The Application of Heat Transfer Analysis in Condition Monitoring System of Wind Generators

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Abstract— **Effective cooling is required in power generation, processing, and distribution to avoid failure that could occur during operations. As heat loads continue to increase, manufacturers of wind turbines are turning to improve the cooling system to remove high intensity heat loads from many active parts particularly in the generator part. Wind generators need an effective cooling system due to the large amount of heat that is released during power production. Many large wind turbines (more than 5MW rated power) particularly offshore wind turbines where the water is available, heat exchangers with water-air cooling system is used, in which the water is utilized to cool the hot air. This type of heat exchangers are desired, since they are more efficient and reliable than the air-air heat exchangers, which are used in small wind turbines. Because of the growing number of failures that occurred in wind turbine generators due to high generator's temperatures owing to power losses of generator, applying condition monitoring system on wind generators depending on heat transfer analysis through the heat exchangers of wind generators plays an effective role. This helps avoid failures and maintain wind turbines to be protected. In this paper new methodology has been applied by considering the heat transfer and fluid mechanics analysis through a heat exchanger of wind generator, which uses water to air cooling system. Case study based on data collected from actual measurements demonstrates the adequacy of the proposed model.**

Index Terms—**condition monitoring system, wind turbine, wind power.**

I INTRODUCTION

Wind turbine capacity, particularly for offshore turbines, continues to grow each year in a range 5-10 MW, and the number of wind turbine failures due to high generator temperatures has been shown to be significant [1,2]. Certain advances wind generator heat exchangers play an important role to remove the released heat from wind generator active parts like generator stator and rotor. While traditional air-air heat exchangers of wind generators have lower cost than water-air heat exchangers, large wind generators work with water to air heat exchangers are one of the most widely adopted approaches to cool the rotor and stator windings efficiently. This because the cooling capability of water is much larger than air, and the availability of water especially for offshore wind turbines places where the water is more available. Water-air heat exchangers can be utilized to cool generators, by circulating hot air inside it to absorb the heat by the cold fluid and then exhausting the absorbed heat to another area outside the generator. Electro-magnetic losses within wind generators are a significant source of heat which warms up the generator and cause a temperature rise in stator bars reducing the life-span of the insulation materials [2,3,4,5,6,7] . This fact leads wind turbine manufactures to create an effective cooling system for the active parts inside generators, and attracts engineers to develop a proper condition monitoring on the wind turbine generator parts.

Limited researches utilize some methods to apply a condition monitoring on the wind turbine generator due to high temperature. For instance, a temperature trend analysis method based on the nonlinear state estimate technique (NSET) is proposed in which the differences between predication and actual values are used as an important indication to study the potential fault due to high temperatures of wind generators [5]. However, different condition monitoring system techniques are available to detect failures in generator due to open or short circuit in one or more turns of a stator winding, and open or short circuited rotor winding in wound rotor synchronous machines. Applying a proper condition monitoring system on the wind generators by using the mechanical characteristics to diagnose the faults that can happen in generator was presented in another paper [7]. The impacts of wind turbines working under different conditions have been simulated. The authors proposed a method using the possibility of detecting mechanical and electrical faults in wind turbines by applying wavelet transform through analyzing the power signal using a valid signal processing technique. They assumed in their work that when the applied torque varies slowly relative to the electrical grid frequency, a quasi-steady state approach (when the mechanical torque is approximately equal to electric torque) may be taken for the analysis.

Most of previous papers used the analytical electrical methodologies and theories to create a suitable algorithm for a proper condition monitoring system on wind generators. In this paper, an application of condition monitoring system on wind turbine generators due to high power losses which lead to increase generators temperatures is presented. The proposed methodology is constructed on the heat transfer analysis and fluid mechanics techniques, based on data of 5 MW wind turbine collected from actual measurements. Using the heat transfer and fluid techniques relations of heat exchangers are very effective in this application. The main concept of the proposed model depends on computing the heat exchange between the hot air due to the high temperatures of generator parts, and the cold water inside the heat exchangers. This approach represents the generator condition at any time which the obtained algorithm is run based on comparison between normal and critical historical conditions to evaluate the model validity. The paper is arranged as follows. Section II provides knowledge and specifications about the selected wind turbine generator, heat exchanger, cooling system mechanism, and the available measured data, which are used in this paper to test the proposed model. In section III, heat transfer and fluid mechanics analysis through a wind generator heat exchanger is explained to find the proper thermal model to apply an effective condition monitoring system on wind generators due to increase in generator temperature. Section IV presents case study to apply the obtained condition-monitoring algorithm on wind generators. Section V presents the collected results and the capability of the suggested algorithm. Section VI presents discussion, conclusions, and suggestions for further research.

