Remaining Useful Life Prediction of Aluminum Electrolytic Capacitors Used in Wind Turbines

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***Abstract*—Aluminum electrolytic capacitors are widely used in the converter systems of wind turbines. Though vital the capacitors are they are the "weak link" in wind turbines. Accurately predicting its remaining useful life is of great importance. However, traditional estimation methods are only applicable to the static operating conditions. This paper proposed an estimation method by introducing the virtual lifetime instead of the actual operating time to predict the equivalent series resistance (ESR) as well as remaining useful life of capacitor. Compared with measured ESR values, the model is reasonable for complicated operating conditions and is of practical significance in the prediction of capacitor's remaining useful life.**

Keywords-wind turbine; aluminum electrolytic capacitor; remaining useful life; equivalent series resistance

I. BACKGROUND

With the development of wind power technology and the increase of the installed capacity, the requirements of safe and reliable wind turbine generator systems (WTGs) are much higher than before. Capacitor has the shortest life span among various components in the converter system which is the essential subsystem of WTGs [1]. Therefore its operation status can gauge the state of the converter and it is necessary to provide accurate real-time prediction of the remaining useful life of the capacitor.

Aluminum electrolytic capacitors are widely used in WTGs. The main failure modes include open circuit, short circuit, leakage, explosion and deterioration of electrical parameters. In the case of without considering the catastrophic failure due to overpressure, overcurrent or excess temperature, the primary wear-out mechanism is vaporization of electrolyte that leads to the deterioration of the electrical parameters [2], for instance, increase in ESR, decrease in capacitance and increase in current leakage or tangent of loss angle.

Standard handbook provides the formula from the design's point of view rather than for real applications [3]. The failure rate of mass production is the multiplication of basic failure rate, capacitance, mass and the correct coefficient of operating conditions. Capacitor manual derives failure rate based on Arrhenius model and shows the relationship between real lifetime and rated lifetime [4]. But complicated operating conditions and nonlinear relationship between real lifetime and rated lifetime will cause large errors in the calculation.

Commonly used methods for monitoring and predicting the lifetime of capacitors in-service are reliable distribution model, circuit model and machine learning model. The paper [6] constructed failure prediction models based on various models. These models are difficult to be extended to general case due to the lack of considerations of the operating conditions. By applying current on the offline circuit and measuring the output value, Xing-Si Pu figured out ESR of the capacitors [7]. Karim Abdennadher estimated the capacitance and ESR of the capacitors by the online measurement of the voltage and current [8]. Weijie Tang implemented the online monitoring scheme to derive ESR [9]. Hamman Soliman suggested an ESR approach using artificial neural network algorithm [10]. However, the methods [6]-[10], whether offline or online, need to measure numerous parameters. Hao Ma proposed the failure prediction model and estimated ESR from the vaporization mechanism of electrolyte [11]. Bo Sun obtained capacitance and the trend of ESR to forecast the remaining useful life from Arrhenius' rule of thumb [12]. However, the method treats the failure rate as a function of temperature without considering the effect of degradation time.

This paper proposes a new method by introducing virtual lifetime instead of the actual operating time to estimate the ESR values from the mechanism models and empirical formulas. Meanwhile, the method could predict the remaining useful lifetime based on the deterioration model of ESR.

II. PREDICTION MODEL OF REMAINING USEFUL LIFE

A. *Deteriotation Model of ESR*

The ESR at time t can be given by A. Lahyani [13] as equation (1).

$$R(t) = \frac{R_0}{1 - k \cdot t \cdot \exp(-\frac{E}{T})} \tag{1}$$

where

R ESR value at time t (mΩ)
R_0 Initial ESR (mΩ)
T Core temperature (K)
k Constant associated with the nature of the capacitors
E Ratio of activation energy to Boltzmann's constant (1/K)
T Usage time (h)

ESR cannot be calculated directly by (1) in real-world situations since the core temperatures of capacitors vary with wind speed, wind direction, ambient temperature and ventilation etc. This paper implementing ESR value at previous time step introduces the virtual time t^* which can be derived by (2) and replaces t with （$t^*+\Delta t$） to obtain the modified present ESR.

