

# Frequency Control of Wind Power Plant Assisted Hybrid Power System



Akshay Anand, Akshay Kumar, and Gauri Shankar

**Abstract** The addition of wind power plants (WPPs) into the mainland system is rising continuously since its large availability and eco-friendly nature. However, WPP works at maximum power point, and hence, WPP may not help in frequency regulation. Therefore, in this paper, frequency control techniques are introduced on WPP for the improvement of primary frequency regulation. This may be realized by creating a reserve power margin using pitch angle control and overspeed operations. The reserve power margin depends on wind velocity and blade pitch angle. The frequency support from deloaded WPP (WPP operates at reduced power point instead of maximum power point) may control based on the droop value, which depends on the available reserve and frequency deviation. From the MATLAB simulation results analysis, the effect of droop action is investigated in terms of minimizing the frequency deviation and smoothening power fluctuations of WPP.

**Keywords** Blade pitch angle control · Deloading · Droop control · Frequency control · Wind power plant

## 1 Introduction

Due to the continuous increase in pollution levels, it has become a matter of discussion among the international bodies to find the alternative of non-renewable energy sources. Since energy productions by renewable sources have a very little environmental impact, so most of the country are paying more concern to increase electric power generations by renewable sources [1]. Due to the easy accessibility of

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winds, it is dominated to be used over other renewable energy sources for generating electrical power. If wind energy is effectively captured, then the environmental problems caused by fossil fuels-based conventional plants may be minimized to a large extent. The above facts give the motivation for generating wind power which is better in terms of performance and efficiency [2]. The wind energy conversion system (WECS) extracts the mechanical power of wind and sends it to the permanent magnet synchronous generator (PMSG), which converts this mechanical power to electrical power. The popularity of PMSG is gaining more since the speed of PMSG may be varied according to wind speed and load demands. Also, PMSG has the highest efficiency among all machines since all movable magnetic sources are inside itself [3, 4].

Most of the wind power plants (WPPs) operate at the maximum power point (MPP) to generate maximum power from a particular wind speed which is effective in case of running cost. However, this type of WPP may not help in primary frequency support during disturbance between generations and load demands. Also, WPP offers low inertia to the power system when compared to similar sized conventional power plants. The flow of wind is a natural phenomenon, and it may not smooth throughout the day. Hence, the developed electrical power from WPP varies according to speed of wind. To make the participation in primary frequency regulation and smoothening power output fluctuations of WPPs, WPPs may have sufficient reserve margin, and this depends on deloading operation [5]. Deloading operation may be achieved by either speed control strategy or pitch angle control strategy [6]. Speed control strategy may be achieved by either underspeed control or overspeed control. In general, overspeed control strategy is implemented on WPP due to the stability point of view [7]. In the pitch angle control strategy, the value of blade pitch angle increases to enhance reserve power margin. The value of blade pitch angle may vary between  $0^\circ$  and  $90^\circ$ . Pitch angle control strategy may also use for controlling the speed of the wind turbine [8, 9].

The emphasis of the present work is to develop a mechanism to control the frequency support from deloaded WPPs (WPP operates at reduced power point instead of maximum power point) on the basis of the available power margin. This may be achieved using overspeed operation, and speed variation is controlled through pitch angle. The amount of power supply from WPP to the power system during system disturbances may be achieved by droop value [10]. The aim of the present paper is to develop a model of WPP with PMSG to control the frequency deviation and smoothening power output of WPP. Also, variable droop control strategy is implemented on WPP to provide frequency support according to frequency deviation. The theoretical results are fully verified by the MATLAB/SIMULINK<sup>R</sup>. The rest of the paper is summarized in the following way: The modeling of WPP components is discussed in Sect. 2; different control strategies on WPP are obtainable in Sect. 3; simulation outcomes and discussions are presented in Sect. 4. Lastly, conclusion is discussed in Sect. 5.