II Selected Wind Turbine, Generator, Cooling System Mechanism, and the Available SCADA

Actual data was collected from a variable speed wind turbine with rated power of 5 MW, 60Hz, three blades, 126m rotor diameter, and rated rotor speed 12.1 rpm. The wind turbine has synchronous permanent magnet generator with rated speed 1500 rpm; generator efficiency is 94.4%. The cooling-system of the generator includes water-air counterblow heat exchanger with six cold fluid pipes. The generator cooling-system is schematically shown in Figure 1. The inlet air takes the heat from the generator parts like generator rotor and stator winding and transfers it to the water-air heat exchanger. This step is considered the first cooling operation in the system. There are two axial fans, one to draw the outside air inside the generator (fan 1), and the other to recycle the cold air which comes from the heat exchanger to transmit it through the system (fan 2). The airflow is separated directly by using valves after passing both fans. The design of the cooling system forces about 25 % of the airflow leaving both fans and flows through the stator's end-windings to cool them. The rest of airflow (75%) enters the rotor region in an axial direction through the slots between the rotor poles, which guide the air in a radial direction towards the stator-core. The air-gap space between rotor and stator is about 15mm, and airflow leaves the air-gap apace and enters the cooling- ducts of the stator-core. After leaving the stator-core both airflows (stator-core airflow and stator's end-windings airflow) are mixed and then directed to the water-air counterflow heat exchanger where are cooled and returned to the circuit at the inflow-sides of both axial fans [8].

There are several temperature sensors installed within the generator in order to measure the stator winding temperatures or stator-core temperatures. The manufacturer handbook emphasizes that the generator temperature should not exceed 100 C° to protect the electric generator, and the wind turbine will shut down when the generator temperature reaches 135 C°. More additional temperature measuring devices are available to measure the water inlet and outlet temperatures and pressure drop through the heat exchanger [8]. This can be done by installing them at the inlet and outlet slots of the heat exchanger to gauge the water properties.

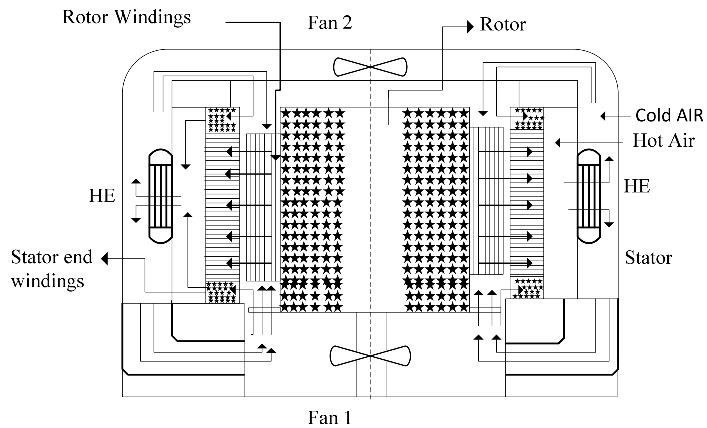

Figure 1 Wind generator cooling system [8,9]

The required SCADA system provides enough details about the generator stator temperatures, which are considered as the generator temperatures itself, and the generator power values. Moreover, the temperature of the air inlet to the rotor and stator winding can be measured which depend on the outside temperature. There is a valve to control the inlet mass flow rate of the water to the heat exchanger, and according to the manufacturer handbook is roughly 2.6 kg/s. In addition, the air mass flow rate into the rotor winding and stator end windings is designed to equal almost 4.7 kg/s. The data of the experiment represent three conditions: normal, warning, and critical conditions through the performance of the selected wind turbine and the information of each condition is available through SCADA system, which offers detailed information about the system. These conditions occurred in different days and present the wind turbine situation [8]. Table I displays the occurrence of the three different conditions according to the generator temperature.