$$t^* = \frac{1-\dfrac{R_0}{R(t-\Delta t)}}{k\cdot\exp(-\dfrac{E}{T(t)})} \tag{2}$$

where
Δt Time increment (h)

B. Core Temperature of The Capacitor

The core temperature of the capacitor is the sum of the ambient temperature and the rise caused by resistive heating.

$$T = T_a + R_{th}P_v \tag{3}$$

where
T_a Ambient temperature (K)
R_{th} Capacitor thermal resistance (K/W)
P_V Power loss (W)

The power loss consisting of two parts, dielectric power loss and current loss, is hard to obtain online since it is affected by many factors: capacitance, ESR, dielectric loss coefficient, ripple current, average voltage and current frequency etc. Based on past test, this paper implements the linear relationship between ripple current and active power given by (4) and derives the power loss given by (5).

$$I_{rms} = b_0 + b_1 P_W \tag{4}$$

where
I_{rms} Ripple current (A)
P_w Active power (kW)
b_0,b_1 Coefficients

$$P_V = I_{rms}^2 R_h \tag{5}$$

where
R_h ESR at operating temperature
R_h Could be alculated from ESR at rated temperature given by (6).

$$\ln(\frac{R_h}{R(t)}) = \alpha_1 \Delta T^{\alpha_2} \tag{6}$$

where
ΔT Difference between operating temperature and rated temperature
α_1,α_2 Constants derived from experiments

$R(t)$ and ΔT in equation (6) can be obtained by iteration method.

C. Remaining Useful Life

Equation (1) shows that ESR is a monotone increasing function of time. The remaining useful life can be figured out by (7). An alert will be issued if the remaining useful life is below the threshold.

$$L_{RUL} = L_T - (t^* + \Delta t) \tag{7}$$

where
L_{RUL} Remaining useful life (h)
L_T Lifetime at temperature T (h)

Equation (8) is provided to extrapolate the lifetime at temperature T using Arrhenius model:

$$L_T = L_0 \times 2^{\frac{T_0 - T}{10}}. \tag{8}$$

where
L_0 Rated life at temperature T_0 (h)

III. Calculation Process

Fig. 1 is a flow chart for the necessary calculations. The main process is given as follows:

1) Input capacitor parameters, for instance capacitance and initial ESR etc. to initialize the model.
2) Set previously derived $R(t)$ as R'_h.
3) Obtain R_h using ripple current and active power.
4) Calculate the core temperature T using ambient temperature and the rise caused by resistive heating and obtain virtual lifetime t^* at time (t-Δt) based on equation (2).
5) Calculate $R(t)$ using $t = t^*+\Delta t$.
6) Derive R_h at operating temperature by equation (1).
7) Compare R_h and R'_h. If different, re-calculate until the value converges.
8) Obtain the remaining useful life by subtraction of rated life and lifetime derived by equation (2).
9) Calculate recursively until the estimation is less than the threshold and issue the alert.

IV. Validation and Application

A. Validation

Three wind turbines in different geographical locations are chosen to test the performance of the model using the historical monitoring data. The remaining useful life is corrected to its equivalent value at temperature 85°C. Good fidelity between the model prediction and measured values can be seen in Fig. 2. The model is reasonable since the capacitor endures the rated life when ESR equals 30 mΩ which is in accordance with capacitors' qualifying test.

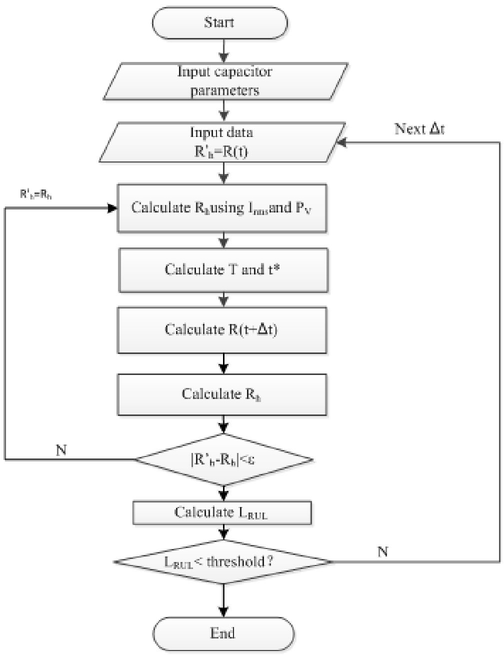

Figure 1. Flow chart representing calculation process.