## 2 WPP Modeling

In WECS, the kinetic energy of wind is first transformed into mechanical energy by wind turbine. Then, the wind turbine fed this energy to the generator from where the electrical power is generated. The rotation of wind turbine is a subject of speed of wind speed and certain mechanical parameters like the angle at which the wind strikes the blade of wind turbine and direction of flow of wind [11]. Wind turbine is an important part of WECS, so wind turbine becomes important to study the different characteristics. From modeling point of view, WPP consists of the following components:

### 2.1 Wind Turbine Modeling

The mechanical power output ( $P_m$ ) extracted from wind speed ( $V_w$ ) by a wind turbine which is a function of power coefficient ( $C_p$ ).  $P_m$  may be calculated as

$$P_m = 0.5\rho AV_w^3 C_p \tag{1}$$

where  $\rho$  is the wind density,  $A$  is the area covered by the blade of wind turbine, and  $C_p$  is the function of blade pitch angle ( $\beta$ ), and tip speed ratio ( $\lambda$ ).  $C_p$  may be defined as

$$C_p = 0.73 \left[ 151 \left( \frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3 + 1} \right) - 0.58\beta - 0.002\beta^{2.14} - 13.2 \right] \exp \left( -18.4 \left( \frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3 + 1} \right) \right) \tag{2}$$

$\lambda$  may be calculated as

$$\lambda = \omega R / V_w \tag{3}$$

where  $\omega$  is the rotor speed of turbine, and  $R$  is the radius of the blade. In most of the cases,  $\lambda$  remains constant under all operating conditions; however, its value may be varied according to the what percentage of power is extracted from the wind turbine. Figure 1 shows actual mechanical power extraction versus rotor speed at rated wind speed (i.e.,  $V_w = 14$  m/s). Figure 2 shows mechanical power output versus rotor speed at different wind speeds. According to Fig. 2, initially, the generated power increases for increasing the value of rotor speed. As the generated power goes to the MPP, it starts decaying from the optimum value for a fixed value of wind speed. Also, it is clear from the figure that as the wind speed increases the value of generated power gets increase. In other words, power observed by the wind turbine for any wind speed is maximum at a certain value of rotor speed.

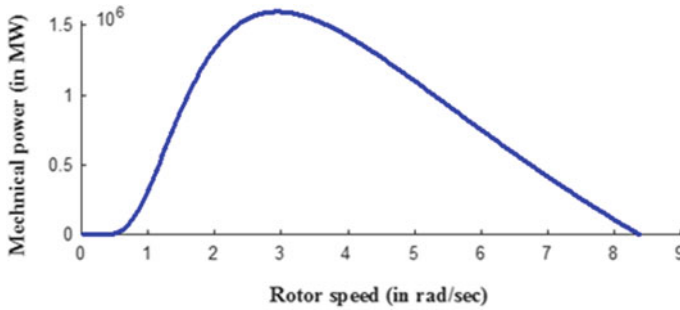
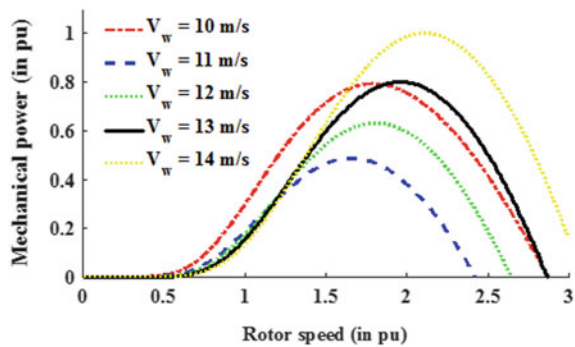


Fig. 1 Mechanical power output versus turbine speed at rated wind speed

Fig. 2 Mechanical power output versus rotor speed at different wind speeds



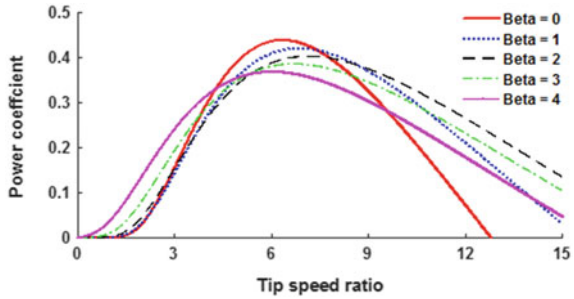
### 2.2 Pitch Angle Control Modeling

Pitch angle control may be used for deloading operation and controlling the rotor speed of turbine. Pitch angle may be controlled through proportional integral derivative (PID) controller. The input of pitch controller is the error between actual rotor speed and reference speed ( $\omega_{ref}$ ). The value of  $\omega_{ref}$  may be calculated as

$$\omega_{ref} = P_{ref}/T_m \tag{4}$$

where  $P_{ref}$  is the power reference, and  $T_m$  is the measured mechanical torque. In Fig. 3, the power coefficient versus tip speed ratio curve at rated wind speed is presented. It may be shown that as the value of beta increases, the value of power coefficient decreases. The wind turbine has the maximum value of power at zero pitch angle (i.e., Beta = 0). The wind turbine produces power at each and every point of the curve and that point is known as the operating point. There is also a point on the curve for each value of pitch angle for which power is maximum. This operating point is known as MPP. At this point, turbine gives the maximum amount of power with maximum efficiency. It is understood from Fig. 3 that wind turbine gives maximum power at a point for a specified tip speed ratio and pitch angle values. Hence, power

**Fig. 3** Power coefficient versus tip speed ratio at different values of pitch angle



coefficient will have a single maximum value for wind speed. To create a reserve power margin, in the present paper, value of beta is fixed at 4°.

