Condition Monitoring System of Wind Generators based on the Effect of Electrical Torque Pulsations and Generator Temperature

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Abstract*— Due to the increase in the failures of the wind generators, Condition Monitoring System (CMS) plays a significant role in overcoming these failures resulting from the harsh operation conditions. The mechanical, thermal, and electrical analyses can be utilized to detect the faults, which are coming from the wind generators by monitoring the changes in their characteristics under different (normal and abnormal) operation conditions. Observing the trend of the electrical torque pulsations of the wind generators under different conditions is beneficial to perform proper condition monitoring. In this paper, different methodology has been adopted to implement a proper condition monitoring system on the wind generators by evaluating the generator electrical torque based on the mechanical and the acceleration torque. Then, in order to specify the generator faults, the trend of the electrical torque with respect to the rotor angular speed of the wind generator under different operation conditions is analyzed. Further, the rate of change in the generator temperature is considered as well as an indicator to define the health of the wind generators with respect to the induced electrical torque, because of the negative effect of the elevated generator temperature on the induced electrical torque. 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.

I. INTRODUCTION

Applying a modern condition monitoring on the parts that are faced to failures, such as gearboxes and generators increases the generated wind power and helps to reduce the operation and maintenance costs particularly when turbines are deployed offshore. Condition monitoring system (CMS) provides detailed information about the wind turbine components' condition by analyzing measured signal to predict and avoid imminent failure in the wind turbine components [1, 2, and 3]. 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 are caused by wind generators during operation. 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]. Researchers have improved several condition-monitoring techniques that can increase the reliability of the wind energy industry and decrease the maintenance and operation costs. Analyzing the temperature trends based on the Non-linear State Estimation Technique (NSET) is one of the proposed methodologies to implement condition monitoring on the wind generators [5]. The differences between the predictions and the actual values used as an important indicator to detect the faults that can potentially occur as a result of the high temperatures of the wind generators. The moving window averaging approach is used to find out statistically significant changes of the residual mean value and standard deviation in an efficient manner; when these parameters exceed previously specified thresholds, an incipient failure is flagged. In Ref. [6], a new condition-monitoring method based on the application of the multiple linear regression model (MLRM) of the wind generators is presented. The method can be used to construct the standard conduct model of the electrical generator temperatures based on recorded data. Measuring the correlation and deviation between the observed and predicted values of the criterion variables is the main idea of the proposed technique. M. Popa, B. Jensen, E. Ritchie, and I. Boldea discussed using the time and frequency domain analysis to apply condition monitoring to a wind generator [7]. The authors emphasized that the generator faults, such as turn-to turn faults, broken rotor bars, and static or dynamic eccentricity, might be detected by monitoring the stator and rotor current line trends when both the stator and generator rotors are under an unbalanced force. The proposed technique is based on the machine current signature analysis (MCSA), which is considered a noninvasive online or offline monitoring technique. In [8], 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. This work presents a new CMS 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. Another paper used the mechanical characteristics to diagnose the faults that can occur in wind generators [9]. The authors suggest 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. The drawback of the proposed work is limited in the assumption of balancing the mechanical with the electrical torque.

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This proposed work presents an application of condition monitoring system on the wind generators based on data collected from actual measurements in order to demonstrate the adequacy of the proposed model. The proposed model considers the acceleration torque to evaluate reliable electric torque values and apply proper condition monitoring on the wind generators under different operation conditions. Further, the effect of the elevated generator temperature on the induced electrical torque is demonstrated through this work in order to estimate the rate of the change in the generator temperature with respect to the induced electrical torque, which aims to determine the system condition. The rest of the paper is arranged as follows: Section II presents the influences of the ripple torque, cogging torque, and the elevated generator temperature on the induced electrical torque. Section III provides knowledge about the selected wind turbine, synchronous generator, and the available SCADA data. This information is necessary to test the proposed model validity through a case study. Section IV explains the effect of the elevated generator temperature on the produced electrical torque. The proposed mathematical model analysis to apply CMS on the wind generators is illustrated in Section V. In order to demonstrate the utilization of the proposed method and its capability, case study is provided in Section VI. The obtained results of the proposed model are showed in Section VII. Finally, discussion, conclusions and suggestions for further research are presented in Section VIII. The methodology of the present work is summarized in the next flowchart:

