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Research Article

Effect of ambient temperature variance on power output of wind turbine and mitigation strategy

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Abstract. Many challenges have been found in the operation of wind turbine under varying weather conditions, which demands novel strategies to address these issues. As far as we know, the variation of weather parameters is crucial for wind turbine operators to monitor the operation of wind turbines and adjust parameters of generator to ensure safe and efficient operation. This study aims to explore the effect of ambient temperature variation on wind turbine parameters including rotational speed, output power and pitch angle, using 10-minute measurement data for temperature ranges from -5°C to +20°C. By understanding such effects, researches can develop a control strategy to minimize their effect and improve the performance of wind turbines by increasing power production and reducing unnecessary loads and control actions. In this research, the mitigation method was developed within the control system to correct the parameters of wind turbine according to ambient temperature variation, offering a more practical strategy for wind turbines that currently in use. The simulation studies were carried out using Matlab/Simulink® software, and the results revealed that the output power of the wind turbine rose by 5.71% compared to standard strategy after mitigation method was implemented.

Keywords: Ambient temperature, PMSG, Parameter correction, Wind turbine, Power generation

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1. Introduction

Global warming can influence the wind energy resource and operating conditions of wind farms around the world (Hassoine et al., 2022) (James et al., 2023). The researchers investigated the possible influences by which climate changes could impact the wind energy industry, developed the tools being used to expose these effects, and discussed the sources of uncertainty from the impact of climate change on wind energy developments (Alizadeh & Kojori, 2015; Tian et al., 2019). However, many of these effects have not been thoroughly explored.

If we thinking in this way, capturing more energy by the wind turbine allows for a higher energy conversion, while receiving less energy results in a lower energy conversion. Majority of wind energy research concentrates on optimizing conversion efficiency through advanced control systems and innovative materials (Desalegn et al., 2022). However, focusing on how to capture more energy by turbine, particularly by mitigating the impact of weather conditions, can offer significant gains in overall power generation. The wind speed is definitely most important for power generation of wind turbine (Sang et al., 2017) . However, authors believe that ambient temperature (T_a) can be also significant factor for wind energy system. Understanding and minimizing the effect of environmental conditions can lead to extend the deployment of wind energy systems, thereby increasing their contribution to reduce CO_2 emissions.

According to IEC 61400-1 standard, the wind turbine can operate regularly within the temperature range from -10°C to 40°C (Larsen & Hansen, 2008) . Only few researchers in (Baskut et al., 2010) (Homola et al., 2010) (Xu et al., 2023) (Van et al., 2008) attempted to investigate effect of atmospheric temperature on wind turbine operation. We selected papers, which are similar in content to our study. Article in (Danook et al., 2019) illustrated how changes in humidity affect the efficiency of wind turbines, which could be related to our study. It concluded that winter has higher air density while summer has lower air density, resulting in reduced power generation in summer and increased power generation in winter. Additionally, the study in (Baskut et al., 2010) reached same conclusion. Also, shape of airfoil of turbine blade can be changed when temperature has changed. However, this method is not practical due to its requirements of extra cost (Xu et al., 2023) . Research in (Şahin et al., 2023) provides insights into the specific ways in which icing affects turbine performance, highlighting the need for considering icing effects in the design and operation of wind turbines, especially in cold climates. Also, study emphasizes the importance of understanding and mitigating the impacts of low atmospheric temperature on large-scale wind turbines to enhance their efficiency and reliability. (Rodríguez-López et al., 2020) concluded that global warming has led to increased power losses in wind turbines. To determine this effect, an artificial neural network (ANN) system was developed to estimate the power curve. The main

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results indicate that higher temperatures reduce the performance of wind turbines. However, the impact of rising temperatures on wind energy performance is likely to be modest, as the wind turbine control system can compensate for energy losses by adjusting the angle of the wind blades.

Based on a review of existing studies, research regarding the effect of ambient temperature variance on capability of wind turbine are rare, which creating a research gap in discovering and minimizing above effect. For this reason, the aim of this research is to reveal the effect of ambient temperature and discover strategy to minimize such effect for effective operation of wind energy system. To minimize the effect of ambient temperature variations, it is necessary to appropriately readjust the pitch angle and rotational speed of wind turbine according to current ambient temperature. Optimizing the parameters of a wind turbine based on ambient temperature does not require additional equipment or components, making it a more practical strategy. The modified pitch angle and rotational speed are recorded in lookup table. 3 scenarios of simulation study are conducted to illustrate the drawbacks of standard system and effectiveness of proposed strategy in wind energy system. Results proved the power production of wind turbine increased after parameters of wind turbine were corrected according to air temperature variance.