### 3 Different Control Strategies on WPP

#### 3.1 Overspeed Operation

WPP may be operated at a deloaded power point with a decreased power level despite MPP. Reserve power available is only due to deloading operation that may be further utilized to maintain the power system stability for frequency regulation during active power mismatch between generations and load demands. Deloading operation may be achieved by overspeed operation. Deloaded power point ( $P_{del}$ ) may be calculated as

$$P_{del} = P_{max}(1 - x) \tag{5}$$

where  $P_{max}$  is the MPP, and  $x$  is the deloading value. In some scenarios,  $P_{del}$  is taken as  $P_{ref}$ . In deloading operation, speed of wind turbine reaches beyond the acceptable range. To avoid this, pitch control scheme activates and the value of pitch angle increases.

#### 3.2 Droop Control

Droop control may be implemented on WPP as a primary control to improve the short-term frequency dynamics. In this work, deloading parameter is fixed, and the droop parameter of WPP is dynamically adjusted. The droop control gives better power system performances in terms of frequencies excursion and smoothing the power output from WPP. Mathematically, droop ( $R$ ) may be written as

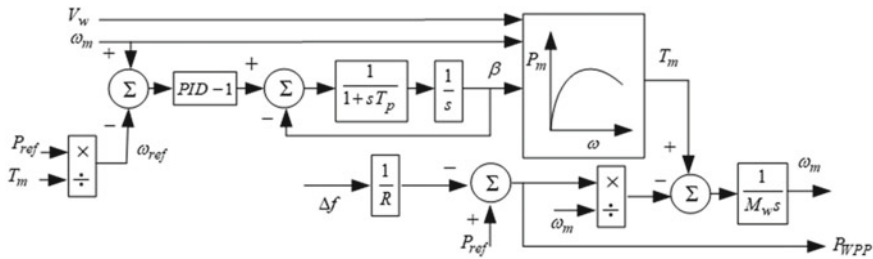


Fig. 4 Dynamic model of WPP

$$R = \frac{\Delta f}{\Delta P} \times 100 \tag{6}$$

where  $\Delta f$  is the frequency dip, and  $\Delta P$  is the change in power output. Figure 4 shows the dynamic model of WPP.

### 4 Simulation Results and Discussion

To study the effect of WPPs into the power system, a single-area system model comprising of four WPPs and one diesel power plant (DPP) is considered (see Fig. 5). The different parameters of WPP, DPP, and power system are displayed in Table 1. The simulation outcomes are conducted in MATLAB/SIMULINK<sup>R</sup>. The different cases are taken as follows:

- Different penetration levels of WPP into the power system without primary frequency control.
- Effects of WPP under with and without frequency control.