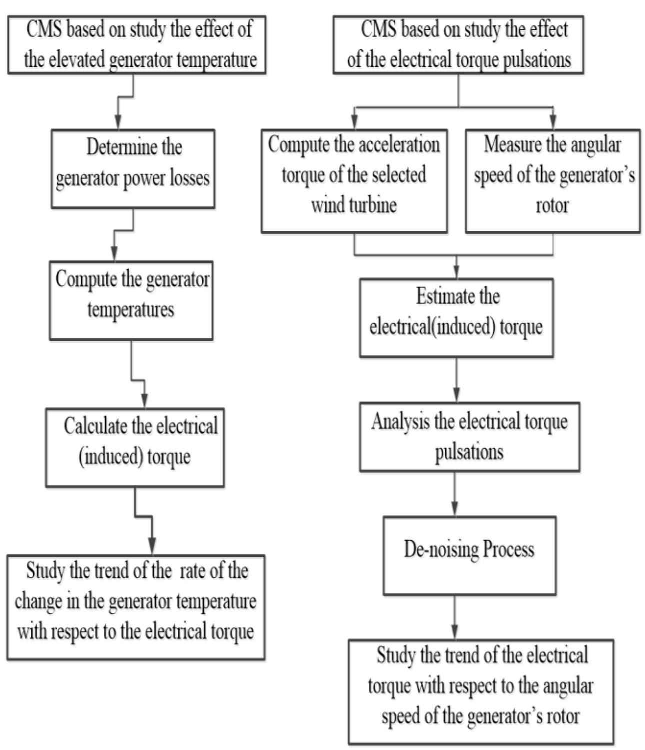

Figure 1. The Methodology of the Proposed Work.

II. THE INFLUENCE OF THE RIPPLE TORQUE AND COGGING TORQUE ON THE INDUCED ELECTRICAL TORQUE

The failures, which occur due to different faults, such as bearing faults, stator inter-turn faults, and eccentricities are related to all types of synchronous machines. While some faults are related to the wound rotor machines, such as rotor winding faults, broken damper bars, or end-rings. [10, and 11]. One major drawback to the permanent magnet machines is the ripple torque and its accompanying torque, which is called the cogging torque. The electrical torque pulsation is represented in the summation of the ripple and cogging torque with zero mean value and produces vibration and phonic noise, which might be grown in variable speed drives. In this context, the induced electrical torque will be affected negatively in the case of the ripple and cogging torques.

Ripple torque causes mechanical vibration, acoustic noise, and problems in the drive systems, which reduce the lifetime of generators. This torque is created by the interaction between the magnetomotive force (MMF) due to the stator windings and the MMF due to the rotor magnets [12-14]. Ripple torque changes according to the relative magnet width of the machine, which is partly reflected in the harmonics of the air-gap flux density. Fig. 2 presents the ripple torque behavior, which indicates a dramatic irregular change in the torque path with respect to the time [11-14].

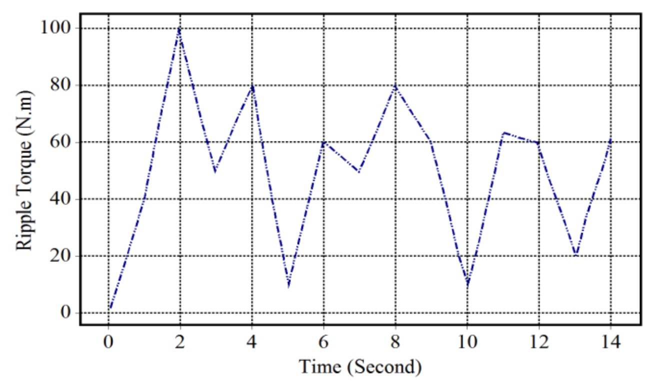

Figure 2. Ripple torque trend, [12-14]

On the other hand, cogging torque is caused due to the interaction between the permanent magnets and the stator slots. This interaction causes an uneven air-gap permeance resulting in the magnets regularly seeking a position of minimum reluctance [12-14]. Negative effects are produced from cogging torque, such as producing noise and mechanical vibration on the wind turbines, influencing the induced electrical torque, and affecting self-start running. Reaching low cogging torque is necessary because of lower mechanical vibrations, less noise and longer operational life of the gearing and other mechanics. For small wind turbines in the low wind speed, noise and mechanical vibration may be excited by the cogging torque, which threaten the safety of the whole structure. While, in high wind speed, there is enough of torque and the kinetic energy, which stored in the turbine rotor leads the cogging torque to be insignificant. The cogging torque can be canceled by forcing the air-gap reluctance to be stable with respect to the rotor position [12-14]. Fig. 3 shows a typical cogging torque waveform for synchronous wind generator. It can say that during the start-up process— cogging torque is low, which is desirable— while the wind turbine may never start with the high cogging torque.