Table I
THE WIND TURBINE WORK CONDITIONS [8].

State	Generator Temperatures
Normal condition	$T < 90\ C°$
Warning condition	$90\ C° < \mathrm{T} < 110\ C°$
Critical condition	$110\ C° < \mathrm{T} < 135\ C°$

In order to apply heat transfer and fluid mechanics analysis, the thermal properties of the cold fluid (water), and the hot fluid (air) are available according to the experiment data of each condition which will be explained in the following sections.

III Heat Transfer and Fluid Mechanics Analysis for Heat Exchangers of Wind Generators

Heat exchangers are utilized to transfer heat from a hot fluid flow to a cold fluid flow. Heat losses or gains of the entire heat exchanger with the surroundings can be ignored in comparison with the heat flow between both fluid flows; therefore, heat exchangers are considered as adiabatic devices (no heat exchange with the surrounding through the heat exchangers). They are classified according to flow configuration and type of construction. Many kinds of heat exchangers could be used in wind generators to provide a suitable cooling system. Counterflow tube heat exchangers are the most common and desirable type of heat exchanger, which are used in the cooling system of the wind generators [10,11,12]. Figure 2 illustrates the mechanism of work of a tube heat exchanger, where one flow goes along a bunch of tubes and the other within an outer shell in cross-flow. The hot and cold fluid temperatures distribution along counterflow heat exchanger length is shown in Figure 3.

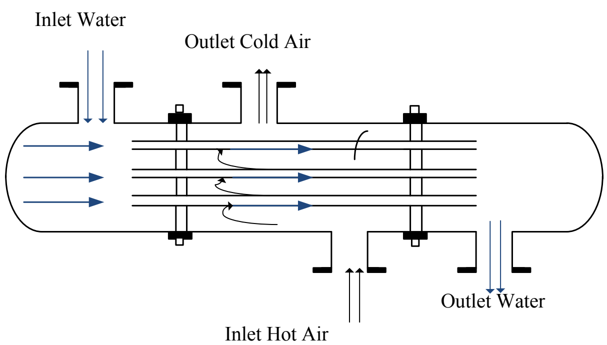

Figure 2. Tube counterflow heat exchanger mechanism of work [[10,11,12].

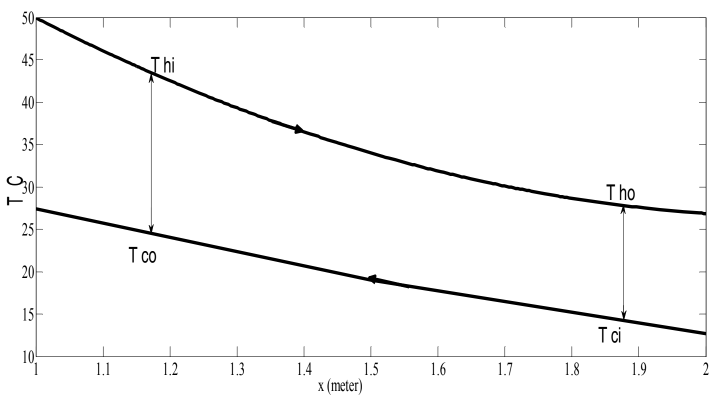

Figure 3. Temperature distribution for a counterflow heat exchanger [[10,11,12].

By applying the energy balance to each fluid which states that the heat losses from the hot fluid equal to the heat gains for the cold fluid assuming that the potential and kinetic energy are negligible and the specific heat values for each fluid over the time are constant, the following relation can be obtained:

$$Q_h = Q_c \dots\dots\dots\dots(1)$$

$$\dot{m}_h \, c_{p,h} \left(T_{h,i} - T_{h,o} \right) = \dot{m}_c \, c_{p,c} \left(T_{c,o} - T_{c,i} \right) \dots\dots\dots(2)$$

Q_h, Q_c the heat losses of hot fluid and the heat gain of the cold fluid, respectively.

$\dot{m}_h, \dot{m}_c$ the hot and cold fluid mas flow rate, respectively.

$T_{h,i}, T_{c,i}$ the hot and cold fluid inlet temperatures, respectively.