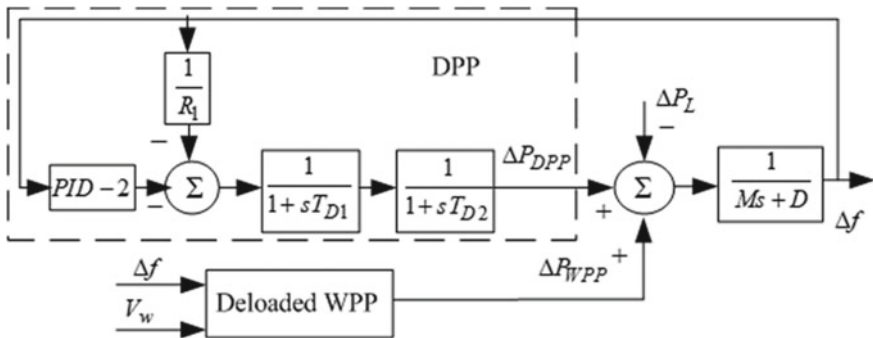


Fig. 5 Dynamic model of the studied system

**Table 1** The different parameters of WPP, DPP, and system are as follows

Model	Parameters
WPP	Capacity = 1.5 MW, rated rotor speed ( $\omega$ ) = 13 rpm, rated wind speed ( $V_w$ ) = 14 m/s, $\lambda = 4.94$ , swept area ( $A$ ) = 5346 m <sup>2</sup> , rotor blades = 3, blade length = 38 m, gearbox ratio = 1:1, $M_w = 5$ s, $T_p = 0.1$ s, pitch angle limits: 0° to 90°, $k_{p1} = 0.1$ , $k_{i1} = 0.2$ , $k_{d1} = 0.3$
DPP	Capacity = 5 MVA, $T_{D1} = 0.1$ s, $T_{D2} = 0.25$ s, $R_1 = 0.06$ , $k_{p2} = 2$ , $k_{i2} = 7$ , $k_{d2} = 5$
System	$M = 10$ s, $D = 0.6$ , $f = 50$ Hz

Frequency support by WPP under different droop values (i.e.,  $R = 4\%$  and  $R = 6\%$ ).

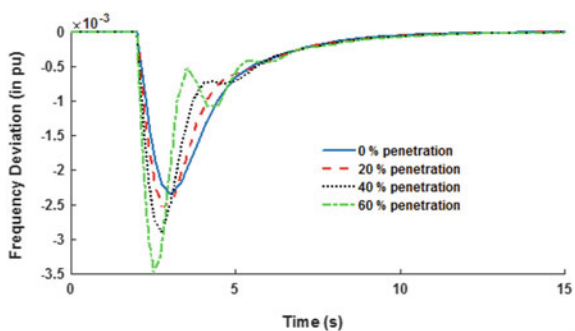
**Case (a):** Initially, the value of  $M$  is taken as 10, and after the penetration of WPP, the values of  $M$  changes and these are: 8 (20% penetration level), 6 (40% penetration level), and 4 (60% penetration level). A load of 1% disturbance is applied at  $t = 2$  s.

When penetration level of WPP into the system (WPP without frequency support) increases, then frequency deviation increases (see Fig. 6). Hence, it may activate under frequency relay, and the system may become unstable. Therefore, penetration of WPP without frequency support into the system is not good for the stable system.

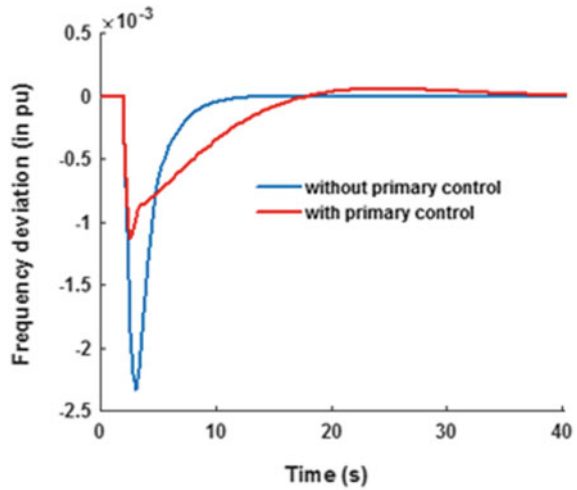
**Case (b):** To study the effect of frequency regulation, the simulation results are conducted with two strategies and these are: (a) without primary control from WPP and (b) with primary control from WPP. In these strategies, 1% of step load disturbance is applied at  $t = 2$  s, and WPP is operating at a wind speed of 14 m/s having deloading value of 10% with blade pitch angle of 4°. The value of  $M$ ,  $D$ , and  $R$  are taken as 10, 0.6, and 0.04, respectively.

From Fig. 7, it is clearly found that without primary control, the frequency deviation is high, as compared to with primary control. Figures 8, 9, and 10 show that without primary control, power output from WPP is zero, and there are no variations in rotor speed and blade pitch angle. However, in case of with primary frequency control, power output from WPP (see Fig. 7) increases when load increases to support frequency regulation by changing rotor speed and pitch angle (see Figs. 8, 9, and

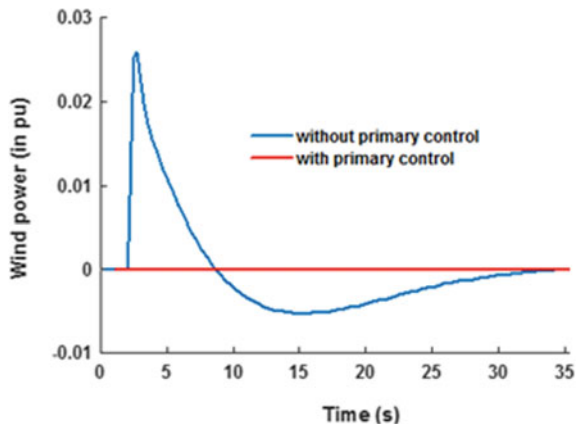
**Fig. 6** Frequency deviation versus time