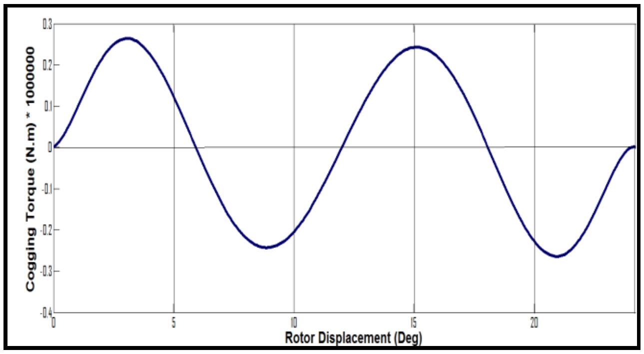

Figure 3. Typical cogging torque waveform [12-14]

In order to perform an effective condition monitoring system on the wind generators, the approach of analyzing the electrical torque pulsations and the generator temperature at different generator's speeds in the normal and abnormal conditions is adopted. The proposed algorithm is based on the acceleration torque, which is taken into account at different rotational speeds of the generator's rotor. This assumption leads to accurate results, which will be presented later.

III. KNOWLEDGE ABOUT THE SELECTED WIND TURBINE, GENERATOR, AND SCADA SYSTEM

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 and gearbox ratio 1:43. The combined generator rotor and wind turbine moment of inertia (J) is equal to 2252 $kg.m^2$ [15]. 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. The mechanical torque is measured by the SCADA system, which represents the high speed shaft torque. The angular speed of the high speed shaft is balanced with the rotor rotational speed of the synchronous generator and measured over time based on the gearbox ratio. Fig. 4 displays the pulsations behavior of the estimated electric torque with respect to the rotor rotational speed of the selected synchronous generator (rpm) in the normal and abnormal conditions according to the measured data. The synchronous generator shows different torque-speed attributes in the normal and abnormal conditions, which confirms that the torque-speed relationship could be a significant indicator for applying condition monitoring on the wind generators. As was mentioned previously, the proposed methodology is based on the acceleration torque, which is estimated in order to obtain accurate electric torque to perform a proper condition monitoring on the selected wind generator. Further, determine the rate of change in the generator temperature with respect to the electrical torque provides knowledge to defining the operation condition of the system. In the following section, the effects of the elevated generator temperature on the induced electrical torque is demonstrated.

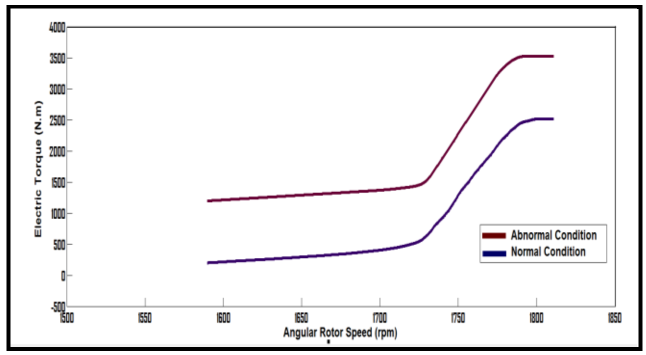

Figure 4. The electric torque trend with rotor rotational speed

IV. THE EFFECT OF THE ELEVATED GENERATOR TEMPERATURE ON THE PRODUCED ELECTRICAL TORQUE.

The elevated generator temperature plays a remarkable role in decreeing the induced electrical torque, which affects negatively the efficiency of the system. When the temperature reaches high values in the permanent magnet generators, a reversible demagnetization effects the torque capability and reduces the efficiency of the entire system. Therefore—the stator winding temperature, which is assumed the generator temperature itself— can be considered an important indicator to define the system operation condition. The residual flux density and the field intensity of the magnet decline with the increase of the generator temperature and return to the initial value with the decrease in the generator temperature. This change in the residual flux density of the magnet along and the change in the armature resistance of the motor with respect to the temperature affect the torque capacity and the efficiency of the system [16]. The nature of the reversible demagnetization is due to the low values of the force of the field intensity and the remanent flux density. The relationship between the generator temperature and both remanent magnetic flux density and the forced field intensity can be determined respectively as follows:

$$B_r = B_{r_{amb}}[1 + \frac{\alpha_B}{100} .(T_G - T_{amb}). \quad (1)$$

$$H_c = H_{c_{amb}}[1 + \frac{\alpha_H}{100} . (T_G - T_{amb}). \quad (2)$$

where, T_G and T_{amb} are the generator and ambient temperatures respectively, B_r and $B_{r_{amb}}$ are the remanent magnetic densities at the operation and ambient temperature respectively, H_c and $H_{c_{amb}}$ are the forced or coercive field intensities at the operation and ambient temperature respectively, and α_B and α_H are the temperature coefficients for the remanent magnetic density and for the coercive field intensity respectively [16].

