CONDITION MONITORING SYSTEM FOR WIND GENERATOR BASED ON THE EFFECTS OF THE GENERATOR PERMANENT TEMPERATURE

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الملخص

نتيجة لتزايد الأعطاب بمولدات توربينات الرياح نجد أن نظام مراقبة حالتها التشغيلية يلعب دوراً هاماً في التغلب على هذه الاعطاب الناجمة عن عملها في ظروف قاسية. يمكن الاستفادة من نماذج التحليل الرياضي والحراري والكهربائي للكشف عن العيوب الخاصة بمولدات طاقة الرياح عن طريق رصد التغيرات في الخصائص التشغيلية تحت ظروف مختلفة. دراسة السلوك الدوراني للمجال المغناطيس الخاص بهذه المولدات يمكن أن يوضح الحالة التشغيلية العامة للنظام. فعلى سبيل المثال يتأثر عزم دوران المجال المغناطيسي الدائم للمولد بالتذبذب في درجة الحرارة الخاصة بهذا المجال المغناطيسي وبالتالي فإن مراقبة عزم الدوران المغناطيسي وفقاً لمعدل التغير في درجة حرارة هذا المجال المغناطيسي يمكن أن يحدد الحالة الصحية لمولدات توربينات الرياح. بالإضافة إلى ذلك، فإن معدل التغير في درجة حرارة المولد تعتبر مؤشراً إضافياً لتحديد الحالة الصحية لمولدات الرياح أثناء العمل وفقاً للعزم الكهربائي الناتج. وذلك بسبب التأثير السلبي لارتفاع درجة حرارة المولد على هذا العزم الكهربائي. في هذا البحث تم اعتماد نهجاً مختلفاً لتنفيذ نظام مراقبة للحالة التشغيلية لمولدات توربينات الرياح بشكل دقيق وذلك من خلال تقدير معدل التغير في درجة حرارة المولد وفقاً للتغير في العزم المغناطيسي الناجم تحت ظروف تشغيل مختلفة. أُجريت دراسة معملية تستند على بيانات تم جمعها من أجل إظهار مدى ملاءمة النموذج المقترح للعمل تحت ظروف تشغيل مختلفة.

ABSTRACT

Due to the increased rate of failure of wind generators, condition-monitoring system plays a significant role in overcoming failures resulting from the harsh operation conditions. The mathematical, thermal, and electrical analyses may be utilized to detect the faults of wind generators by monitoring the changes in their characteristics under different operation conditions. The behavior of the rotating permanent magnet of the generator can indicate the wind generator's condition. For instance, the torque of the permanent magnet of the generator is affected by the oscillation of the magnet temperature. Therefore, monitoring the torque of the permanent magnet with respect to the rate of change in the permanent magnet temperature defines the generator health. Furthermore, the rate of change in the generator temperature is considered an additional indicator to define the health of the wind generators with respect to the induced electrical torque. That is because of the negative effect of the elevated generator temperature on the induced electrical torque. In this study, a different methodology has been adopted to implement a proper condition monitoring system on the wind generators by evaluating the rate of change in the generator temperature and permanent magnet temperature with respect to the induced electrical torque and the driving torque of the rotating permanent

magnet under different operation conditions. A case study, which is based upon collected data from actual measurements, is presented in this work in order to demonstrate the adequacy of the proposed model.

KEYWORDS: Condition-Monitoring System; Permanent Magnet Temperature; Induced Electrical Torque; Magnetization Angle.

INTRODUCTION

Condition monitoring system (CMS) for wind turbine components increases the generated wind power and helps to reduce the operation and maintenance costs particularly when turbines are deployed offshore. An inclusive monitoring system provides diagnostic information on the health of the turbine components, and issues warnings to the maintenance crew that potential failures or critical malfunctions might be imminent [1-4]. The failures that occurred in wind turbines due generator has been shown to be significant, which leads to increased attention in order to avoid the technical problems that caused by wind generators during running under different loads. The most important components of a wind generator, which experience likely failures are bearing, stator, and rotor, and certainly the failures ratios are different in every single component [4,5].

