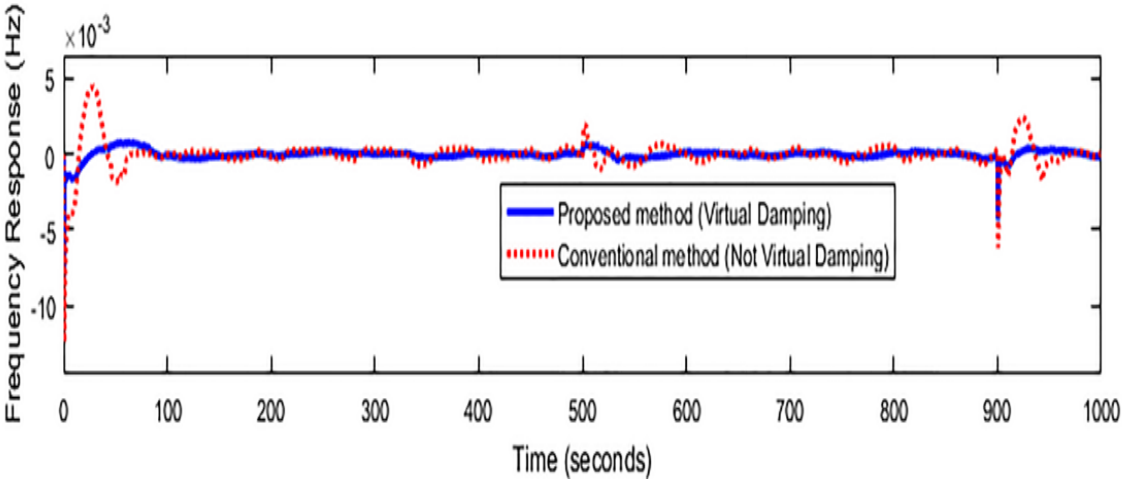

Figure 12. The frequency response of power system, Scenario (3)

Scenario (4): In this scenario, the performance of the proposed method against disturbances and uncertainties related to the parameters of the power system is investigated. The disturbances are entered into the power system according to Figure 11. The uncertainty in the damping parameter of the power system D is considered to be -20 %. Figure 13 shows the frequency response of the power system disturbances and the uncertainty of system parameters. As shown in Figure 13, the maximum frequency deviation using the proposed method is 0.0053 Hz. The maximum frequency deviation using conventional methods (without virtual damping) is 0.022 Hz. The proposed method (virtual damping) has better performance in damping the frequency fluctuations related to the power system than conventional methods (without virtual damping).

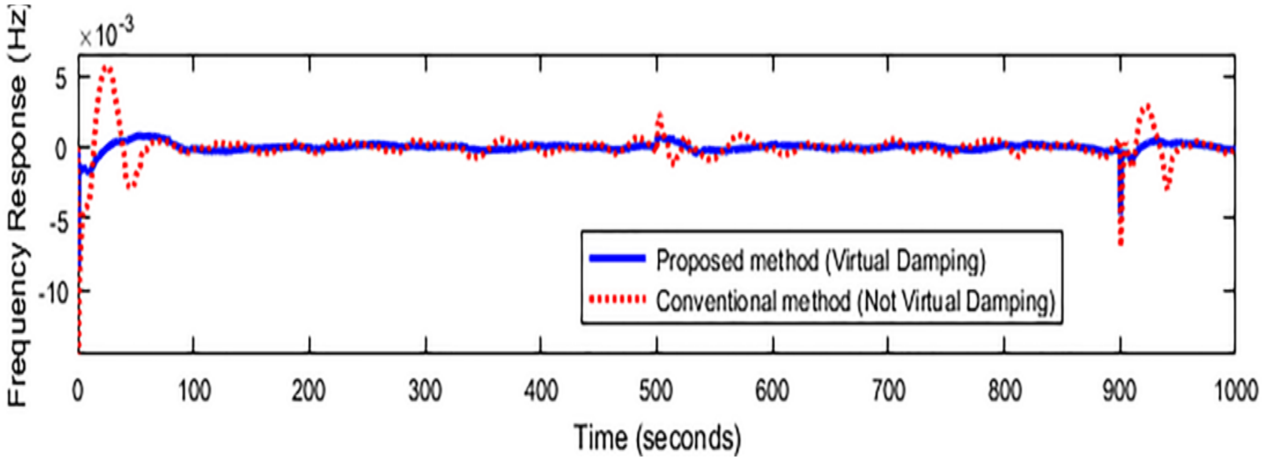

Figure 13. The frequency response of power system, scenario (4)

5. CONCLUSIONS

Distributed generation sources such as wind turbines undeniably impact the power system. The presence of these resources in the power systems poses challenges. The complexity of frequency control is one of the most significant challenges associated with the presence of wind turbines in the power system. Because wind turbines naturally oscillate and are not involved in frequency control. The paper aimed to design and implement a control method (virtual damping) for a wind turbine that has the following advantages:

- Improvement of the damping speed of frequency deviations: Wind turbines reduce the damping speed of frequency deviations caused by disturbances (load and wind turbine), to be then dampened. The presence of this issue may result in power system frequency instability. The proposed method's design (virtual damping) on the wind turbine increases the damping speed associated with the power system's frequency deviations and a decrease in the maximum deviations.

- Wind turbines' proactive role in power system frequency regulation: Wind turbines played no role in the frequency control methods proposed in the power system frequency control field. Due to the presence of wind turbines in today's power systems, this source must be capable of actively controlling the system frequency. According to the proposed method, the wind turbine participates actively in the power system during disturbances, thereby enhancing the frequency stability of the power system.

- Improvement of the power system's frequency stability in the presence of time delay: Time delay in the power system can result in frequency instability. The methods used to control the power system's frequency in the presence of wind turbines do not address the issue of time delay. This paper studied the effects of time delay on the power system. Inclusion of time delay effect results in a more comprehensive frequency response model for controlling the frequency of the power system.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

Δf	The power system frequency deviation
$\Delta P_{Non-Reh}$	The generated power from the non-reheat power plant
ΔP_{Reh}	The generated power from the reheat power plant
ΔP_{g2}	The generated from the governor. 2
ΔP_{g3}	The generated from the governor. 3
ΔP_{Hydro}	The generated power from the hydropower plant
ΔP_L	The load power
ΔP_{SMES}	The generated power from the superconducting magnetic energy
τ	Time delay
R_1	Governor speed regulation non-reheat plant (Hz/pu MW)
R_2	Governor speed regulation reheat plant
R_3	Governor speed regulation hydro plant (Hz/pu MW)
β	Bias factor (pu MW/Hz)
T_w	Water starting time in hydro intake (s)
T_h	Time constant of reheat thermal plant (s)
P_{n1}	Nominal rated power output for the non-reheat plant (MW pu)
P_{n2}	Nominal rated power output for reheat plant (MW pu)
P_{n3}	Nominal rated power output for the hydro plant (MW pu)
$P_{w,1}$	Nominal power of wind turbine 1
$P_{w,2}$	Nominal power of wind turbine 2
m	Fraction of turbine power
T_d	Dashpot time constant of hydro plant speed governor (s)
T_1	Valve time constant of the non-reheat plant (s)
T_2	Steam valve time constant of reheat plant (s)
T_3	Water valve time constant hydro plant (s)
H	Equivalent inertia constant (pu s)
D	System damping coefficient of the area (pu MW/Hz)

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