In AC synchronous generators, the electrical power P_{el} can be converted to mechanical power P_{mech} by adding the frictional losses power P_{loss} as follows:

$$P_{el} = P_{mech} + P_{loss}. \quad (3)$$

The frictional losses power P_{loss} for the AC generators can be determined as follows [17]:

The frictional losses power = Stray losses P_{SL} + Friction and windage losses $P_{F\&W}$ + copper losses P_{cu} + Core losses P_{CL} (4)

$$P_{loss} = P_{SL} + P_{F\&W} + P_{CL} + P_{cu}. \quad (5)$$

The mechanical power loss and power loss can be ignored in the advanced synchronous generators at the rated condition. In this proposed work, the copper loss is only considered, and changed based on the armature current flow and the armature resistance. The copper loss in the three phase synchronous generators is defined as follows:

$$C_{cu} = 3\, I_A^2\, R_A. \quad (6)$$

where, I_A, R_A are the armature current flow and armature resistance respectively. Then, (5) can be formulated as follows:

$$P_{loss} \approx 3\, I_A^2\, R_A. \quad (7)$$

The heat resulting from the copper losses in the coil is diffused by conduction through the generator components and airflow in the air gap. The dissipated heat is a function of the generator type, insulation system, operation conditions, and construction. The generator manufacturers typically provide an indication of the generator's ability to diffuse heat by providing thermal resistance values. The thermal resistance is a measure of the resistance to the transfer of heat through a given thermal path. In the case of the AC generators, there is a thermal channel from the generator windings to the generator case and a second between the generator case and the generator environment (ambient air). The generator temperature can be determined based on the power loss and the thermal resistances as follows [16]:

$$T_G = P_{loss} * (R_{th1} + R_{th2}) + T_{amb}. \quad (8)$$

where, R_{th1} is the thermal resistance from the windings (C°/Watt), and R_{th2} is the thermal resistance of the ambient (C°/Watt). Consequently, the generator temperature can be expressed as follows:

$$T_G = [(3\, I_A^2\, R_A) * (R_{th1} + R_{th2})] + T_{amb}. \quad (9)$$

In the AC generators, the induced electrical torque τ_{el} can be determined as follows:

$$\tau_{el} = I_A . K_M. \quad (10)$$

where, K_M is the generator torque constant. By substitution of (10) into (9), the generator temperature will equal to the next relation:

$$T_G = [\ (3.(\tau_{el}^2/K_M^2)\ R_A) * (R_{th1} + R_{th2})\ ] + T_{amb} \quad (11)$$

The previous equation indicates that the relationship between the electrical torque and the generator temperature is curvilinear. Based on (11), the induced electrical torque for the AC generators can be defined as follows:

$$\tau_{el} = \left[\frac{(T_G - T_{amb}).K_M^2}{3R_A.(R_{th1} + R_{th2})}\right]^{1/2} \quad (12)$$

The induced electrical torque is based on two variables, the generator temperature, and the armature resistance since the rest of the terms are constants. The frequency response of the generator is reduced due to the decreasing in the torque capability. Further, the magnet flux density comes down at higher generator temperature, which affects the induced electrical torque as shown in Fig. 5.

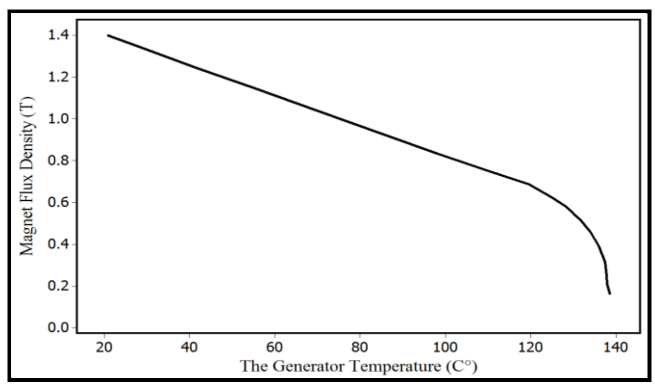

Figure 5. The measured magnet residual flux density

V. THE PROPOSED MODEL ANALYSIS

Mechanical parameters are easily measured and more available than the electric parameters. In addition, it is very tricky and complicated to use the electrical methodology in order to estimate the electric torque. Consequently, the electromagnetic torque τ_e can be estimated easily from the mechanical aspect. When a synchronous machine is operated as a generator, the prime mover drives the generator at synchronous speed ω_s. The mechanical torque of the prime mover τ_m can be defined from the next relation:

$$\tau_m = \tau_e + \tau_{acc}. \quad (13)$$

where T_{acc} is the acceleration torque, which can be determined as follows:

$$\tau_{acc} = J\frac{d\omega_r}{dt} \tag{14}$$

where J is the combined inertia coefficients for the generator's rotor and the wind turbine during the steady-state (constant speed), and $\frac{d\omega_r}{dt}$ is the change in the rotational angular speed of the high speed shaft per time which is equal to the change in the rotational angular speed of the generator rotor shaft per time [8, and 15]. The mechanical torque τ_m that produced by the wind accelerates the wind turbine and counterbalances with the torque of the low speed side shaft τ_{Ls} (the torque produced by the torsional movement of the low speed side shaft). From Fig. 6, the relation between τ_m and τ_{Ls} can be estimated as follows:

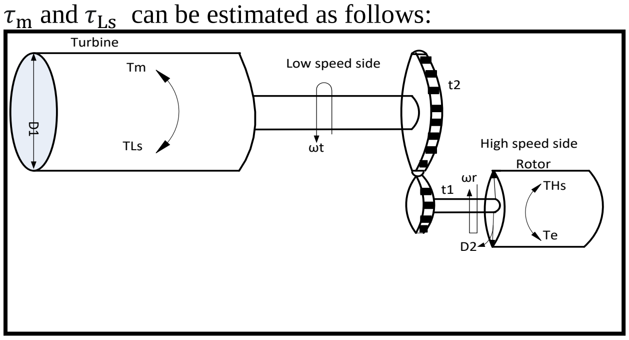

Figure 6. Wind Turbine Drive Train [19]

$$\tau_m - \tau_{Ls} = J_{B,H}\frac{d\omega_t}{dt} \tag{15}$$

where ω_t is the rotational angular speed of the low speed shaft, and $J_{B,H}$ is the total moment of inertia for both the blades and hub of the wind turbine$(kg.m^2)$, which can be calculated as follows:

$$J_{B,H} = J_B + J_H. \tag{16}$$

$$J_B = \frac{3}{12}\,[\,l^2 + b^2 + cos^2\,\alpha^2 + 3\,m_B\,c^2]. \tag{17}$$

$$J_H = m_H.D_1^2/8. \tag{18}$$

where J_B is the turbine's blades moment of inertia, J_H is the turbine' hub moment of inertia, l is the blades measured length, b is the average width the blades, α is the blade angle, c is the center of mass displacement of the blades, m_H is the weight of the hub, and $D_1$is the diameter of the hub [9, 18, and 19]. Similarly, the torque that produced by the high-speed shaft τ_{Hs} accelerates the rotor of the synchronous generator and equalizes with the electromagnetic torque τ_e that produced by the generator. The relation between the electromagnetic torque τ_e and high-speed side torque τ_{Hs} is determined as follows:

$$\tau_{Hs} - \tau_e = J_g.\frac{d\omega_r}{dt} \tag{19}$$

where J_g is the moment of inertia of the generator's rotor, which depends on the weight m_g and diameter D_2 of the generator, and ω_r is the angular speed of the generator's rotor. The gear ratio is defined as follows:

$$\frac{\tau_{Ls}}{\tau_{Hs}} = \frac{\omega_r}{\omega_t} = \frac{t_1}{t_2} = \text{Gear ratio} \tag{20}$$

where t_1 is the number of teeth on the output gear, t_2 is the number of teeth on the input gear, and ω_r is the rotational angular speed of the generator rotor's shaft. The rotational angular speed of the turbine ω_t can be defined such as:

$$\omega_t = \omega_r\,\frac{t_2}{t_1} \tag{21}$$

With the help of the previous relations, the electromagnetic torque can be determined as follows [9, and 19]:

$$\tau_e = \tau_m.\frac{t_1}{t_2} - J_g.\frac{d\omega_r}{dt} - \left[J_m\,\frac{d\omega_r}{dt}.\left(\frac{t_2}{t_1}\right)^2\right] \tag{22}$$