Researchers have improved several condition-monitoring techniques that can increase the reliability of the wind energy industry and decrease the maintenance and operation costs. Normal behavior models are employed for condition assessment of wind turbine generator systems [6]. In order to establish an assessment index system, monitoring parameters, which are collected by the supervisory control and data acquisition systems of wind farms are utilized. A neural network and Parzen estimation are used to establish the normal behavior models of the collected parameters to determine the health degree of the wind generators. Further, the fuzzy synthetic evaluation is employed to initiate the assessment process. Analyzing temperature trends by using the nonlinear state estimation technique (NSET) is one of the proposed methodologies to perform condition monitoring on wind generators [7]. To detect a fault that can potentially occur as a result of high temperatures of wind generators, the differences between the predictions and the actual values are used as essential indicators. Popa et al. discussed using the time and frequency domain analysis to apply CMS by monitoring the stator and rotor current line trends when both the stator and generator rotors monitoring to a wind generator [8]. The authors emphasized that generator faults may be detected under an unbalanced force. They applied the machine current signature analysis (MCSA) method, which is a noninvasive online or offline monitoring technique to diagnose faults in generators, such as turn-to-turn faults, broken rotor bars, and static or dynamic eccentricity. In another study, heat transfer analysis and fluid mechanics relations were used to develop a proper CMS on wind generators based on the increase in the generators' temperatures [9]. This work presents a new CMS model that is applied to wind generators that work with water-air heat exchangers. The results obtained from the proposed model show that the increase in the heat loss is not desirable with respect to the logarithmic average of the temperature differences of the generator heat exchanger. An application of a condition-monitoring system based on a polynomial regression model (PRM) to study the influence of heat loss on a wind generator's temperatures was [10]. The proposed technique is also used to construct a normal behavior model of the electrical generator's temperatures based on the recorded data. These regression models may predict wind generator temperatures by evaluating the correlation between the observed values and the predicted values of the criterion variables. Anotherwork by Yang et al. used the mechanical characteristics to diagnose the faults that can occur in wind generators [11]. The authors introduced a method to detect the electrical faults in wind generators by applying wavelet transform theory. They assumed in their work that when the applied electrical torque with respect to the generator rotor speed varies dramatically over time, the likelihood of detecting generator faults is possible. This model, however, may only be used when mechanical and electrical torques are equal. In this paper, the approach of determining the torque of the permanent magnet of the generator with respect to the temperature of the permanent magnet, which is slightly higher than the generator temperature, is proposed to implement CMS on the wind generators. Based on the mathematical analysis of the differential equations, the permanent magnet torque can be estimated with respect to the magnet temperature with the aim of Matlab simulation.

The methodology applied in this paper is illustrated in Figure (1) it starts with the influence of the permanent magnet temperature on the driving torque of the rotating permanent magnet by introducing a set of partial differential equations, derived for the characterization of the rotations of the permanent magnet. In order to demonstrate the utilization of the proposed method and its capability a case study is provided. The obtained results of the proposed models are then presented and finally discussion, conclusions and suggestions for further research are presented.

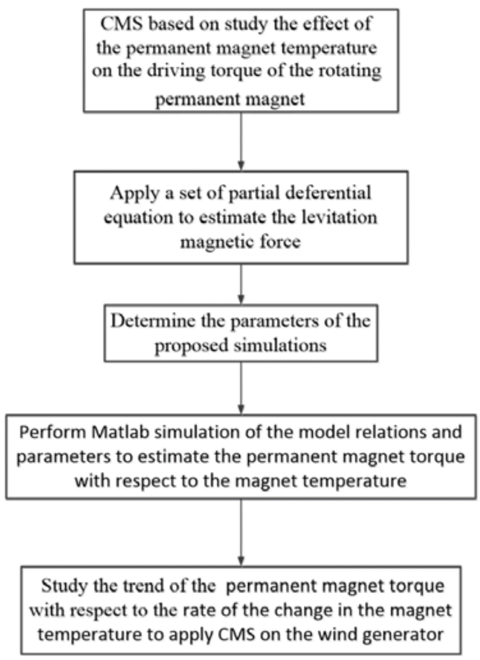

Figure 1: The flowchart of the proposed CMS approach

THE EFFECT OF THE PERMANENT MAGNET TEMPERATURE ON THE DRIVING TORQUE OF THE ROTATING PERMANENT MAGNET

Due to the increase in the permanent magnet temperature, the driving torque of the rotating permanent magnet oscillates with increasing the amplitude based on the change in the magnetization angle of the permanent magnet. An important reason for the driving torque of the permanent magnet is the temperature dependence of the magnetization since the temperature range decreases with the magnetization increases [12]. In such conditions, defining the behavior of the rotating permanent magnet is significant to apply CMS on the wind generators. The permanent magnet model should describe the rotating permanent magnet condition during operation in the normal and abnormal situations. This section presents a set of partial differential equations, which are devolved for the characterization of the rotations of the permanent magnet.

It is supposed that the permanent magnet has a cylindrical shape and volume ∀ as shown in Figure (2). The length of the cylinder is L and the radius is r. Thus, the volume of the cylindrical shape (∀) is $\pi r^2 L$. The density of the permanent magnet is considered to be constant (ρ); consequently, the total mass of the permanent magnet (m) is $\pi r^2 L \rho$. A coordinate system is determined in such a way that the axis of the cylinder corresponds with the $z - axis$. Therefore, the z-coordinator of the cylinder is in the range $[0, L]$. In the case of the two-dimensional setting, a cross section of the cylinder, such as a circle is considered. The cross section area of the circle is A in the $xy - plane$ with radius r and center$(0,0)$. The normal vector at a point of the boundary ∂A is denoted by n and assumed to reference into the surrounding air.

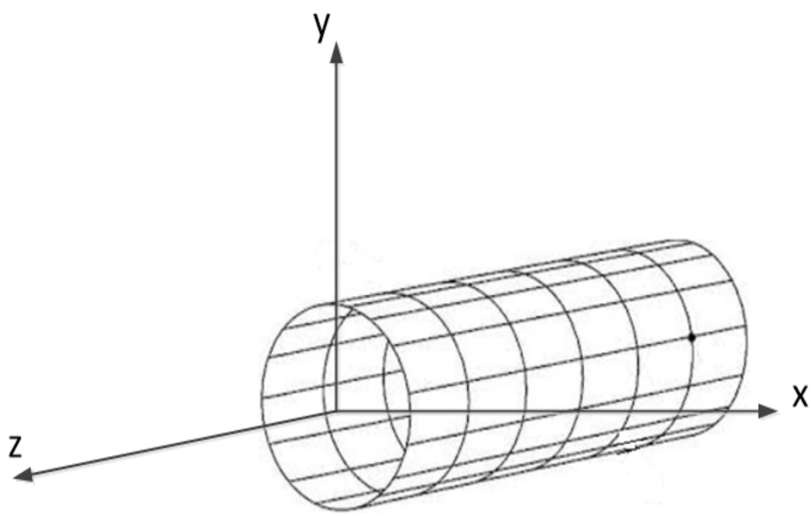

Figure 2: The cylindrical shape of the permanent magnet.