In this research, following contributions were made: (1) one-year datasets were investigated to study an influence of ambient temperature variation (2) strategy that regulating parameter of wind turbine according to ambient temperature changes is investigated to minimize said effect. The following sections were described: Section 2 analyzes effect of T_a variation using one year measurement data. The method to minimize impact of T_a changes were given in section 4. Section 5 explained the conventional and proposed control scheme of wind turbine. Section 6 illustrated the results by conducting 3 scenarios, and the conclusions were given in section 7.

2. Analysis of annual ambient temperature effect on parameters of wind turbine

Few research suggested that wind turbine blades are iced when temperature is between -5^oC to -15^oC, which causes to reduce the power production of wind turbine (Dai et al., 2016) . However, if ice accretion is not formed on the blades, you will observe that low temperature has a beneficial effect on the operation of wind turbines. Also, the most operational wind turbines are installed in regions where there is no ice accretion on wind turbine blades (Song et al., 2019). Therefore, the authors exclude the analysis of ice accretion effects

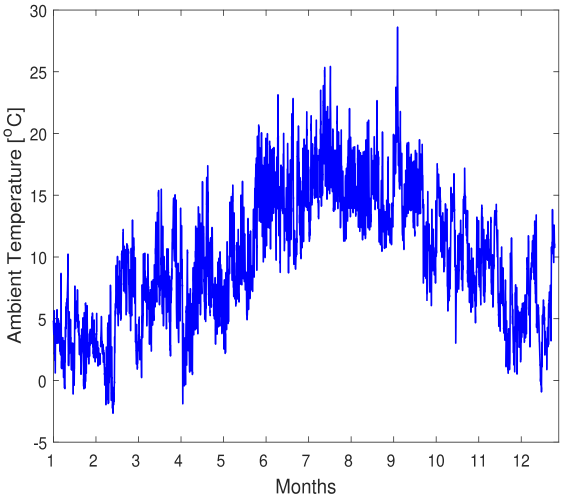

Fig. 1 Measured ambient temperature for 12 months

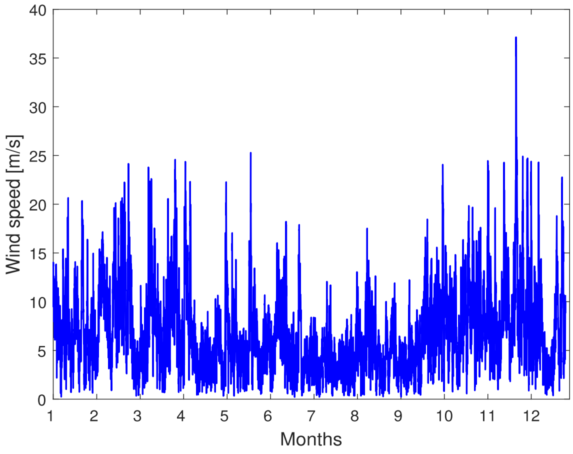

Fig. 2 Measured wind speed for 12 months

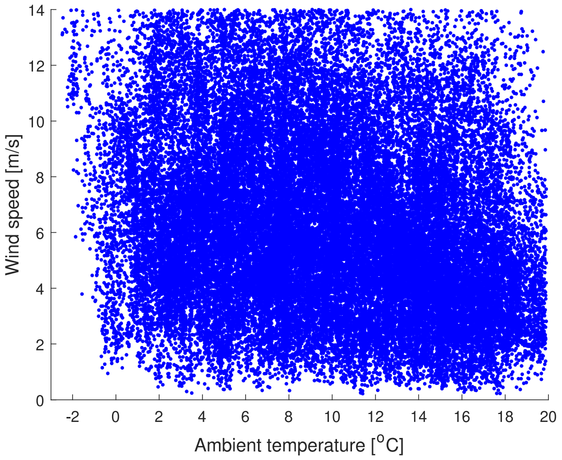

Fig. 3 Wind speed versus ambient temperature

from this study because we assumed that chosen wind turbine did not encounter icing conditions during the low temperature period. From this view, operational behavior of wind turbines under various temperature changes should be investigated using real measurement data (Yang et al., 2013). Authors analyzed a year-long length dataset which recorded at 10-minute intervals, and findings from the analysis were presented below.