As was mentioned before, estimating the electromagnetic torque is not complicated when the information of the mechanical or thermal parameters is available by SCADA system. In order to derive a proper algorithm to apply a condition monitoring system on wind generators depending on the study of the electrical torque pulsations, following the electrical analysis on the generator part is very beneficial. There are two magnetic fields in the synchronous machine under normal condition. One produced from the rotor circuit and another from stator circuit. The electric torque is produced due to the interaction between those magnetic fields. In a three-phase non-salient pole synchronous generator, the electromagnetic torque T_e that produced by the generator can be determined as follows:

$$\tau_e = 3\,E_a\,\frac{V_\emptyset}{\omega_s X_s}\sin\delta. \tag{23}$$

where E_a is the internal voltage that produced in one phase of a synchronous generator, $V_\emptyset$ is the output voltage of a particular phase, X_s is synchronous reactance of the generator, ω_s is the generator synchronous rotational speed, and δ refers to the torque angle of the synchronous generator and can be defined as the angle between the internal generated voltage and output voltage [9, 12, 13, 14 and 18]. The simple generator electrical circuit is shown in Fig. 7. The Kirchhoff's voltage law equation for this electrical circuit can be derived as:

$$V_\emptyset = E_a - (j\,X_s + R_a)\,I_a. \tag{24}$$

where R_a is the resistance of the generator's stator, and I_a refers to the state phase current [7]. The winding resistance R_a can be ignored in the large synchronous generators since it is very small value. Consequently, the synchronous voltage can be written as follows:

$$V_{\emptyset_a} \approx E_a - (jX_s)I_a. \tag{25}$$

Then, the electrical torque can be estimated in different formula as follows:

$$\tau_e = 3E_a . \frac{E_a - (j\,X_s)I_a}{\omega_s X_s} \sin\delta. \quad (26)$$

The internal voltage that produced in one phase of a synchronous generator E_a can be written in another form as follows:

$$E_a = \sqrt{2}\,\pi\,N_C\,\emptyset\,f_e. \quad (27)$$

where $\emptyset$ is the magnetic flux, N_C is the coil turns of the stator, and f_e is the electrical frequency in hertz. The internal voltage also can be written in another form:

$$E_a = \frac{\sqrt{2}}{4} N_C\,\emptyset\,\omega_r\,p. \quad (28)$$

From (24) it becomes clear that:

$$E_a - (j\,X_s + R_a)\,I_a \propto {E_a}^2. \quad (29)$$

With the aid of (28), the (29) should be modified as follows:

$$E_a - (j\,X_s + R_a)\,I_a \propto {E_a}^2 = N_c^2\,\emptyset^2\,\omega_r^2\,\frac{p^2}{8}. \quad (30)$$

By substitution of (23) into (30), the electrical torque will be equal to the next relation:

$$\tau_e = 3\,\frac{N_c^2\,\emptyset^2\,\omega_r^2\,\frac{p^2}{8}}{\omega_r X_s} \sin\delta. \quad (31)$$

Consequently, the final formula of the electrical torque is as follows:

$$\tau_e = 3\,\frac{N_c^2\,\emptyset^2\,\omega_r^2\,\frac{p^2}{8}}{\omega_r X_s} \sin\delta. \quad (32)$$

Because N_C, and p are constant parameters, the relationship between the electrical torque and rotational angular speed of the generator's rotor can be written as follows:

$$\tau_e \; \alpha \; \frac{\omega_r}{X_s} \quad (33)$$

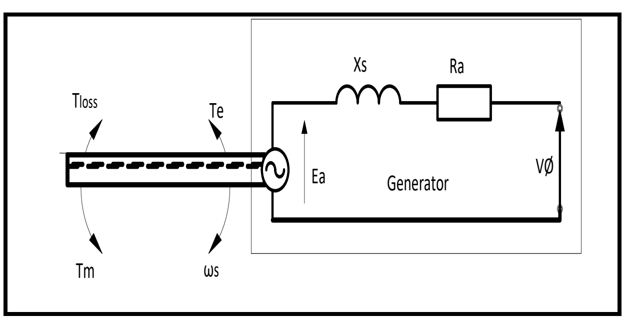

Figure 7. Synchronous machine operated as a generator [9]

The previous equation used when the torque angle δ and magnetic flux $\emptyset$ are stable. A condition monitoring criterion C is proposed in [9] as an indicator to apply a monitoring technique on the wind generators. The electrical torque is directly proportional with the angular rotational speed of the high speed shaft, which is approximately balanced with the generator's rotor angular speed. Therefore, computing the electric torque with respect to the angular speed values of the generator's rotor at each data point is very proper to apply a condition monitoring on the wind turbine generator. When a generator suffers from a specific fault like stator winding fault or rotor imbalance fault, the corresponding reactance of the generator X_S will decrease. Consequently, high electrical torque pulsations created with reference to the angular speed of the generator's rotor in this condition. A case study is presented in the following section in order to confirm the validity of the proposed algorithm.