Assuming the temperature in the limited volume of the cylindrical shape (∀) does not change in the z-direction and the heat flux through the bottom and the top surface of the cylinder is negligible. The temperature distribution $T = T(t, x, y)$ is governable by the two-dimensional time dependent heat equation, [13-15]:

$$\rho c \frac{\partial T}{\partial t} - \nabla . (\lambda \nabla T) = 0, \tag{1}$$

The term $\rho c \, \partial T / \partial t - \nabla . (\lambda \nabla T)$ equals to zero since there are no heat sources. The specific heat is denoted with c, and λ is the thermal conductivity. This equation has to be completed with an initial condition $T(0, x, y) \; or \; T_0 \; (x, y)$ and the boundary conditions. By applying the Newton's law of cooling at the boundary ∂A, the heat flux can be assumed as follows:

$$n. (\lambda \nabla T) = \alpha \, (T_0 - T), \tag{2}$$

where the temperature $T_0 = T_0\,(x,y)$ of the surrounding air, which can be estimated from the measurements and α is the heat transfer coefficient. The coordinate system is fixed and is not rotating with the magnet. Therefore, the point (x,y) moves with the velocity $\omega(-y,x)^T$. Further, the convective heat transfer should be taken into account by modifying the heat equation as follows:

$$\rho c\left[\frac{\partial T}{\partial t}+\omega\begin{pmatrix}-y\\x\end{pmatrix}.\nabla T\right]-\nabla.(\lambda\nabla T)=0 \quad \textit{In the cross section area } (A) \tag{3}$$

With respect to the boundary conditions, the time dependent heat equation equals to:

$$h\frac{\partial T}{\partial n}+T=T_0, \tag{4}$$

where h is the heat transfer coefficient by convection and T_0 is continuously differentiable on ∂A.

In order to estimate the torque on the permanent magnetic, a detailed consideration of the magnetic forces is necessary. Since the permanent magnet is levitated above the superconductor, the total levitation force in the three dimension is defined as follows:

$$F=\begin{pmatrix}0\\ \pi r^2 L\rho g\\ 0\end{pmatrix} \tag{5}$$

The permanent magnet consists of a spatial homogeneous volume density. Let B is the magnetic field due to the induced current, then the magnetic force of the permanent is defined as follows:

$$F=\int_{\nabla}\nabla(m.B)d\forall=\int_{\nabla}(m.\nabla)Bd\forall \tag{6}$$

The permanent magnet mass has components in the z-direction m_z (the permanent magnet axis), thus:

$$F=\int(m.\nabla)\,Bd\forall=m_z\frac{\partial B}{\partial z} \tag{7}$$

Using that $\frac{\partial}{\partial y}B_z=\frac{\partial}{\partial z}B_y$, the y-component of the magnetic force F_y is defined as follows:

$$\mathrm{F_y}=\int_{\forall}\mathrm{m_z}\frac{\partial}{\partial y}\mathrm{B_z d\forall}=\int_0^1\int_A \mathrm{m_z}\frac{\partial}{\partial y}\mathrm{B_z\,da\,dz}=\mathrm{L}\int_A\mathrm{m_z}\frac{\partial}{\partial y}\mathrm{B_z\,dA}=\mathrm{L}\int_A\mathrm{m_z}\,\nabla\,\mathrm{B_z\,dA} \tag{8}$$

Since the diameter of A is small, linearization of B in A is beneficial, which means ∇B_z is constant in A:

$$\nabla B_z=\begin{pmatrix}0\\g_B\\0\end{pmatrix} \tag{9}$$

Based on a suitable constant g_B, the $x-$ and $z-$components are zero due to the fact that the total force has zero value in $x-$ and $z-$ components. Thus, the y–component of the force is given by:

$$F_y=L\,g_B\int_A m_z\,(x,y)dA, \tag{10}$$

where F_y is the levitation force at the limit temperature which can be modified as follows:

$$F_y = L\pi r^2 \rho\, g \tag{11}$$

According to the Bloch's $T^{\frac{3}{2}}$ relation [16], a linear function of the permanent magnet mass in the z −direction can be introduced before the torque is calculated as follows:

$$m_z = u + qT, \tag{12}$$

where u and q are parameters and can be determined by using specific relations. The levitation force will define as follows:

$$F_y = L \int_A m_z \frac{\partial}{\partial y} B_z\, dA = L \int_A (u + qT) g_B\, dA \tag{13}$$

The torque of the permanent magnet τ_{pm} around the $z - axis$ can be estimated in a similar way:

$$\tau_{pm} = L \int_A x\, m_z \frac{\partial}{\partial y} B_z\ d = L \int_A x\,(u + qT)\, g_B\ d = \rho g_B L \int_A x\, dA + q g_B\, L \int_A x\, T\, dA \tag{14}$$