Fig. 1 illustrates the one-year temperature variation in the area, measured from the nacelle temperature sensor. The minimum temperature recorded is approximately -3^oC, while the maximum temperature reaches $+28^oC$. This provides insights into how these temperature fluctuations impact the parameters of the wind turbine, including power production, pitch angle regulation, rotational speed regulation, and others. Fig 2 shows the wind speed measurement for one year period (10-minute measurement). In Fig. 3, the correlation between wind speed and ambient temperature is depicted. It shows no obvious relationship between temperature and wind speed. The lack of a clear trend in the plot suggests that wind speed and ambient temperature operate as independent variables, each exhibiting its own variations without a consistent interdependence. This also suggested that control system should consider effect of ambient temperature at same time maximizing output power of wind turbine when using MPPT control.

2.1 $\boldsymbol{T_a}$ effect on power production

Fig. 4 illustrates the one year recorded data for $Pvsv_w$ curve of wind turbine. It illustrates the normal nonlinear relationship between generated power and wind speed, but it does not provide information how T_a changes affect power generation. So, these data need to be analyzed to be understood for our purpose. To investigate the effect of T_a on wind turbine power production, we filtered the data based on T_a values. Specifically, we considered temperature ranges: low temperature of -5^oC to -1^oC, medium temperature of $+10^oC$ to $+11^oC$, and high temperature of $+18^oC$ to $+19^oC$.

As shown in Fig. 5, blue-colored dots are power and wind speed data point within low ambient temperature period. Red dots are data point within medium ambient temperature period. Green colored data in this figure is for data points within high ambient temperature period. It is clearly shown that low temperature leads to higher power production as shown blue dotted points. High temperature leads to lower power production with green-colored dots. Power production in medium ambient temperature period falls between low and high

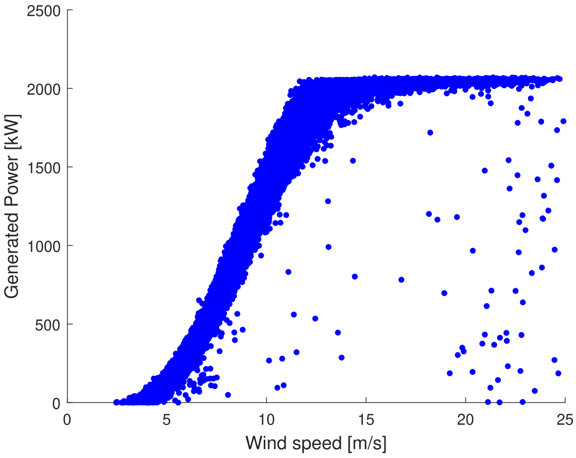

Fig. 4 Measured $\boldsymbol{Pvsv_w}$ curve

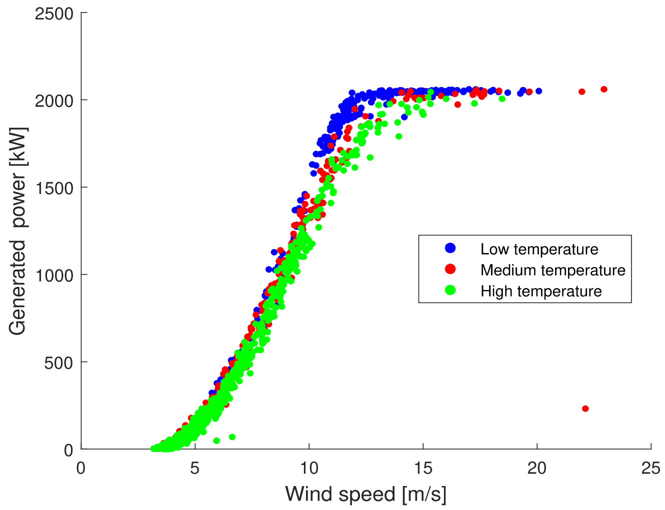

Fig. 5 Filtered $\boldsymbol{Pvsv_w}$ curve

temperatures period as expected. From this data, we can conclude that temperature variation can affect the power yields of the WT. Therefore, the control system of wind turbine should consider T_a variation effect.

2.2 $\boldsymbol{T_a}$ *effect on pitch angle activity*

Fig. 6 illustrates data for pitch angle regulation (βvsv_w $curve$) according to wind speed. The cut-in wind speed of used wind turbine is 3.5 m/s. The pitch angle tended to be constant when wind speed is between 3.5-11 m/s because pitch angle should be set

