Condition Monitoring System Based on Effects of Electrical Torque Pulsations of Wind Turbine Generators

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***Abstract*— Due to the increase in the number of failures in the wind turbine generators, the condition monitoring system plays a significant role in overcoming the negative effects resulting from the difficult operation conditions. Mechanical and electrical properties can be combined to detect the faults coming from wind turbine generators by analyzing their behavior under different (normal and abnormal) operation conditions. Studying the trend and effect of the electrical torque pulsations on wind turbine generators under different conditions allows for a proper condition monitoring. In this paper, different methodology has been adopted to develop a proper condition monitoring system on the wind generators by evaluating the generator electrical torque based on mechanical torque and taking into account the acceleration torque, which has not been considered in previous work. Using the electric torque with respect to the rotor angular speed of the generator, when it is running under different operation conditions, indicates the generator health, which is the main methodology of the proposed work. 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.**

I. INTRODUCTION

Applying a modern condition monitoring on the parts that are faced to failures such as gearboxes and generators definitely 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 turbines 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]. Previous research utilizes multiple methods to apply condition monitoring on the wind turbine generator. For instance, a temperature trend analysis method based on the nonlinear state estimate method (NSET) is proposed to apply a condition monitoring system on wind generators [5]. The differences between the estimated generator temperatures values of the proposed model and the generator temperatures data which are measured by SCADA are used as an important indicator in order to identify the faults that can occur due to an increase in the wind generator's temperatures. When the generator experiences a fault, new observation vectors will generally deviate from the normal working space and the NSET estimate of the residual distribution and its time development will change. The moving window averaging approach is used to find out statistically important 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. A new condition monitoring method based on applying Multiple Linear Regression Model for a wind turbine generator is proposed in another paper [6]. The method is used to construct the normal conduct model of electrical generator temperatures based on the historical generator temperatures data. Measuring the correlation between the observed and predicted values of the criterion variables based on the historical generator temperatures is the main idea of the proposed technique.

Condition monitoring of a wind generator was discussed in another work by using the time and frequency domain analysis [7]. The authors emphasize that by monitoring the stator and rotor line current trend when both stator and generator rotor are under unbalanced force, the detection of generator faults is available. They apply the machine current signature analysis (MCSA) method which is a noninvasive online or offline monitoring technique for the diagnosis of faults in generators, such as turn-to turn fault, broken rotor bars, and static or dynamic eccentricity. Another paper used the mechanical characteristics to diagnose the faults that can occur in wind generators [8]. 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 and electrical torque.

This proposed work presents an application of condition monitoring system on wind turbine 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 the reliable electric torque values and apply proper condition monitoring on the wind turbine generators under different operation conditions. The rest of the paper is arranged as follows:

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Section II presents the synchronous wind generator failure modes and the torque pulsations effect. 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. The proposed mathematical model analysis in order to apply the condition monitoring system on the wind turbine generator and the electrical torque derivative are illustrated in Section IV. A case study is provided in Section V in order to demonstrate the utilization of the proposed method and its capability. Section VI presents discussion, conclusions and suggestions for further research. The methodology of the present work is summarized in the next flowchart:

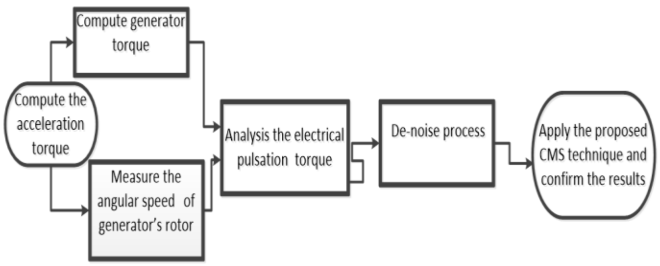

Fig. 1. The Methodology of the Proposed Work

II. SYNCHRONOUS GENERATOR FAULTS DIAGNOSIS AND TORQUE PULSATIONS EFFECT

Failures like bearing faults, stator inter-turn faults, and eccentricities are related to all types of synchronous machines. While some failures are related to wound rotor synchronous machines such as rotor winding faults, broken damper bars, or end-rings, stator inter-turn fault is one of the most widespread failures in synchronous machines. There are various symptoms that appear when synchronous machines suffer faults while operation, such as unbalanced line currents and air-gap voltages, low torque average, increased power losses, and high torque pulsations [9, and 10]. In this paper, the behavior of electric torque pulsations is considered as an effective approach in order to develop a condition monitoring system on a wind turbine generator. This is because high torque pulsations are a significant sign to electric faults that occur in the generator part. Therefore, the problem of pulsation in the generated electrical torque requires additional attention [11, 12, and 13]. Electric torque pulsations are represented in the sum of the ripple and cogging torque with zero mean value and produces vibration and acoustic noise, which might be increased in variable speed drives. Ripple torque is created by the interaction between the magnetomotive force (MMF) due to either the stator windings or the rotor magnets. Ripple torque is generally undesirable since it causes vibrations and noise, and may reduce the lifetime of generators [11, 12, and 13]. When the rotor of a generator is rotated with respect to the stator at no electrical load, cogging torque is created. This type of torque is popular in synchronous generators and occurs due to the geometry of the generator. Many undesirable effects are produced from cogging torque such as noise and mechanical vibration on wind turbines, and negatively affects the self-start running. The cogging torque can be calculated for different rotor positions when the stator winding carries no current and the magnetic field is available. Reaching lower cogging torque is beneficial since it reduces mechanical vibrations, noise, and extends the operational life of the gearing and other mechanics. [11, 12, and 13]. In order to perform an effective condition monitoring system on wind generators, the approach of analyzing the electrical torque pulsations 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.

III. THE SELECTED WIND TURBINE, GENERATOR, AND THE AVAILABLE SCADA

Actual data was collected 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 $\mathrm{kg.m^2}$ [14]. 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 measured over time by utilizing the gearbox ratio, which is balanced with the rotor rotational speed of the synchronous generator. Figure 2 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 based on measured data. The synchronous generator shows different torque-speed attributes at the normal an abnormal conditions, which confirms that torque-speed relationship could be a significant indicator for applying condition monitoring of a wind turbine generator. Furthermore, there is a linear relationship between the electric torque and rotor rotational speed of the synchronous generator in both conditions as shown in Figure 2. As was mentioned previously, the proposed methodology is based on the acceleration torque which is estimated in order to obtain accurate electric torque values and perform a proper condition monitoring on the selected wind generator. In the following section, the mathematical analysis of the proposed model is illustrated.

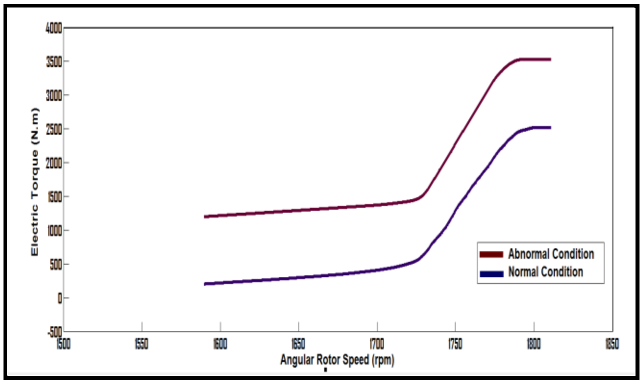

Fig. 2. The electric torque trend with rotor rotational speed

IV. 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. Therefore, it is very simple and flexible to estimate the electromagnetic torque T_e 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 T_m can be defined from the next relation:

$$T_m = T_e + T_{acc} \quad (1)$$

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

$$T_{acc} = J\frac{d\omega_r}{dt} \quad (2)$$

where J is the combined generator rotor and wind turbine inertia coefficient in steady-state at a fixed 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 T_m that produced by the wind accelerates the wind turbine and is counterbalanced with the torque of the low speed side shaft T_{Ls} (the torque produced by the torsional movement of the low speed side shaft). From Figure 3, the relation between T_m and T_{Ls} as follows:

$$T_m - T_{Ls} = J_{B,H}\frac{d\omega_t}{dt} \quad (3)$$

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:

$$J_{B,H} = J_B + J_H \quad (4)$$

$$J_B = \frac{3}{12}\left[\, l^2 + b^2 + \cos^2\alpha^2 + 3\, m_B\, c^2\right] \quad (5)$$

$$J_H = m_H . D_1^2/8 \quad (6)$$

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 [8, and 15].

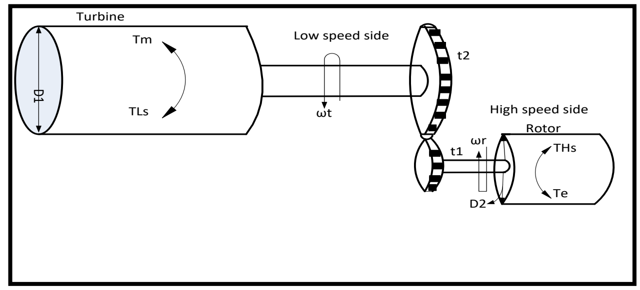

Fig. 3. Wind Turbine Drive Train [15]