Since $\int_A x\, dA = 0$, the final version for the torque of the permanent magnet τ_{pm} as follows:

$$\tau_{pm} = q\, g_B L \int_A x\, T\, dA, \tag{15}$$

where g_B can be calculated using the next relation:

$$g_B = \frac{\rho\, g}{u + q\ \bar{T}}, \tag{16}$$

where is $\bar{T}$ the mean temperature of the permanent magnet and the parameter q is computed as follows:

$$q = \frac{\mu_r}{J_{pm}}, \tag{17}$$

where μ_r is the friction coefficient and J_{pm} is the moment of inertia for the cylindrical permanent magnet, which can be defined as follows:

$$J_{pm} = \frac{\pi L \rho r^4}{2} \tag{18}$$

The parameter u is estimated from the following formula [16]:

$$u = \frac{2.5\ x\ 10^{-6} F_y}{J_{pm}} \tag{19}$$

The mean temperature of the permanent magnet can be estimated based on the time-dependent Eq. (3) in the polar coordinates ($x = a\ cos\varrho, y = a\ sin\varrho$) as follows:

$$\frac{\partial T}{\partial t}+\ \omega\frac{\partial T}{\partial \gamma}-\lambda\left(\frac{\partial^2}{\partial a^2}+\frac{1}{a}\frac{\partial}{\partial a}\right)T-\ \frac{\lambda}{a^2}\frac{\partial^2}{\partial \gamma^2}\ T=0, \qquad (20)$$

where $a\ \in(0,r)$ and γ is the magnetization angle of the permanent magnet. By integrating the last equation from 0 $to\ 2\pi$. It can obtain:

$$\int_0^{2\pi}T(t,a,\varrho)d\gamma+\ \omega\int_0^{2\pi}\frac{\partial}{\partial \varrho}T(t,a,\gamma)d\gamma-\lambda\left(\frac{\partial^2}{\partial a^2}+\frac{1}{a}\frac{\partial}{\partial a}\right)\int_0^{2\pi}T(t,a,\gamma)d\gamma-\frac{\lambda}{a^2}\int_0^{2\pi}\frac{\partial^2}{\partial \gamma^2}(t,a,\gamma)d\gamma=0 \qquad (21)$$

Suppose the abbreviation $\xi(t,a)=\ \int_0^{2\pi}T(t,a,\gamma)d\gamma,$ the integrals with partial derivatives with respect to γ modify the singular differential equation to:

$$\frac{\partial}{\partial t}\ \xi(t,a)-\ \lambda\ \left(\frac{\partial^2}{\partial a^2}+\frac{\partial}{a\partial a}\right)\ \xi(t,a)=0 \qquad for\ a\in(0,r), \qquad (22)$$

For the boundary condition we get similarly:

$$h\frac{\partial \xi}{\partial a}+\ \xi\,|_{\ a=r}=\ \int_0^{2\pi}T_0\ d\gamma \qquad (23)$$

Setting the time derivative to zero, Eq. (22) becomes a stationary heat equation to obtain rotational symmetric solution. For this situation, the solution of $\xi(a)$ becomes constant [16, 17], so that:

$$\pi r^2 T=\ \int_0^{r}\xi(a)a\ da=\frac{1}{2}r^2\ C=\frac{1}{2}r^2\int_0^{2\pi}T_0\ d\gamma \qquad (24)$$

Thus,

$$\bar{T}\ =\ \frac{1}{2\pi}\int_0^{2\pi}T_0\ d\gamma \qquad (25)$$

The previous mathematical analysis can be utilized to find the effect of the permanent magnet temperature on the driving torque of the rotating permanent magnet to define the generator operation condition based on Matlab simulation of the model relations and parameters.

CASE STUDY

In order to utilize the proposed model to develop a proper condition monitoring on the generator of the selected wind turbine, the collected data by SCADA system is categorized and analyzed according to the operation conditions. Actual data was obtained from a variable speed wind turbine with rated power of 600 kW, 60Hz, two blades, 43.3m rotor diameter, and rated speed 12.7 m/s with upwind horizontal axis. The turbine height is 36.6m and has a permanent magnet synchronous generator with 1800 rpm rated synchronous speed. The collected data represent two operation conditions of the selected wind turbine; normal and abnormal conditions. The SCADA system offers sufficient knowledge about the system's condition during running based on many parameters that are measured and recorded over 600 seconds. Based on evaluating the driving torque of the rotating permanent magnet with respect to the magnet temperature, CMS on the wind generators can be applied by processing the parameters of the proposed algorithm. The parameters of the simulations should be known in order to estimate the other characters, which govern the permanent magnet torque with respect to the permanent magnet temperature. Table (1) presents the parameters, which process the data of the proposed algorithm [18].