VI. 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 are categorized and analyzed according to the operation conditions. With the aid of (13), and (14) the electric torque can be calculated based on the acceleration torque. Further, the electric torque can be estimated from the thermal aspect based on (12). The rotational angular speed of the generator's rotor can be estimated from (20), which depends on the wind turbine gear ratio and the rotational angular speed of the low speed shaft. The SCADA system submits enough details for the rotational angular speed of the low speed shaft, high-speed shaft torque, and low-speed side shaft torque every 0.01 second. The collected data present two conditions, the first condition is a stator winding fault condition (abnormal condition), and the second condition is a normal operating condition [15]. Study the trend of the electric torque pulsations can be considered an indicator to perform a condition monitoring system on the wind generators. Based on Fig. 4, there is a linear proportional relationship between the electric torque of the synchronous generator and the rotor angular speed in both conditions. The electrical torque in the abnormal condition is higher than the electrical torque in the normal condition, which implies that the generator reactance X_S changes according to the operation condition. In order to compare and analyze the electrical torque pulsations through the normal and abnormal conditions, the duration time of each operation conditions was divided to 200 seconds. Table I demonstrates the data classification over time for both conditions.

TABLE I DATA CONDITIONS CLASSIFICATION [15]

Time Interval (Second)	The Operation Condition
0 - 200	Normal
200 - 400	Abnormal
400 - 600	Normal
600 - 800	Abnormal
800 - 1000	Normal
1000 - 1200	Abnormal

In addition, de-noising process was required since the torque and the angular speed signals were very noisy. With the aid of Matlab software, the electrical torque and rotor angular speed signals are de-noised efficiently. The time-waveforms of the electrical torque and angular speed of the generator's rotor signals are shown in Figs. 8 and 9. On the other hand, the elevated generator temperature affects the induced torque, which indicates that the change in the generator temperature with respect to the electrical torque can be considered an additional indicator to determine the operation condition. The influence of the generator temperature on the induced electrical torque with respect to the armature resistance is illustrated in Fig. 10 based on the collected data. The high generator temperature due to different reasons, such as improper cooling system or high power losses, reduce the electrical torque remarkably.

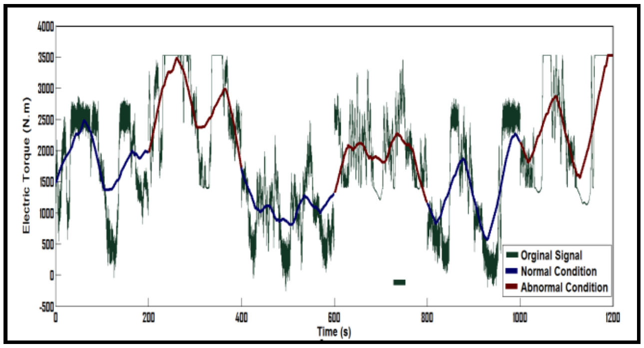

Figure 8. The time-waveform of the electrical torque

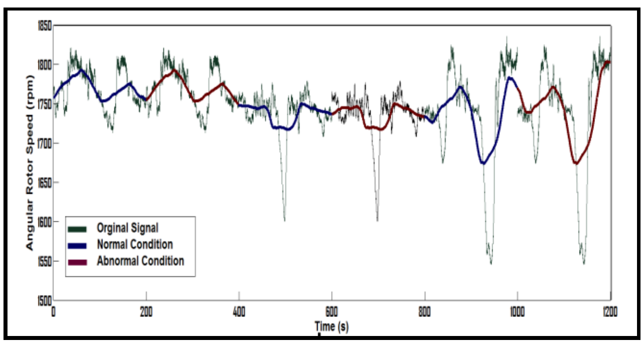

Figure 9. The time-waveform of the angular rotor speed

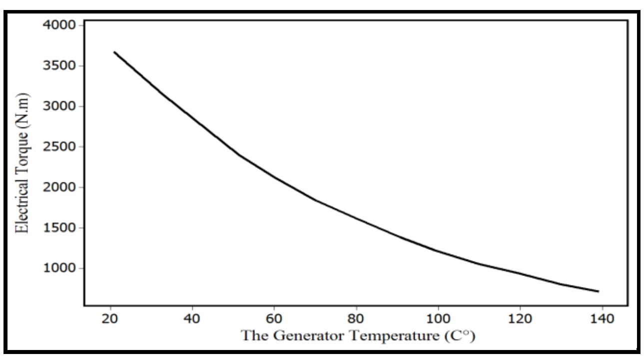

Figure 10. The induced torque trend with respect to the generator temperature

According to the manufacturer's handbook, the abnormal operation condition will be considered when the generator temperature exceeds 110C°. The second goal of this work is to determine the effect of the high generator temperatures on the induced electrical torque, which aims to identify the generator health. Table II presents the operation conditions of the selected wind turbine based on the generator temperature.