$T_{h,o}, T_{c,o}$ the hot and cold fluid outlet temperatures, respectively.

$c_{p,h}, c_{p,c}$ the hot and cold fluid specific heat, respectively.

The specific heat of the hot or cold fluid is not constant, which changes according to the temperature condition at the inlet and outlet points. To simplify the calculations, the average temperature of the inlet and outlet points of the hot or cold fluid is assumed to represent the hot and cold fluid inlet temperatures [10,11,12]. For a heat exchanger with countercurrent flow, is commonly referred in high exchangers design to the LMTD, which is the logarithmic average of the temperature difference between the hot and cold streams at each end of the exchanger with constant flow. It is the maximum mean temperature difference that can be achieved for any given set of inlet and outlet temperatures through the heat exchangers [10,11,12].

$$\text{LMTD} = \frac{\left[\left(T_{h,i} - T_{c,o} \right) - \left(T_{h,o} - T_{c,i} \right) \right]}{\ln\left[\frac{\left(T_{h,i} - T_{c,o} \right)}{\left(T_{h,o} - T_{c,i} \right)} \right]} \dots\dots\dots(3)$$

In addition to energy balance, the heat transfer can be described based on the logarithmic average of the temperature difference as follows:

$$Q = U.A.\text{LMTD} \dots\dots\dots\dots\dots(4)$$

whereas, A is the heat exchanger area, and *U* is the overall heat transfer coefficient and can be calculated from the next formula:

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}} \dots\dots\dots\dots(5)$$

h_i, h_o the internal and external heat coefficients respectively [10,11,12].

In order to apply an effective condition monitoring system on wind generators due to increasing temperature, the trend of heat transfer through generators heat exchangers over time and the logarithmic average of the temperature difference of hot fluid could be considered as indictors since they are related directly to the winding stator temperatures. Stator winding temperatures could take into consideration as generator temperatures, and the air used to cool the stator winding flows through the heat exchanger, which is related to the thermal properties of the cold or hot fluid [13,14]. The generator heat losses, which increase directly the generator temperature can be computed as follows:

$$\begin{aligned} &\text{Generator heat losses} = \text{Air friction losses} + \\ &\text{Generator bearing losses} + \text{Iron losses} + \\ &\text{stator winding losses} + \\ &\text{Harmonic losses in the generator rotor [9]} \end{aligned}$$

However, generator losses should be calculated from the thermal aspect since the generator heat losses are equal to the air heat gains which flow through the heat exchanger. Therefore, the water heat gain through the heat exchanger is supposed to equal the generator heat losses. Moreover, the trend of either heat losses or gains is a perfect indictor to provide details about the generator conditions. With the aid of Eq. (2) and (3) a criterion S_1 as a versatile function for monitoring the running condition of wind turbine is proposed,

$$S_1 = \frac{Q_h}{\text{LMTD}} \dots\dots\dots(6)$$

In general, criterion S_1 can be used to detect the occurrence of a generator electrical fault due to high temperature. Moreover, criterion S_1 is independent of the variable wind demonstrated by the linear relationship between Q_h, LMTD in all operation conditions. Figure 4 presents the linear relationship between Q_h, LMTD in the three conditions. This figure shows the of the heat losses trend with respect to the logarithmic temperature difference through the heat exchanger of the proposed generator of 5MW wind turbine in three different conditions.

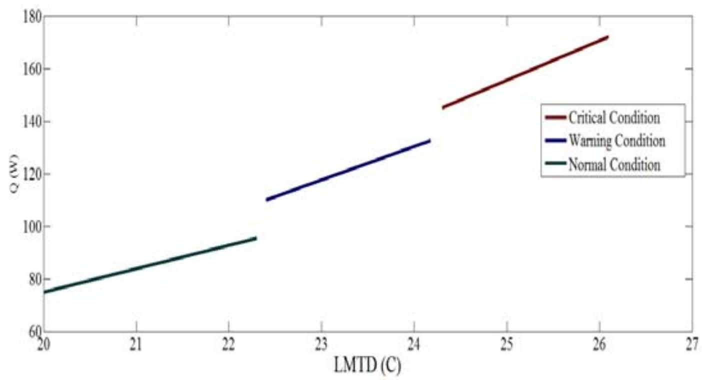

Figure 4. The trend of the heat losses with respect to the logarithmic temperature difference through heat exchanger in three different conditions.