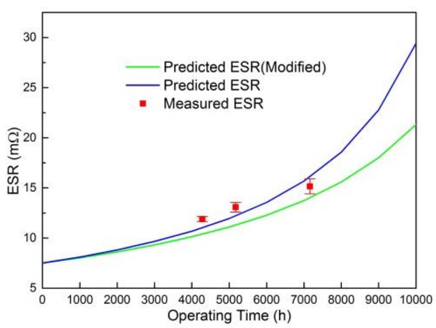

Figure 2. Comparison of calculated esr with measured ESR.

B. Application

Wind turbines #1 and #2 in certain south farm are selected as the research objects. The device chosen to test the model is a 6800 μF capacitance with a 10000h rated life at 85°C. Test data from the annual monitoring data in 2016 is shown in Fig. 3.

Fig. 4 shows the remaining useful life and the rated life. Both of them are highly correlated to temperature and active power shown in Fig. 3. Since the model prediction fluctuates continuously with the temperature and active power, the remaining useful life is corrected to values at the average temperature and active power (32°C, 360kW) for comparison. Fig. 5 shows that the transformed values decrease monotonically over time and gives more obvious results. Moreover, if the predicted remaining useful life is less than one year, this model could derive a more accurate prediction using temperature and wind speed etc.

Wind turbine #9 in the same farm and wind turbine #11 in farm #2 are chosen and their model predictions arecorrected to the equivalent values at the same operating condition as wind turbine #22. Since the location of insulated gate bipolar transistor (IGBT), composed of multiple capacitors, varies in the cabinet, and so does the location of each capacitor in IGBT, the ventilation and heat dispersion which affect the remaining useful life differ in capacitors. It is hard to predict the remaining useful life of each capacitor and only the worst case is considered.

From the historical data, parameters such as temperature and active power fluctuate largely over time and their relationships with predicted remaining useful life are nonlinear. The parameter granularity (calculation step) has great impact on the results. Fig. 6 shows the remaining useful life calculated by hourly, daily, monthly and yearly data which is averaged on the calculation step. The remaining useful life increases as the calculation step increases since the averaged values offset the effect of the extreme conditions that have great impact on the lifetime. (Lifetime behalves as the temperature increases every 10°C). Besides, the relatively small differences between results calculated hourly and minutely, are accordance with the experience that the operation and environment parameters of the wind turbines vary slightly within ten minutes or one hour. Hence it is reasonable to calculate the remaining life of capacitors hourly.

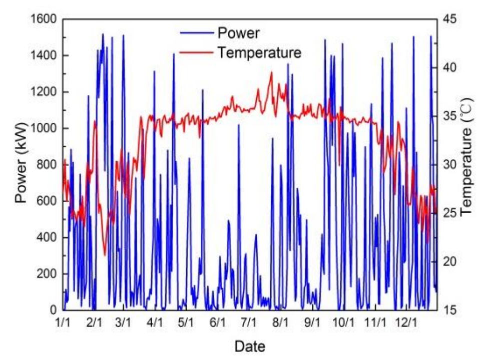

Figure 3. Annual monitoring data in 2016.

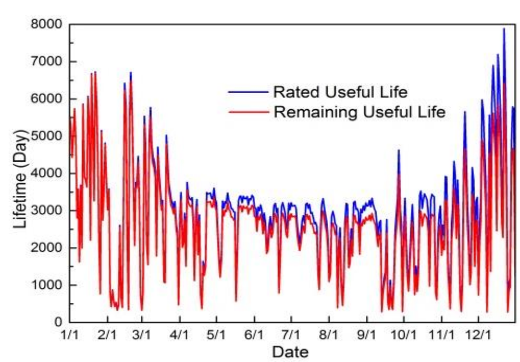

Figure 4. Comparison of rated useful life and remaining useful life.