TABLE II THE OPERATION CONDITIONS OF THE SELECTED WIND TURBINE BASED ON THE GENERATOR TEMPERATURE [15]

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

VII. RESULTS AND DISCUSSIONS

As was mentioned previously, there is a significant change in the trend of the torque-speed signal over time. This confirms that the torque-speed curve behavior can be used as an obvious indicator with a view to perform a suitable CMS on wind generators during running. The fluctuation in the electric torque pulsations through the normal and abnormal conditions is due to the ripple and cogging torque. The value of $\left(\frac{T_e}{\omega_r}\right)$ can be utilized to figure out the presence of the electrical faults in the wind generators, e.g. stator winding fault or rotor imbalance fault. Further, the proposed monitoring model is based on the parameters that control the operation condition, such as the generator reactance. The change of the generator reactance X_S, which is corresponding to the operation condition, is one of the most significant effects that lead up to electrical faults in the generator. Fig. 7 shows the dramatic changes over time in the signal of the criterion $\left(\frac{T_e}{\omega_r}\right)$ during the operation. When the generator suffers from an electric fault, such as stator inter-turn fault, the generator reactance decreases automatically, which increases the variable $\left(\frac{T_e}{\omega_r}\right)$ remarkably. Therefore, high values of the criterion $\left(\frac{T_e}{\omega_r}\right)$ represent a real impression of the abnormal operation condition of the generator.

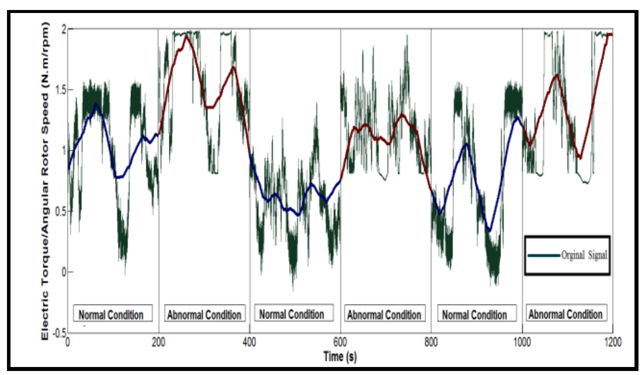

Figure 11. The proposed indicator $\left(\frac{T_e}{\omega_r}\right)$ trend

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. Fig. 12 illustrates the rate of change in the generator temperature trend with respect to the electrical torque in the normal and abnormal conditions respectively.

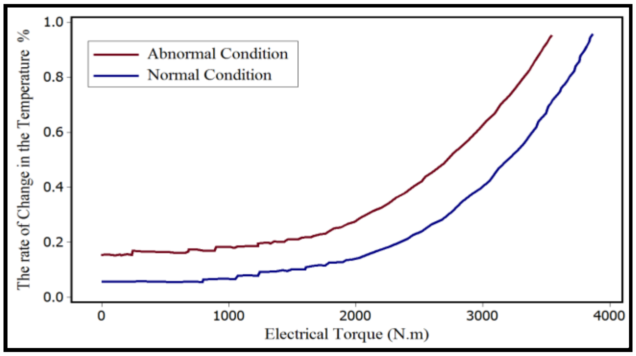

Figure 12. The rate of change in the generator temperature with respect to the electrical torque.

VIII. CONCLUSION

This paper indicates that the mechanical and thermal characteristics can be used to diagnose the faults that can occur in wind generators. High electric pulsations torque can be considered a significant indicator to identify the generator operation condition. Electric torque pulsations consist of the sum of cogging torque and ripple torque. Therefore, the behavior of the electric torque pulsations is considered an effective approach for a condition monitoring system on the wind generators. In the abnormal condition, the generator faults cause decreases in the generator reactance, and the value of the proposed model $\left(\frac{T_e}{\omega_r}\right)$ increases remarkably. On the other hand, 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 model.

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