One more parameter that can be used in condition monitoring system of wind generators due to increase temperature is the pressure drops of the flow streams through heat exchanger. It is a considerable indicator since it is depending on the fluid condition which are used to cool the generator and indicate the generator condition. The cooled fluid pressure drop which represent the water in the proposed application can be calculated from the next relations:

$$\Delta P = \frac{0.184 * R_e^{-\frac{1}{5}} * \rho_c * V_c^2 * L}{2*d} * N \;\ldots\ldots (7) \quad \text{For turbulent flow}$$

$$\Delta P = \frac{0.316 * R_e^{-\frac{1}{4}} * \rho_c * V_c^2 * L}{2*d} * N \;\ldots\ldots (8) \quad \text{For laminar flow}$$

[10,11,12,15]

where L is the effective pipe length of the heat exchanger, d is the pipe internal diameter, N is the number of pipes, V_C cold fluid velocity, ρ_c cold fluid density, and R_e is the shell-side Reynolds number, which can be calculated as follows:

$$R_e = \frac{4\dot{m}}{\pi . \mu_T . d} \ldots\ldots (9)$$

where μ_T is the cold fluid viscosity which depends on average fluid temperature, and can be determined from the next relation:

$$\mu_{T=2.414*10^{-5}} * 10^{(247.8)/(T-140)} \ldots\ldots\ldots (10)$$

The cold fluid density changes with temperature, and can be determined as follows:

$$\rho = \frac{\rho_0}{1 + 0.002 * (T - T_0)} \ldots\ldots (11)$$

where T is the average temperature of the cold fluid, ρ_0 is the cold fluid density at T_0 which is assumed to equal 20C° in this application. [10,11,12,15].

The pressure drop in the heat exchanger over the logarithmic average of the temperature difference is logic parameter to apply condition monitoring system on the wind generators since the pressure drop of cold fluid (water) is related directly to the hot fluid (air) temperatures and heat losses. Consequently, any change in the generator temperatures leads to change in the hot fluid temperatures which effects the pressure differences of cold fluid. Therefore, it could be used as another criterion as a versatile function for monitoring the running condition of the wind generator as follows:

$$S_2 = \frac{\Delta P}{\text{LMTD}} \ldots\ldots (12)$$

The linear relationship between the pressure drop and the logarithmic average of the temperature difference is plotted in Figure 5 which shows the trend of the pressure drop with respect to the logarithmic temperature difference through heat exchanger under three different conditions. The chart emphasizes that when the wind generator working in ideal conditions (normal case), the pressure drop of the cold fluid stream through the heat exchange increases dramatically with respect to the logarithmic temperature difference. And vice versa, when the wind generator working in imperfect conditions (critical case), the pressure drop of the cold fluid stream through the heat exchange decreases significantly with respect to the logarithmic temperature difference. Case study will be presented in the following section to demonstrate the validity of the proposed technique

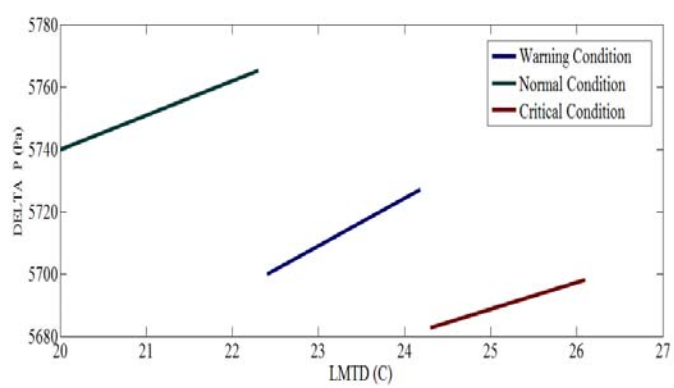

Figure 5. The trend of the pressure drop with respect to the logarithmic temperature difference through heat exchanger in three different conditions.

IV Case Study

Actual measured data is collected and used to test the validity of the proposed technique for condition monitoring on wind generators. The collected data present three different conditions as follows:

- Normal Condition.
- Warning Condition.
- Cortical Condition [8].