**Fig. 7** Frequency deviation versus time



**Fig. 8** Wind power output versus time



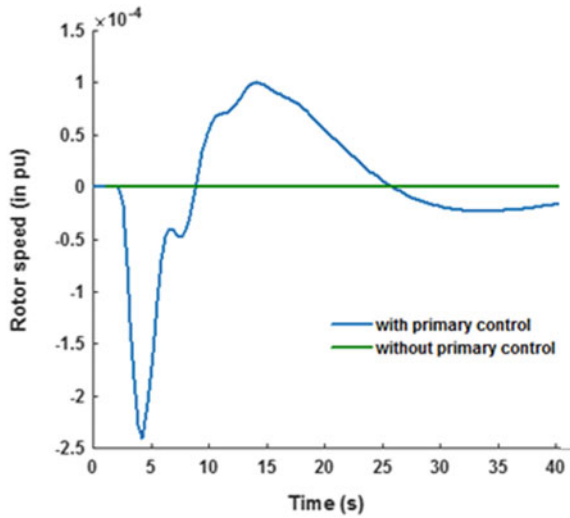
10). Pitch angle supports rotor speed so that it does not go beyond the permissible range.

**Case (c):** In this case, WPP is operating at a wind speed of 14 m/s having deloading value of 10% with blade pitch angle of  $4^\circ$ . Under a step increase in load demand, the dynamic performance analysis of load frequency control is carried out for the following different conditions: (a) system simulation takes place with droop control value of 4%, and (b) system simulation takes place with droop control value of 6%. In these cases, 1% of step load disturbance is applied at  $t = 2$  s.

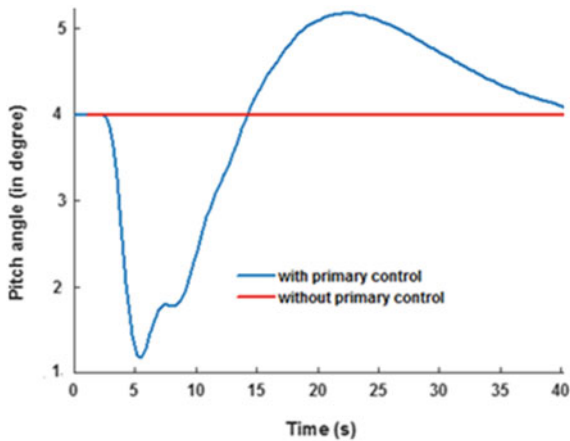
The response profiles of frequency deviation, power output deviation from WPP, rotor speed deviation from WPP, and power output deviation from DPP using different cases are shown in Figs. 11, 12, 13, and 14. From the simulation results, it is found that if the value of droop control is low, then the frequency deviation is minimum