Table 1: The proposed model parameters [18]

Geometry and Mechanical Properties	
g	$9.81\ \mathrm{m/s^2}$
r	$0.2\ \mathrm{m}$
L	$0.34\ \mathrm{m}$
ρ	$8236\ \mathrm{kg/m^3}$
μ_r	$1.04635 \times 10^{-10} \mathrm{N.m\ s}$
λ	$8\ \mathrm{W/(m.K)}$
$\propto$	$50\ \mathrm{W(m^2K)}$
T_0	$18\ \mathrm{C^{\circ}}$

The magnetization angle of the permanent magnet changes when the permanent magnet torque oscillates due to the fluctuation in the permanent magnet temperature. Figure (3) illustrates the trend of the permanent magnet torque with respect to the magnetization angle of the permanent magnet. When the magnetization angle is within the range $(0\ to\ 15\ rad)$, the permanent magnet torque is increased. The reason of this situation is due to a decrease in the permanent magnet temperature. After that, a sudden decrease in the permanent magnet torque when the magnetization angle is within the range $(0.15\ to\ 0.45\ rad)$, which confirms the increase in the temperature of the permanent magnet torque. Finally, the permanent magnet torque regularly increases with respect to the magnetization angle $(\gamma > 0.45\ rad)$ and the decrease in the temperature of the permanent magnet.

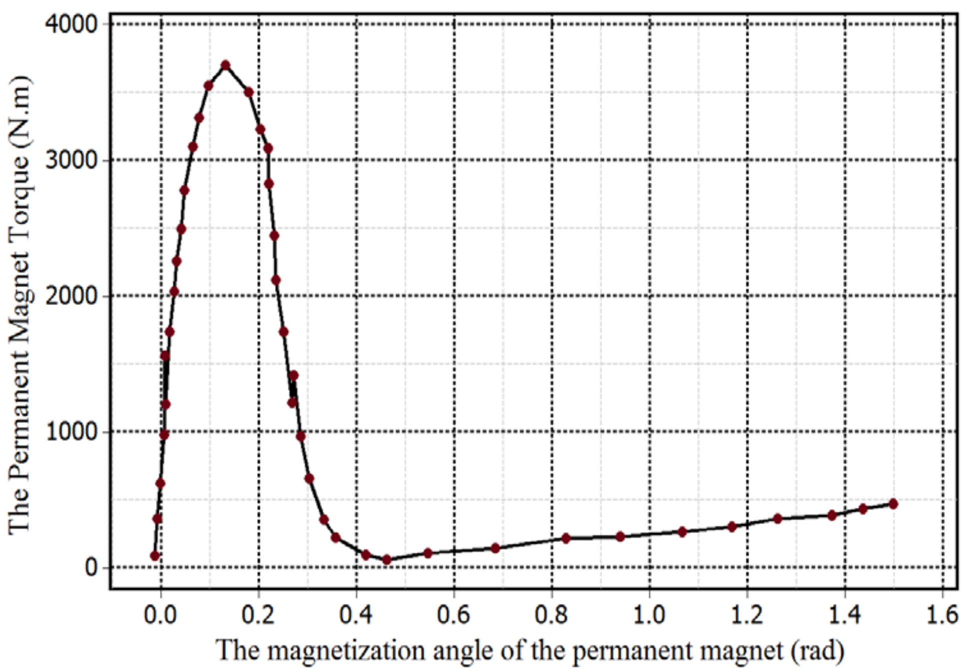

Figure 3: The driving torque of the rotating permanent magnet trend with respect to the magnetization angle.

According to the manufacturer's handbook, the abnormal operation condition is considered when the generator temperature exceeds 110 ^{o}C or the permanent magnet temperature overtakes 112 ^{o}C. One of the major goals of this study is to determine the effect of the high generator temperatures on the induced electrical torque and the high temperature of the permanent magnet on the permanent magnet torque, which aims to identify the generator health. Table (2) presents the operation conditions of the selected wind turbine based on the generator temperature and the permanent magnet temperature [18].

Table 2: The operation conditions of the selected wind turbine based on the generator temperature and the permanent magnet temperature [18]

The Operation Condition	Generator Temperatures	Permanent Magnet Temperatures
Normal condition	$T < 110\ C°$	$T < 112\ C°$
Abnormal condition	$T > 110\ C°$	$T > 112\ C°$

RESULTS AND DISCUSSIONS

The simulation results of the induced driving rotating permanent magnet torque show low values in the abnormal condition with respect to the rate of change in the rotating permanent magnet temperature as shown in Figures (4 and 5). These figures illustrate the trend of the permanent magnet torque of the wind generator in the normal and abnormal conditions with respect to the rate of change in the rotating permanent magnet temperature and the magnetization angle of the permanent magnet.