The LMTD between the hot and cool streams with respect to the heat losses should determine the generator condition. When the generator temperatures change dramatically, the cold fluid thermal properties through the generator heat exchanger vary in each situation. By computing LMTD and the exchanged heat between the hot and cold streams at each end of the exchanger with constant flow, powerful indication emphasizes an expected fault could be detected due to high temperature of generator. In addition, by calculating the pressure drop of the cold fluid in the three conditions with respect to the logarithmic average temperature difference, strong sign gives enough details about the generator health. The collected measured data which are the generator temperature in the current application presents 60,000 samples in three different conditions over 10 minutes. Moreover, all cold and hot fluid thermal properties are calculated. Figures 6, and 7 show the heat losses and logarithmic average of the temperature difference trends over time in three different conditions.

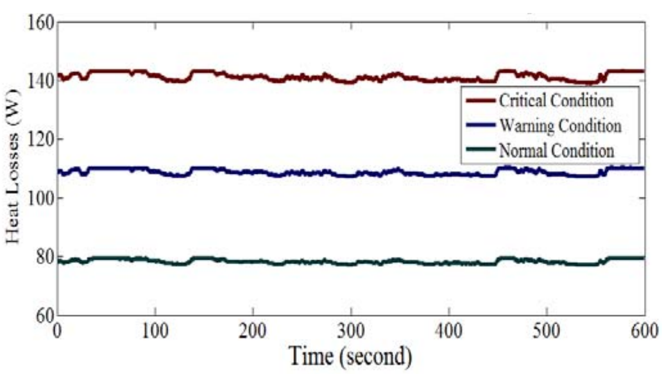

Figure 6. The heat losses trends over time through three different conditions.

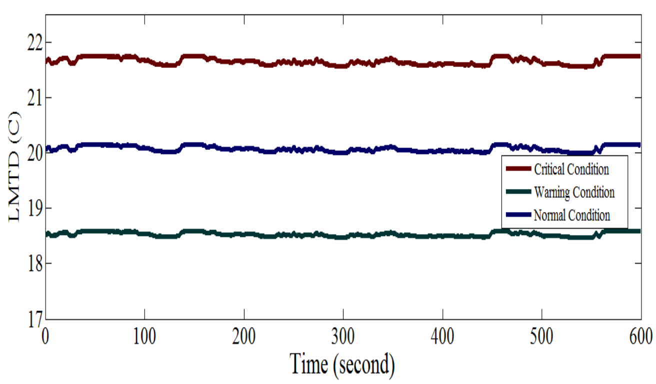

Figure 7. The logarithmic temperature differences trends over time through three different conditions

From Figures 6, 7, it becomes clear that when the generator suffers from high temperatures (critical case) due to some reasons such as overload, winding insulation failure, core insulation failure, so on [16], the amount of heat losses rises dramatically which leads to increase the logarithmic average of the temperature difference between the hot and cold streams at each end of the exchanger. Therefore an expected increase in generator component temperature is occurred and the critical condition is imminent. The normal condition presents smooth performance of the wind generator, and it could see the heat losses, and the LMTD values become small over the time. The warning condition is transition stage between the critical and normal conditions, and occurs when the generator temperature trend increases gradually, and exceeds the safe operation temperature limit due to the heat losses. Electrical heat losses calculations through wind generators could be determined from two aspects, electric and thermal aspects. In this paper, heat losses calculations focused on the thermal aspect, which is roughly presented in the gain heat of the air that used to cool wind generator. In fact, there is little difference between heat losses calculations from the thermal and electric aspects, but in many cases it is difficult to calculate the heat losses from the electric analyses, and it is very reasonable to use the thermal anatomies, since the simplicity and flexibility of the heat transfer relations.

VI Results and Discussions

According to the obtained results, using thermal relations is very powerful in condition monitoring system and designed analysis for wind generators due to high temperatures under abnormal conditions. Figure 8 displays the trend of the criterion S_1 as a versatile function for monitoring the operating condition of generator wind turbine. The criterion S_1 depends on the linear relationship between the heat loses from the generator and logarithmic average of the temperature differences through the heat exchanger in three different conditions. The results confirm that high value of criterion S_1 is not desirable since it demonstrates and emphasizes that the generator health is not adequate and operation conditions of generator is risky due to increase in the generator temperatures. In addition, using the heat transfer analysis gives alternative way to utilize some of thermal parameters as effective tool to detect generator faults.