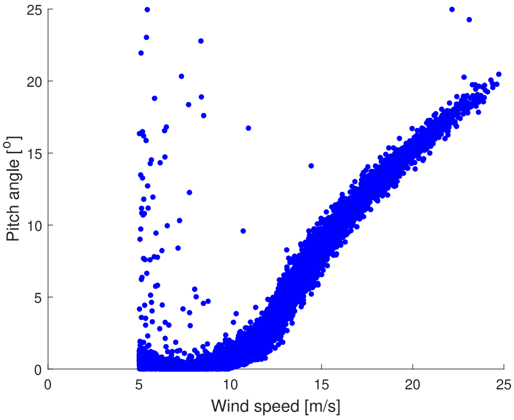

Fig. 6 Measured $\boldsymbol{\beta vsv_w}$ curve

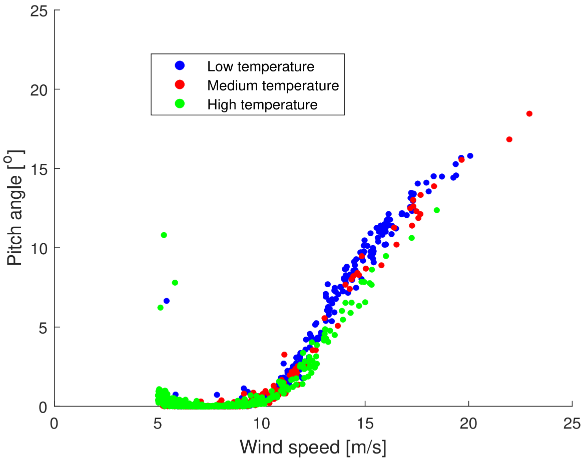

Fig. 7 Filtered $\boldsymbol{\beta vsv_w}$ curve

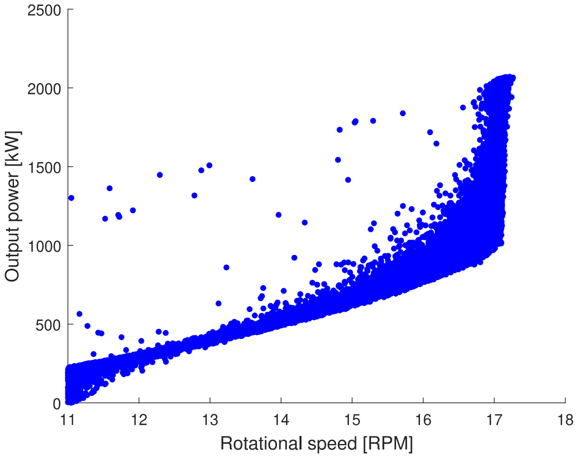

Fig. 8 Measured $\boldsymbol{Pvs\omega}$ curve

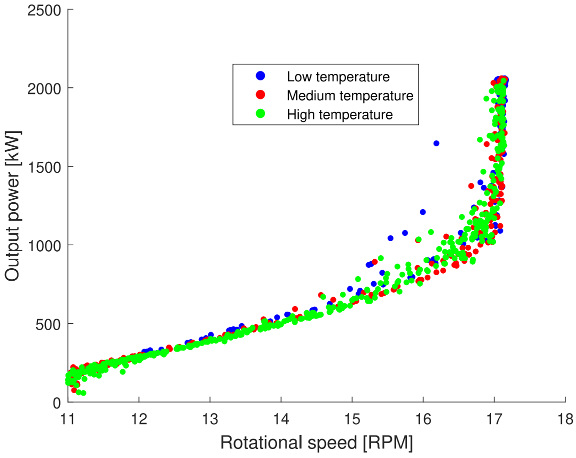

Fig. 9 Filtered $\boldsymbol{Pvs\omega}$ curve

at optimal constant value. When wind speed is above 11 m/s, the pitch angle value was increased with wind speed increases. At this time, wind turbine enters to full load operating region where mechanical power is maintained at its maximum value by regulating the pitch angle value.

To explore the effect of the temperature variation on use of pitch angle control system, these data are filtered based on the low, medium, and high ambient temperature ranges as shown in Fig. 4. The results are given in Fig. 7. In this figure, the data points within lower temperature ranges (blue-colored data) tend to be higher than those in medium and high-temperature ranges. This measurement result shows that at lower temperatures, the wind turbine utilizes higher pitch angle value which subsequently reduce with in- creases of ambient temperature. The reason is that turbine generate convert more power under low temperature region where requires more pitch angle to maintain aerodynamic torque at its rated value in full load operating region.

2.3 $\boldsymbol{T_a}$ effect on rotational speed

Also, another crucial parameter that warrants attention is the rotational speed of the wind turbine under varying T_a conditions as depicted in Figs. 8 and 9. Unlike pitch angle and output power deviations, the rotational speed remains unaffected, showing no obvious and distinguished effect. This is because the generator control system ensures that rotational speed tracks it reference value under any weather conditions. Moreover, reference speed is determined by using information of wind speed and few parameters of turbine.

Based on above analysis, results proved that rise in ambient temperature can potentially reduce the power generation of wind turbine. So that, this brings us to the question that how to minimize this effect and to enhance the performance of the wind turbine. Let's explore this discussion in the following sections.