**Fig. 9** Rotor speed versus time

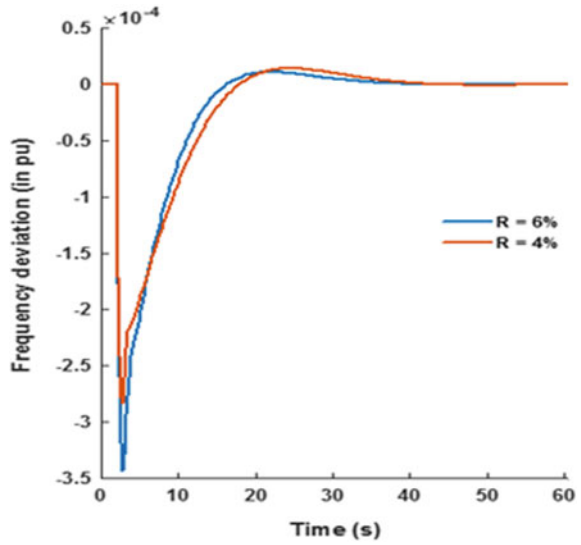


**Fig. 10** Pitch angle versus time

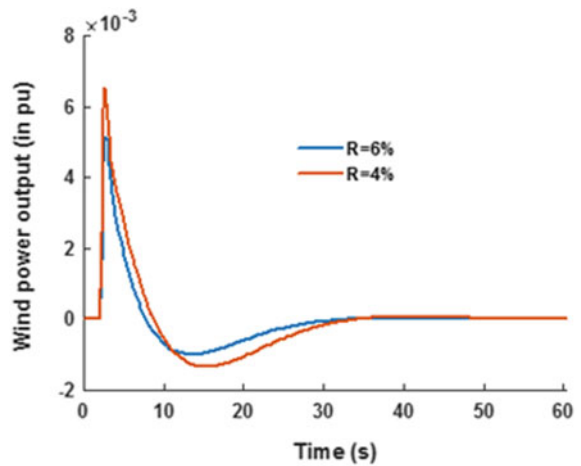


(see Fig. 11). At  $R = 4\%$ , the maximum frequency deviation is  $-2.83 \times 10^{-4}$  pu at  $t = 5.63$  s. As further increasing the  $R$  value to 6%, the maximum change of frequency profile is  $-3.436 \times 10^{-4}$  pu at  $t = 5.65$  s, and its settling time is large. In Fig. 12, power output variation of WPP is shown. WPP supports active power during transient state, and it becomes zero during steady state. The extreme value of power injection is  $5.15 \times 10^{-3}$  pu when  $R$  is 6%, and the extreme value of power injection is  $6.21 \times 10^{-3}$  pu when  $R$  is 4%. In Fig. 13, when power increases then speed of wind turbine decreases. The minimum value of speed is  $-6.04 \times 10^{-5}$  pu at  $t = 7.14$  s when  $R$  is 6%. The minimum value of speed is  $-4.8 \times 10^{-5}$  pu at  $t = 7.24$  s when  $R$  is 4%. DPP increases power output to compensate load demand rapidly, and it achieves peak deviation output to 0.01141 pu in case of 4% regulation and 0.01106 pu in case of

**Fig. 11** Frequency deviation versus time



**Fig. 12** Wind power output versus time

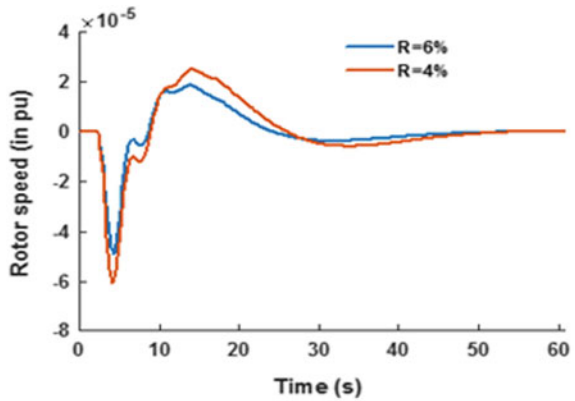


6% regulation (see Fig. 14). It is found that with primary control of WPP, WPP may help to decrease the burden on DPP and improves the system stability.

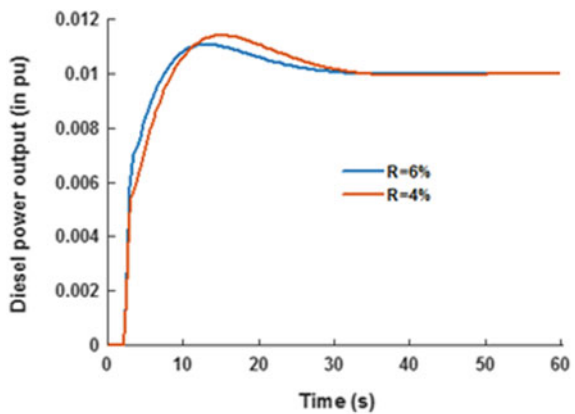
### 5 Conclusion

In this present work, PMSG-based WPP is chosen as a renewable energy source to generate active power during system disturbances. Deloading operation is performed

**Fig. 13** Rotor speed versus time



**Fig. 14** Diesel power output versus time



on WPP and speed of rotor are controlled by pitch control. In this work, WPP is deloaded by 10% to generate reserve margin for supporting frequency regulation, and pitch angle is set at  $4^\circ$ . To analysis, the primary frequency contribution from WPP, droop control technique is introduced. For optimum power output, the droop parameter is regulated, and it depends on the availability of the reserve margin. In case of low value of droop, WPP supplies large power to the system; however, speed of rotor decreases drastically. Therefore, pitch angle control limits the speed of rotor. From simulation results, it is found that if load demand increases, then power output from WPP increases quickly to compensate generation and load demand. It is also seen that frequency does not deviate very much.

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