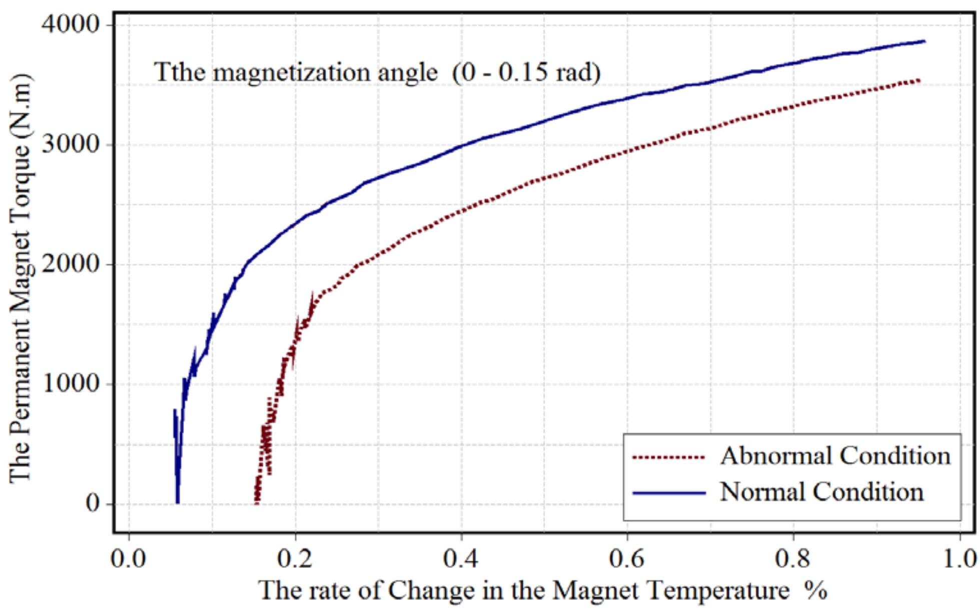

Figure 4: The trend of the permanent magnet torque with respect to the rate of change in the magnet temperature when the magnetization angle is within (0 – 0.15 rad).

The influence of the permanent magnet temperature on the driving permanent magnet torque and the magnetization angle is clear in the normal and abnormal conditions. Table (3) shows high correlation coefficients of the permanent magnet torque with the permanent magnet temperature and magnetization angle. The high values of the correlation coefficients confirms that the trend of the permanent magnet torque depends on these independent variables, which restrict the driving torque of the permanent magnet obviously.

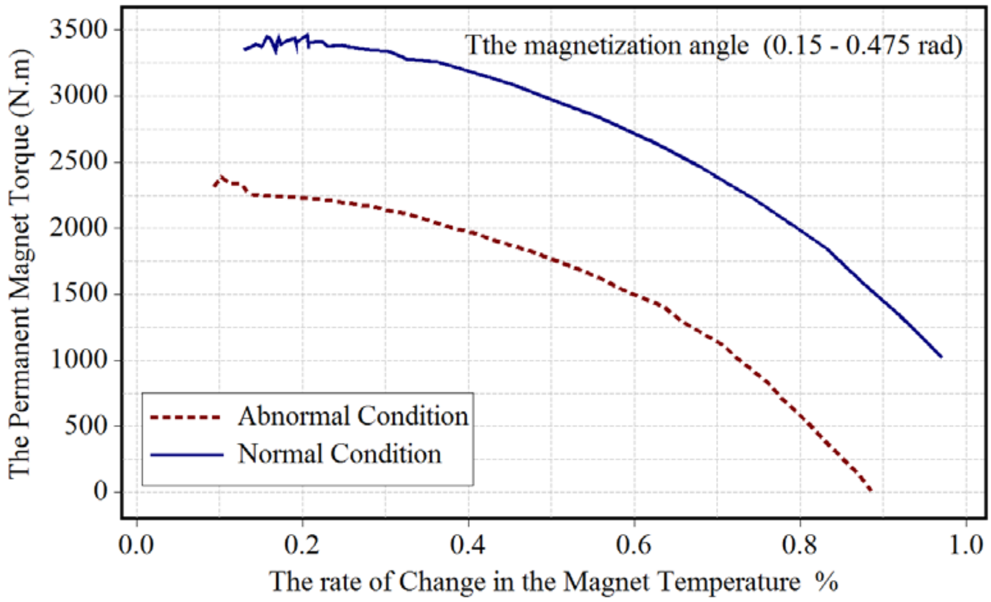

Figure 5: The trend of the permanent magnet torque with respect to the rate of change in the magnet temperature when the magnetization angle is within (0.15 – 0.475 rad).

Table 3: The correlation coefficients of the permanent magnet torque with the permanent magnet temperature and magnetization angle

The Variables		Electrical Torque
Generator Temp.	Corr. Coeff.	0.98
	P-Value	0.00
Magnetization angle	Corr. Coeff.	0.95
	P-Value	0.00

Likewise, the excitation flux in the core of the generator and connected power transformers are directly proportional to the ratio of the voltage to the frequency on the terminals of the equipment. The losses that are due to the eddy currents and hysteresis rise the temperature and hence increase in proportion to the level of excitation. In the abnormal operation condition, the generator reactance X_S might rapidly decrease, and the ratio of the change in the generator temperature increases with respect to the electrical torque and rotor rotational speed. Therefore, the ratio of the change in the generator temperature could be considered an indicator to detect the faults in the generators [19,20]. Figure (6) illustrates the behavior of the rate of change in the generator temperature with respect to the rotor rotational speed in the normal and abnormal conditions respectively.