3. Modelling of Wind Turbine and Generator

In this study, simulation model which includes model of the turbine, shaft system, generator, and control system was used. Also, ambient environ- mental model which reflects ambient temperature variation is integrated in simulation model as shown in Fig.10 (Jargalsaikhan et al., 2023). Direction of arrow in this model indicates blocks where these parameters affect.

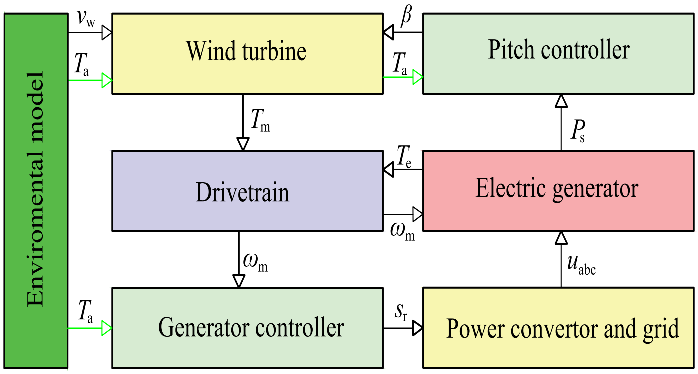

Fig. 10 Simulation model

By using these detailed components and control system of wind turbine, the simulation model not only mirrors the complexities of real wind turbine but it also provides an opportunity for analysis of it responses to varying weather conditions. It enables the exploration of mechanical, electrical, and control dynamics, providing intuition into how the system responds to changes in wind speed, ambient temperature, pitch angles, and other environmental factors.

4. Mitigation method to weaken effect of T_a *variation*

In this section, we will explore how to minimize the effect of T_a using proper changing of wind turbine parameters. Table 1 illustrated result of the simulation study under various T_a conditions. The pitch angle (β) was 2^0, and rotor speed (ω_m) of wind turbine remained due to speed tracking controller. It indicated that the output power was decreased with increasing T_a, which is similar findings with the measurement data.

Table 1

Variation of parameters with T_a changes

T_a [°C]	ρ_{air} [kg/m^3]	P_m [kW]	ω_m [rad/s]	K^{opt}	β [°]
-10	1.341	334.7	1.280	1.0	2.0
-5	1.316	329.5	1.280	1.0	2.0
0	1.292	322.5	1.280	1.0	2.0
5	1.268	316.7	1.280	1.0	2.0
10	1.246	312.1	1.279	1.0	2.0
15	1.225	308.4	1.279	1.0	2.0
20	1.204	302.3	1.279	1.0	2.0
25	1.184	298.3	1.279	1.0	2.0
30	1.164	292.1	1.279	1.0	2.0
35	1.145	285.6	1.279	1.0	2.0
40	1.127	279.1	1.279	1.0	2.0

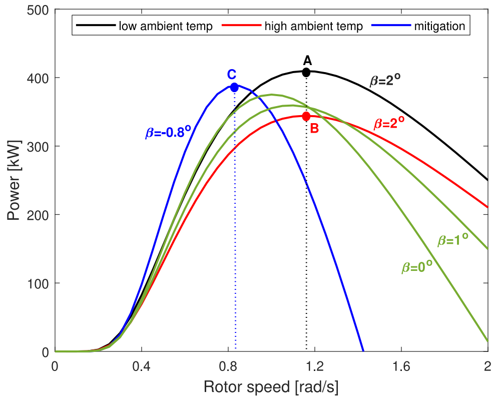

Fig. 11 Operation of wind turbine under T_a changes

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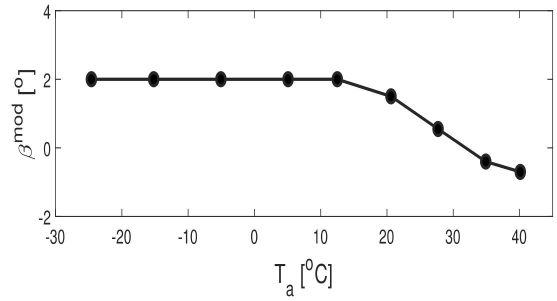