Similarly, the torque that produced by the high-speed shaft T_{Hs} accelerates the rotor of the synchronous generator and is balanced with the electromagnetic torque T_e produced by the generator. The relation between the electromagnetic torque T_e and high-speed side torque T_{Hs} is determined as follows:

$$T_{Hs} - T_e = J_g.\frac{d\omega_r}{dt} \quad (7)$$

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 velocity of the generator's rotor. The gear ratio is defined as follows:

$$\frac{T_{Ls}}{T_{Hs}} = \frac{\omega_r}{\omega_t} = \frac{t_1}{t_2} = \text{Gear ratio} \quad (8)$$

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:

$$\omega_t = \omega_r\frac{t_2}{t_1} \quad (9)$$

With the help of the previous relations, the electromagnetic torque can be determined as follows [8, and 15]:

$$T_e = T_m.\frac{t_1}{t_2} - J_g.\frac{d\omega_r}{dt} - \left[J_m\frac{d\omega_r}{dt}.\left(\frac{t_2}{t_1}\right)^2\right] \quad (10)$$

As was mentioned before, estimating the electromagnetic torque values is not complicated when the mechanical parameters information is available by SCADA system. In order to derive a proper algorithm to apply a condition monitoring system on wind generators depending on study the electrical torque pulsations, following the electrical analysis on the generator part is very beneficial. There are two magnetic fields in 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:

$$T_e = 3\, E_a\frac{V_\emptyset}{\omega_s X_s}\sin\delta \quad (11)$$

where E_a is the internal voltage that generated in one phase of a synchronous generator, $V_\emptyset$ is the output voltage of a 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 synchronous generator, which can be defined as the angle between the internal generated voltage and output voltage [8, 11, 12, and 13]. The simple generator electrical circuit is shown in Figure 4. The Kirchhoff's voltage law equation for this electrical circuit can be derived as:

$$V_{\emptyset} = E_a - (j\,X_s + R_a)\,I_a \qquad (12)$$

where R_a is the resistance of the generator's stator, and I_a refers to the state phase current [7].

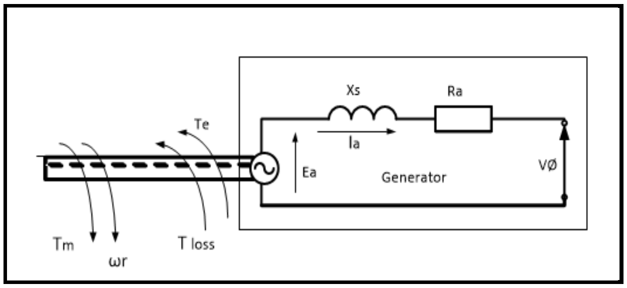

Fig.4. Synchronous machine operated as a generator [8]

The winding resistance R_a can be ignored in the large synchronous generators since is very small value. Then, the synchronous voltage can be written as follows:

$$V_{\emptyset_a} \approx E_a - (jX_s)I_a \qquad (13)$$

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

$$T_e = 3E_a \,.\, \frac{E_a - (j\,X_s)I_a}{\omega_s X_s} \sin\delta \qquad (14)$$

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

$$E_a = \sqrt{2}\,\pi\, N_C\, \emptyset\, f_e \qquad (15)$$

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

$$E_a = \frac{\sqrt{2}}{4}\, N_C\, \emptyset\, \omega_r\, p \qquad (16)$$

From equation (12) it becomes clear that:

$$E_a - (j\,X_s + R_a)\,I_a \propto {E_a}^2 \qquad (17)$$

With the aid of equation (16), equation (17) should be modified as follows:

$$E_a - (j\,X_s + R_a)\,I_a \propto {E_a}^2 = N_c^2\, \emptyset^2\, \omega_r^2\, \frac{p^2}{8} \qquad (18)$$

By substitution of (11) into (18), the electrical torque will be equal to the next relation:

$$T_e = 3\, \frac{N_c^2\, \emptyset^2\, \omega_r^2\, \frac{p^2}{8}}{\omega_r X_s} \sin\delta \qquad (19)$$

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

$$T_e = 3\, \frac{N_c^2\, \emptyset^2\, \omega_r^2\, \frac{p^2}{8}}{\omega_r X_s} \sin\delta \qquad (20)$$

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:

$$T_e \,\alpha\, \frac{\omega_r}{X_s} \qquad (21)$$

The previous equation used when the torque angle δ and magnetic flux $\emptyset$ are stable. A condition monitoring criterion C is proposed in [8] 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 values 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. This creates high electrical torque pulsations with reference to the angular speed of the generator's rotor. A case study is presented in the following section in order to confirm the validity of the proposed algorithm.