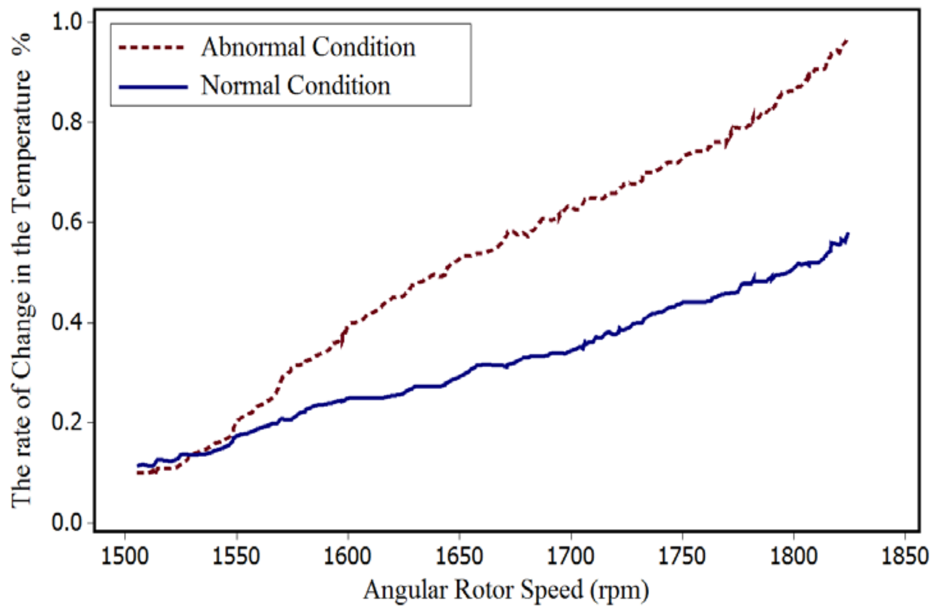

Figure 6: The rate of change in the generator temperature with respect to the angular rotor speed.

The increase in the generator temperature shows high values in the abnormal condition with respect to the generator output power as shown in Figure (7), which illustrates the scatterplot of the generator temperature rise against the relative power output in the normal and abnormal conditions. This figure clearly presents the contrast in the rise of the generator temperature with respect to the relative power output between these conditions. The average generator temperature rise for each $50kW$ increment of the output power in the normal and abnormal conditions is illustrated in Figure (8). The transition condition represents the transit from the normal to the abnormal situation.

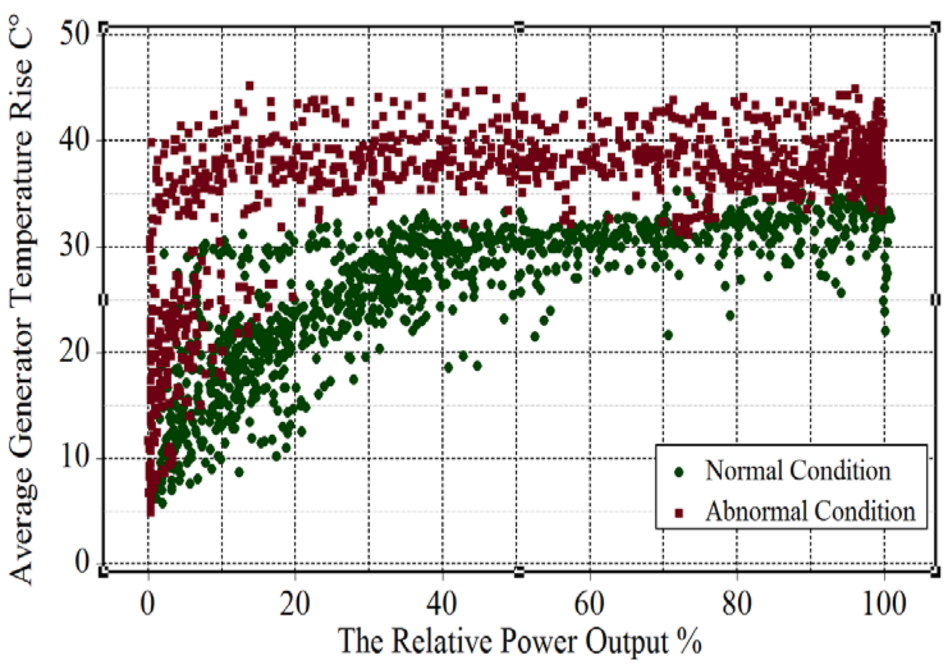

Figure 7: The generator temperature rise against the relative output power.

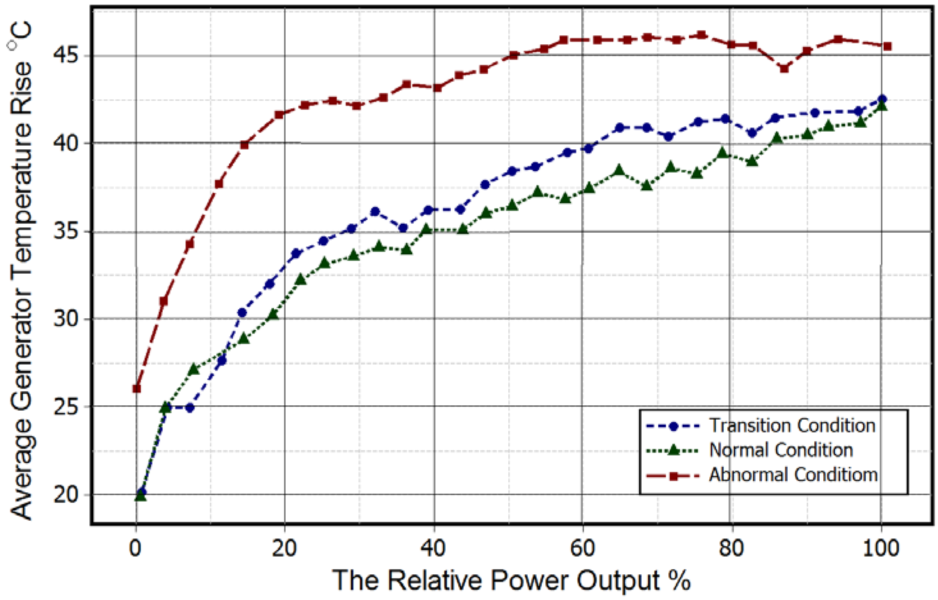

Figure 8: The Generator temperature rise trends against the relative output power.