Fig. 12 $\boldsymbol{\beta vs T_a}$ curve

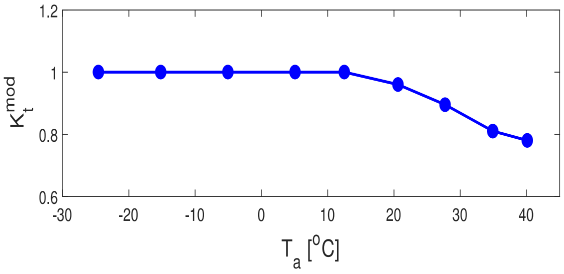

Fig. 13 $\boldsymbol{K_t vs T_a}$ curve

There are only a few parameters that we can control, including the pitch angle of the blade, rotational speed, or generator torque. Majority of wind turbines have constant pitch angle in low wind area. However, we considered that we could adjust the pitch and rotational speed of the wind turbine according to our needs instead of keeping them constant in low wind area. (Li et al., 2023) suggested that blade length can be regulated, but this requires a specially designed blade, which increases costs and may not be available in MW-class wind turbines. Therefore, this method is impractical. So, the only variables we can control in such conditions are the ones mentioned earlier. This raises the question: What values should we regulate these variables such as pitch angle and rotational speed in order to minimize the effect of variable ambient temperature?

To understand this, let's examine the effect of modifying these variables by using Fig. 11. What effect it can bring to wind turbine by changing these parameters to specific value rather than setting it at optimal value? In Fig. 11, black line presents trajectory with low ambient temperature, red colored line illustrates trajectory in high ambient temperature, and blue line shows trajectory after pitch angle is set at -0.8° value when ambient temperature has increased. In this figure, point A represents the operation of the wind turbine in low ambient temperature. Subsequently, the wind turbine's operation shifts to point B as T_a increases. The power is reduced, and the rotational speed remains constant which is same as findings from the data analysis in Section 2. After the pitch angle is corrected according to ambient temperature, operation of wind turbine will trace along the blue curve and with rotational speed regulation, the point C becomes a potential operating point. So that, rotational speed of wind turbine should be adjusted to find optimal operation. With above knowledge, effect of ambient temperature changes can be minimized. To do that, the pitch and rotational speed reference values are modified according to Figs. 12 and 13.

5. Generator control scheme

In this section, control system of wind turbine is illustrated. The main generator controller employed for regulating the generator torque is the tip speed ratio (TSR) control strategy. This strategy calculates the optimal rotational speed by using wind speed measurements and turbine parameters, such as torque coefficient (K_t^{opt}), optimal TSR (λ_t^{opt}), and blade radius (R_t) as follows [20, 21]:

$$\boldsymbol{\omega_m^* = K_t^{opt} v_w} \qquad (1)$$

$$\boldsymbol{K_t^{opt} = \frac{L_t^{opt} r_{gb}}{R_t}} \qquad (2)$$

The standard control scheme is illustrated as the black line in Fig. 14. This approach proves effective as it enables a more precise regulation of rotational speed. Major goal of the conventional control strategy is to adjust rotational speed to ensure that operation of wind turbine is at possible operating point, thereby maximizing power yields. The calculation of ω_m^* relies on measurements of wind speed and parameters specific to the wind turbine, with the resulting value, which is sent to the speed controller. The speed controller generates dq-axis current, which is then compared to its measured value in the current controller block to regulate the T_e by providing appropriate switching signals to the power converter. This scheme is more efficient than other types of schemes because it requires fewer parameters for implementation, provides a faster dynamic response, facilitates easy cooperation with load reduction control, mitigates aerodynamic losses, and so on (Liu et al., 2015) (Takahashi et al., 2020).

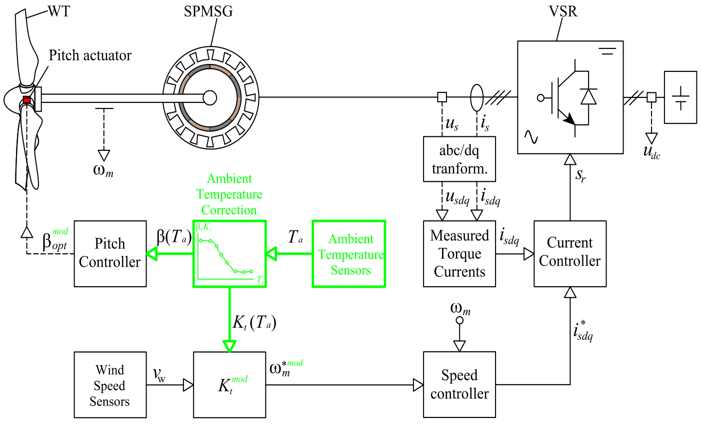

Fig. 14 Control scheme with mitigation of T_a effect

Table 2
Parameter of wind turbine generator

Parameters	Symbols	Value
Power	P_s^{rat}	2 MW
Voltage	V_s^{rat}	690 V
Inductances	$L_d=L_q$	1.5731 mH
Resistance	R_s	0.821 mOhm
Rotor flux	ψ_r	5.8264 Wb
Inertia	J_e	385 kNm
Pole pair	p	26
Blade radius	R	38 m