V. CASE STUDY

In order to utilize the proposed model to develop a proper condition monitoring on the synchronous generator of the selected wind turbine, the required data that collected by SCADA system are categorized and analyzed. With the aid of equations (1, and 2), electric torque can be calculated based on the acceleration torque. The rotational angular speed of the generator's rotor can be estimated from equation (8), 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 [14]. Study the trend of the electric torque pulsations can be considered as a robust indicator in order to perform a condition monitoring system on wind generators. Based on Figure 2, there is a linear proportional relationship between the electric torque of the synchronous generator and rotor angular speed in both conditions. Furthermore, at any specific rotor angular speed, 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 is divided to 200 seconds. Table 1 demonstrates the data classification over time for both conditions.

TABLE I. DATA CONDITIONS CLASSIFICATION [14]

Time Interval (Second)	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 effectively. The timewaveforms of the electrical torque and angular speed of the generator's rotor signals are shown in Figures 5, and 6.

VI. 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 while running. This information emphasizes the variation of the electric torque pulsations through the normal and abnormal conditions. Furthermore, the proposed monitoring model is based on the parameters that control the operation condition, such as the generator reactance. The value of $\left(\frac{T_e}{\omega_r}\right)$ can be utilized to figure out the presence of the electrical faults in any generator, e.g. stator winding fault or rotor imbalance fault. The change of the generator reactance X_S, which is corresponding to the operation condition, is one the most significant effects that lead up to electrical faults in the generator. Consequently, the variable $\left(\frac{T_e}{\omega_r}\right)$ must be considered and its fluctuations need to be spotlighted in order to apply CMS on wind generators. Figure 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 electric fault, such as a shorted winding coil, the generator reactance decreases automatically, since the value of the variable $\left(\frac{T_e}{\omega_r}\right)$ increases remarkably, and vice versa. 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.

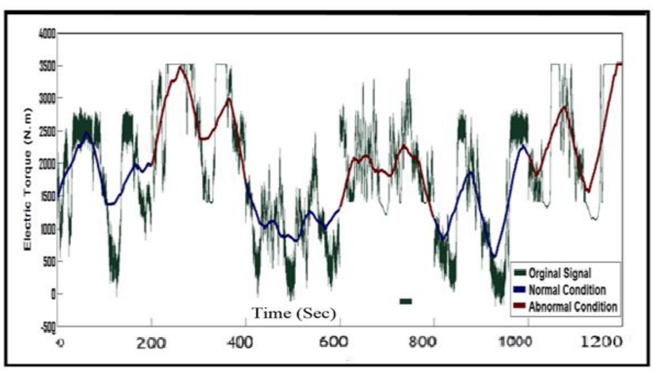

Fig.5: The time-waveform of the electrical torque

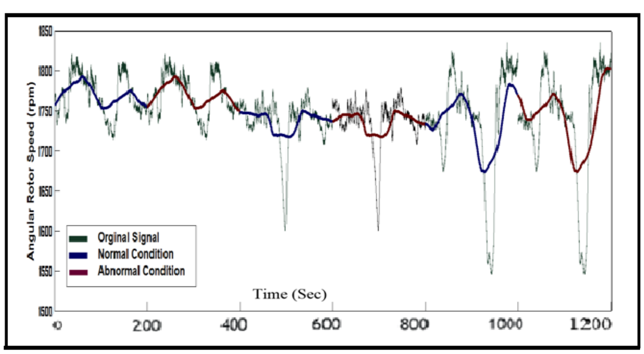

Fig.6: The time-waveform of the angular rotor speed

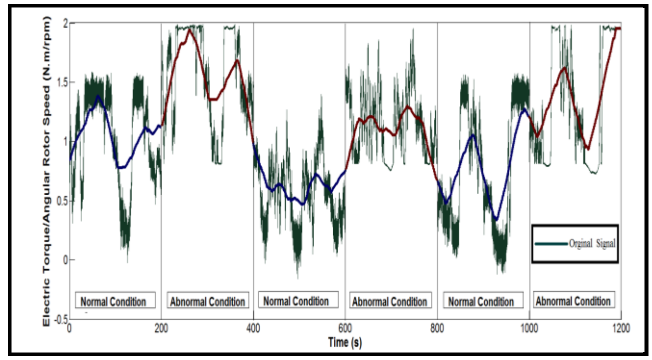

Fig.7: The proposed indicator $\left(\frac{T_e}{\omega_r}\right)$ trend

VII. CONCLUSION

This paper indicates that mechanical characteristics can be used to diagnose the faults that can occur in wind generators. High electric pulsations torque can be considered as 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 can be considered as an effective approach for a condition monitoring system on the wind turbine generator. 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. Future work is required to apply this method on generators that suffer from different electrical faults. Furthermore, the proposed model could be applied on different parts of wind turbines, such as gearboxes, to confirm the feasibility of the proposed model.

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