CONCLUSION

The proposed method presented in this study shows that the behavior of the driving torque of the rotating permanent magnet with respect to the permanent magnet temperature can be employed to develop a proper CMS on the wind generators. In the abnormal condition, when the permanent magnet temperature during operation is higher than the design permanent magnet temperature, the permanent magnet torque decreases dramatically with respect to the magnetization angle of the permanent magnet. Additionally, the rate of change in the generator temperature with respect to the induced electrical torque is also considered an indicator to define the generator health. Potential electrical faults might occur due to a decrease in the generator reactance X_S, and an increase in the generator temperature, which influences the induced torque immediately with respect to the armature resistance of the generator. Future work is required to apply the proposed method on the wind generators that suffer from different electrical faults. Furthermore, the proposed model could be applied on different parts of the wind turbines, such as gearboxes, to confirm the validity of the proposed method.

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REFERENCES

[1] J. Nilsson and L. Bertling, "Maintenance management of wind power systems using condition monitoring systems—life cycle cost analysis for two case studies," Energy Conversion, IEEE Transactions on, vol. 22, pp. 223-229, 2007.

[2] A. Amayri, Z. Tian, and T. Jin, "Condition based maintenance of wind turbine systems considering different turbine types," in Quality, Reliability, Risk,

Maintenance, and Safety Engineering (ICQR2MSE), 2011 International Conference on, 2011, pp. 596-600.

[3] Y. Li, "Discussion on the principles of wind turbine condition monitoring system," in Materials for Renewable Energy & Environment (ICMREE), 2011 International Conference on, 2011, pp. 621-624.

[4] F. P. G. Márquez, A. M. Tobias, J. M. P. Pérez, and M. Papaelias, "Condition monitoring of wind turbines: Techniques and methods," Renewable Energy, vol. 46, pp. 169-178, 2012.

[5] K. Alewine and W. Chen, "A review of electrical winding failures in wind turbine generators," in Electrical Insulation Conference (EIC), 2011, 2011, pp. 392-397.

[6] J. Li, X. Lei, H. Li, and L. Ran, "Normal Behavior Models for the Condition Assessment of Wind Turbine Generator Systems," Electric Power Components and Systems, vol. 42, pp. 1201-1212, 2014.

[7] P. Guo, D. Infield, and X. Yang, "Wind turbine generator condition-monitoring using temperature trend analysis," Sustainable Energy, IEEE Transactions on, vol. 3, pp. 124-133, 2012.

[8] L. M. Popa, B.-B. Jensen, E. Ritchie, and I. Boldea, "Condition monitoring of wind generators," in Industry Applications Conference, 2003. 38th IAS Annual Meeting. Conference Record of the, 2003, pp. 1839-1846.

[9] K. B. Abdusamad and W. D. Gao, "The application of heat transfer analysis in condition monitoring system of wind generator," in Power and Energy Engineering Conference (APPEEC), 2013 IEEE PES Asia-Pacific, 2013, pp. 1-7.

[10] K. B. ABDUSAMAD, D. W. Gao, and E. Muljadi, "The Influence of Heat Loss on Wind Generators to Implement Condition-Monitoring System Based on the Application of the Polynomial Regression Model," International Journal of Renewable Energy Research (IJRER), vol. 4, pp. 401-412, 2014.

[11] W. Yang, P. J. Tavner, and M. Wilkinson, "Condition monitoring and fault diagnosis of a wind turbine synchronous generator drive train," Renewable Power Generation, IET, vol. 3, pp. 1-11, 2009.

[12] K. B. Ma, J. R. Liu, C. McMichael, R. Bruce, D. Mims, and W. K. Chu, "Spontaneous and persistent rotation of cylindrical magnets levitated by Y-Ba-Cu-O superconductors," Journal of applied physics, vol. 70, pp. 3961-3963, 1991.

[13] T. L. Bergman, F. P. Incropera, and A. S. Lavine, Fundamentals of heat and mass transfer: John Wiley & Sons, 2011.

[14] A. Tveito and R. Winther, Introduction to partial differential equations: a computational approach vol. 29: Springer Science & Business Media, 2005.

[15] K. B. Abdusamad.Condition Monitoring System of Wind Turbine Generator, Doctoral dissertation, University of Denverm 2014.

[16] C. Kittel, Introduction to solid state physics: Wiley, 2005.

[17] O. D. Kellogg, Foun16dations of potential theory vol. 31: Springer Science & Business Media, 2012.

[18] Data of a variable speed wind turbine 600 KW rated power, three phase permanent magnetic type 440/660 V 60 Hz. Provided by Dr. Kathryn, Colorado School of Mines and the National Renewable Energy Laboratory, 2013.

[19] C. Lungoci and D. Stoia, "Temperature effects on torque production and efficiency of motors with NdFeB," parameters, vol. 2, 2008.

[20] L. Xin, L. Bin, X. Jianyuan, and T. Yun, "Notice of Retraction A Novel Power Predicting Model of Wind Farm Based on Double ANNs," in Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific, 2010, pp. 1-4.