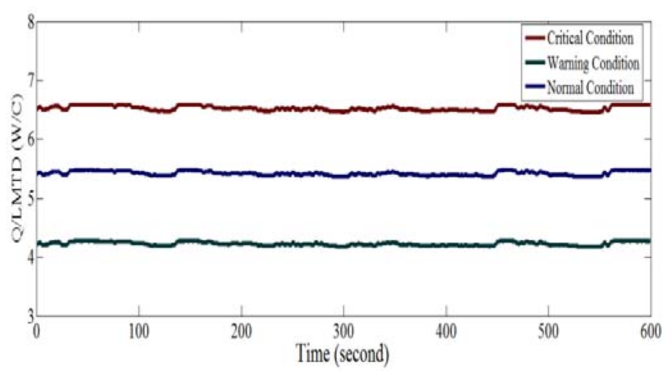

Figure 8. Criterion S_1 trends through three different conditions.

Reynolds number is good indicator in this purpose which is directly related to the generator heat losses and logarithmic average of the temperature differences through the heat exchanger. The Reynolds values in Figure 9 show a significant trend through three different conditions, and emphasize that high Reynolds values of the coolant fluid through the generator heat exchanger are not acceptable since the coolant fluid viscosity decreases dramatically with the increase in generator temperatures. Finally, the pressure drop through generator heat exchanger is good indicator to investigate the generator health. The obtained results confirm that when the generator suffers from high temperatures, the pressure drops of the coolant fluid decrease remarkably since the coolant fluid density increase with high generator temperatures, and Reynolds values increase obviously. Criterion S_2 is another scale for monitoring the operating condition of the generator wind turbine which is directly linked to the pressure drop and logarithmic average of the temperature differences through the heat exchanger. Figure 10 indicates a comparison of the trend of criterion S_2 over 600 seconds in three different conditions, and emphasize that when generator condition is critical, the pressure drop with respect to the LMTD of the generator heat exchanger is lower than normal condition [10,11,12,15].

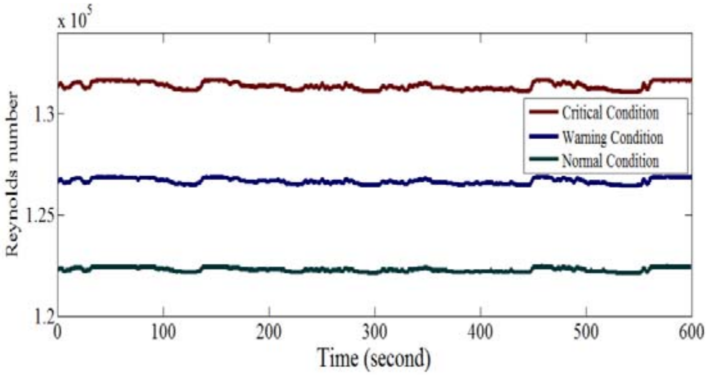

Figure 9. Reynolds values trends through three different conditions.