However, in our perspective, conventional control scheme cannot respond to T_a changes, which reduces the performance of wind turbine. Therefore, the extra module called *ambient temperature mitigation* has been included into the conventional control which is indicated by green line in Fig. 14. Such module contains curves for β^{mod} and K_t^{mod}, which are corrected according to T_a changes, as illustrated in Figs. 12 and 13. Then, reference value of rotational speed will be calculated as $\omega_m^{*mod} = K_t^{mod} v_w$ under varied T_a conditions. T_a can be measured value from temperature sensor.

6. Simulation Results and Discussions

The results of simulation study for 3 scenarios are presented in this section. The ideal scenario (blue line) is when Ta constant at -5^oC during total operation period and the standard control system is activated. Standard scenario (black line) presents the operation with standard control strategy when T_a has varied.

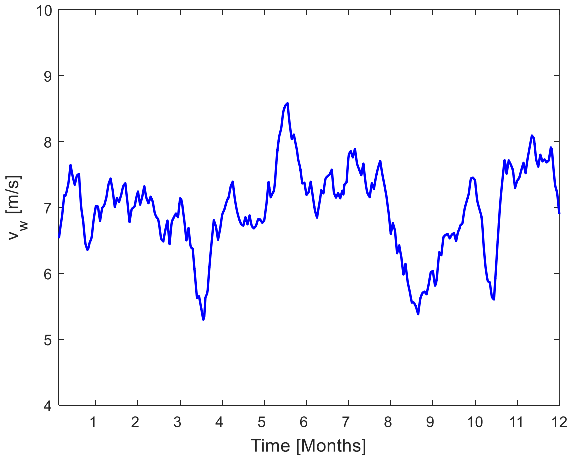

Fig. 15 Wind speed for 12 months

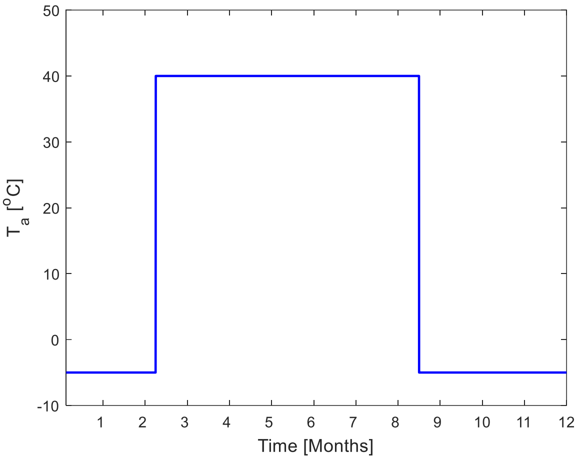

Fig. 16 Ambient temperature for 12 months

The final scenario is about mitigation strategy (red color) where corrections are implemented to minimize the effect of $\boldsymbol{T_a}$ variations. This is depicted by the red line. $\boldsymbol{T_a}$ was considered to be varied between $-\boldsymbol{5^oC}$ to $+\boldsymbol{40^oC}$, representing winter and summer conditions. The low-temperature period represented by the green area and high-temperature period indicated by reddish area for a clear understanding as shown in Fig. 16. The parameters of the WTG are illustrated in Table 2. We considered wind speed as depicted in Fig. 15 and we used mostly low wind speed to see the distinctness of our system as discussed in previous sections.

As shown in Fig. 17a, we observe the power production of the wind turbine with constant temperature as indicated by the blue line. At beginning of 2 months, Ta has increased to a higher value. The power production of wind turbine decreased, as indicated by the black line. In the ideal scenario, the wind turbine produced average power of 400.1 kW, resulting in a total energy production of 3,504,876 kWh over a one-year period (1 year). However, with change in Ta as depicted in Fig. 16, average power output declined to 365.6 kW, resulting the power production to 3,202,656 kWh under standard control. With suggested correction scheme, the power production increased to 386.5 kWh and total energy production also rose to 3,385,740 kWh. Under the suggested scheme with correction, the wind turbine produced an extra electricity generation of 20.9 kW or 183,084 kWh. This indicates that output power was risen by 5.71% rise compared to the standard scheme. The findings show that the proposed correction effectively mitigated the influence of Ta variations, resulting in a substantial expansion of power production efficiency.