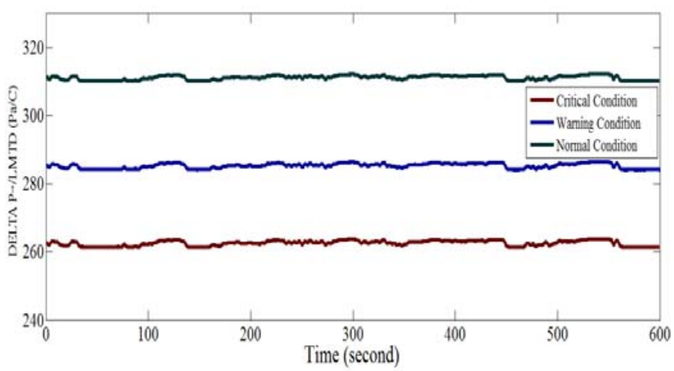

Figure 10. Criterion S_2 trends through three different conditions

V Conclusion

In this paper, the heat transfer analysis and fluid mechanics are used to develop a proper condition monitoring system on the wind generators based on increase in generator's temperatures. Heat exchangers performance plays an effective role to avoid failures and maintain wind turbines to be protected. New methodology has been applied in condition monitoring system of wind generators with water-air heat exchanger to provide a proper cooling system to the generator. The obtained results of the proposed model show that high values of heat losses with respect to the logarithmic average of the temperature differences of the generator heat exchanger is not desirable since this demonstrates that generator health is not adequate and the operation conditions of generator is risky due to increase in the generator temperatures. Reynolds number of the coolant fluid is a good indicator as well since Reynolds number of the coolant fluid depends on coolant fluid viscosity which decreases dramatically with the increase in generator temperatures. In addition, the study demonstrates that the pressure drop through generator heat exchanger is a good indicator to identify generator's health with respect to the logarithmic average of the temperature differences. High value of the pressure drop with respect to the logarithmic average of the temperature differences is acceptable which indicates that generator temperatures are suitable. The cool fluid pressure drop depends directly on the cold fluid density which increases with high generator temperatures. Future work should take into account wind generators that work with air-air heat exchangers and apply the proposed algorithm to confirm its validity.

VI Acknowledgement

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REFERENCES

[1] Frank S. Barnes, and Jonah G. Levine, "Large Energy Storage System Handbook, "CRC Press, Taylor & Francis Group, 2011.

[2] Michael R. Wilkinson, Fabio Spinato and Peter J. Tavner, "Condition Monitoring of Generators & Other Subassemblies in Wind Turbine Drive Trains, " Diagnostics for Electric Machines, Power Electronics and Drives, 2007 IEEE.

[3] Bin Lu, Yaoyu Li, Xin Wu and Zhongzhou Yang, "A Review of Recent Advances in Wind Turbine Condition Monitoring and Fault Diagnosis, "*IEEE, 2009*

[4] Kevin Alewine, "Wind Turbine Generator Failure Modes," Shermco Industries, September 2011

[5] Peng Guo, David Infield, and Xiyun Yang " Wind Turbine Generator Condition-Monitoring Using Temperature Trend Analysis. IEEE Transactions on sustainable energy, VOL. 3, NO. 1, JAN. 2012

[6] Hamid A. Toliyat, Subhasis Nandi, Ngdeog Choi, and Homayoun Meshgin, "Electric Machines Modeling, Condition Monitoring and Fault Diagnosis, " *Taylor & Francis Group, 2013.*

[7] Wenxian Yang, P. J. Tavner, and Michael Wilkinson, " Condition Monitoring and Fault Diagnosis of a Wind Turbine with a Synchronous Generator using Wavelet Transforms *IET, International Comference, PEMO*, York April 2008.

[8] Data of a variable speed wind turbine 5 MW rated power, three phase permanent magnetic type 440/660 V 60 Hz. Provided by Dr. Kathryn, Colorado School of Mines, 2013.

[9] Preecha, and J. Dejvises, "The Power Losses Calculation Technique of Electrical Machines Using the Heat Transfer Theory,"Power Engineering Conference, 2007. IPEC 2007. International.

[10] Ramesh K. Shah, Dušan P. Sekulić "Fundamental of Heat Exchanger Design, " *Published online*, 2007.

[11] Incropera, DeWitt, Bergman, and Lavine, "Fundamentals of Heat and Mass Transfer," *IET Renewable Power Generation*, April 2008.

[12] John H. Lienhard IV, John H. Lienhard V, "Heat Transfer Textbook, Third Edition, 2008.

[13] Y. Amirat, M.E.H. Benbouzid, E. Al-Ahmar, B. Bensaker , and S. Turri a, "A brief Status on Condition Monitoring and Fault Diagnosis in Wind Energy Convers

[14] W. yang, P.J. Tavner, and M.R. Wilkinson, "Condition Monitoring and Fault Diagnosis of a Wind Turbine Synchronous Generator Drive Train," *IEEE*, 2012.

[15] Yanyong Li, "Fluid Mechanices," *Thennal Energy Dynamics Research Institute*, IEEE, 2011.

[16] Z. Hameed, Y.S. Hong, Y.M. Cho, S.H. Ahn, and C.K. Songc, " Condition monitoring and fault detection of wind turbines and related algorithms: A review," *Renewable and Sustainable Energy Reviews*, 2007.