Fig. 17b illustrates the rotational speed of the wind turbine under 3 scenarios. As illustrated in Section 2, our analysis with standard control indicates that there is minimal impact on the rotational speed during variable temperature. It is evident that rotational speed did not change when $\boldsymbol{T_a}$ was changed, which means that this result is supported by similar cases observed in the data analysis. On the other hand, with suggested control system, rotational speed (red line) should be modified to find optimal operating point for maximum power production. Fig. 17c demonstrates the pitch angle of wind turbine in said 3 scenarios. In the first two scenarios, the pitch angle remained at $\boldsymbol{2^o}$, which is optimal value in low wind regions. On the other hand, modified pitch angle was depicted by red line, and the $\boldsymbol{\beta^{mod}}$was corrected to minimize the impact of $\boldsymbol{T_a}$ variations.

7. Conclusion

This research investigated control of wind turbine in varies ambient temperature. Main motivation was to understand how ambient temperature affect to parameter of wind turbine and develop strategy that minimize this effect. One year measurement data was used to discover the effect of ambient temperature and its existence in wind turbine. After proved it affected to wind turbine, the mitigation method was implemented, correcting the wind turbine parameters such as rotational speed and pitch angle, according to ambient temperature. The distinguished advantages of the proposed method are additional wind turbine components does not necessary, avoiding the need for supplementary hardware and implementation is straightforward. Also, the precise ambient temperature measurement is required. Few suggestions from this study are (1) Ambient temperature variation can potentially affect the power generation of wind turbines, (2) the pitch angle of turbine blade can be adjusted when ambient temperature changes and (3) the rotational speed of turbine can be adjusted when ambient temperature changes.

By implementing these suggestions, wind turbines will be able to respond to changes in ambient temperature, producing higher output power than system that does not respond to weather changes.

Author Contributions: N.J.: Conceptualization, methodology, formal analysis, writing—original draft, S.B. M.S.; supervision, resources, project administration, N.B.; writing—review and editing, project administration, validation, B.E.; writing—review and editing, project administration, validation. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

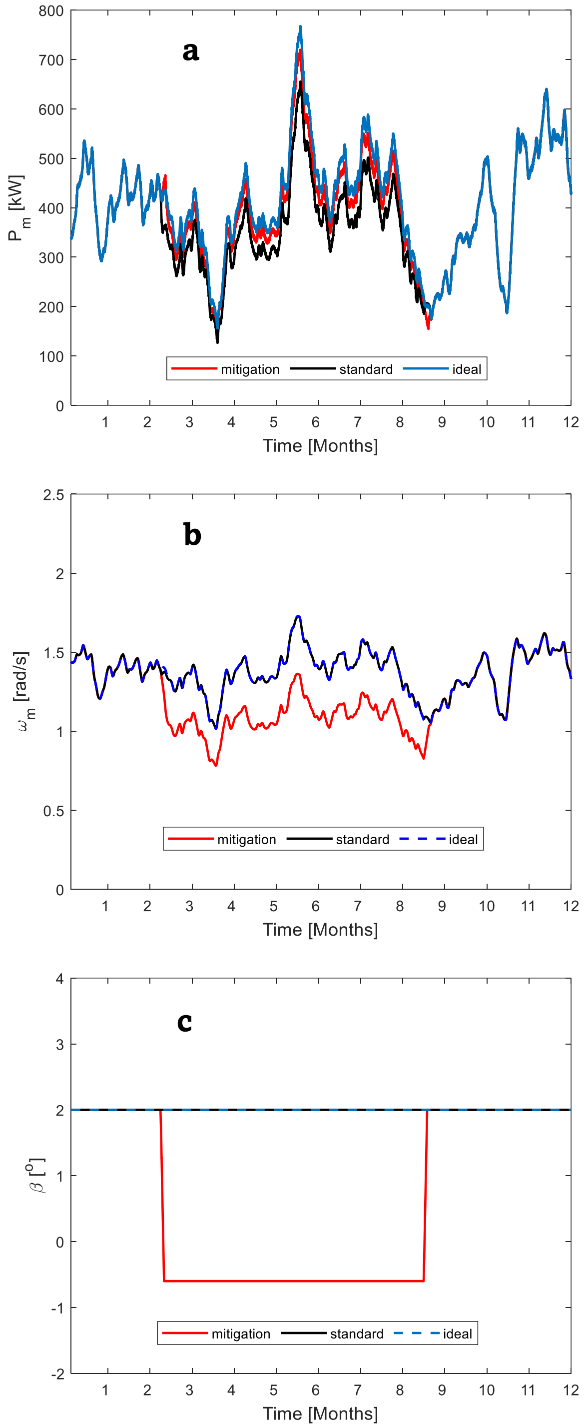

Fig. 17 (a) Active power production (b) Rotational speed of turbine (c) Pitch angle of blade

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