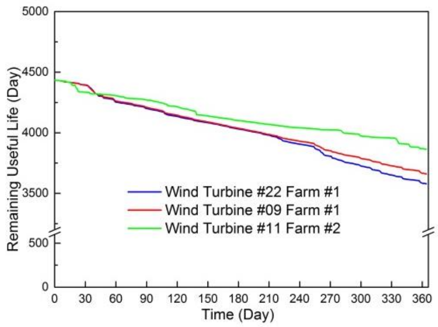

Figure 5. Remaining useful life of different wind turbines.

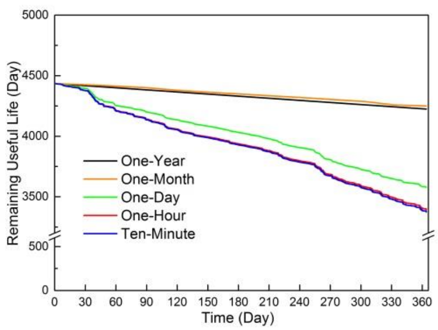

Figure 6. Remaining useful life calculated by different time step.

V. Conclusions

By means of introducing virtual lifetime, we could predict remaining useful life of capacitors using deterioration model of ESR. This method is reasonable due to considering the different operating conditions such as ambient temperature, active power and heat rise caused by power lost.

The results should be corrected to values under the same conditions for comparison. It is more appropriate to make calculations based on hourly parameters and set up models for different wind turbines.

More experimental measurements of different wind turbines under different operating conditions will be done to test and improve the model. Then the method will be implemented practically to monitor the status of wind turbines and make the online failure prediction.

Reference

[1] W. Huai and B.Frede, “Reliability of capacitors for DC-link applications in power electronic converters: An overview,” IEEE Transactions on Industry Applications, vol. 50, pp. 3569-3578, Oct. 2014, doi:10.1109/TIA.2014.2308357.

[2] J.L. Stevens, J.S. Shaffer, and J.T. Vandenham. “The service life of large aluminum electrolytic capacitors: effects of construction and application,” IEEE Transactions on Industry Applications, vol. 38, pp. 2493-2499, doi:10.1109/IAS.2001.955971.

[3] MIL-HDBK-217E: Military handbook reliability prediction of electronic equipment. Defence Department of USA, Washington, 1991.

[4] Nippon Chemi-Con. “Judicious use of aluminum electrolytic capacitors,” http://www.chemi-con.co.jp/ e/catalog /aluminum.html.

[5] S. Hammam, W. Huai, B. Frede. “A review of the condition monitoring of capacitors in power electronic converters,” IEEE Transactions on Industry Applications, vol. 52, pp. 4976-4989, 2015, doi:10.1109/OPTIM.2015.7427012.

[6] F. Perisse, P. Venet, and G. Rojat. “Reliability determination of aluminium electrolytic capacitors by various methods. Application to the protection system of the LHC,” Microelectronics Reliability, vol. 44, pp. 1757-1762, 2004.

[7] P. X. Si, T. H. Nguyen, L. D. Choon, L. K. Beum, and K. J. M. Kim. “Fault diagnosis of DC-link capacitors in three-phase AC/DC PWM converters by online estimation of equivalent series resistance,” IEEE Transactions on Industrial Electronics, vol. 60, pp.4118-4127, Sept. 2012, doi:10.1109/TIE.2012.2218561

[8] A. Karim, V. Pascal, R. Gerard, R. Jean-Marie, and R. Christophe. “A real-time predictive-maintenance system of aluminum electrolytic capacitors used in uninterrupted power supplies,” IEEE Transactions on Industry Applications, vol. 46, pp. 1644-1652, Jul. 2010, doi:10.1109/TIA.2010.2049972.

[9] T. Weijie, K. Yao, H. Wenbin, L. Jiangguo, C. J. cheng. “An online monitoring scheme of output capacitor’s ESR and C for CCM buck converter without current sensor,” Proceedings of the CSEE, vol. 35, pp. 5569-5576, Nov. 2015, doi:10.13334/j.0258-8013.PCSEE.2015.21.021.

[10] S. Hammam, W. Huai, G. Brwene, and B. Frede. “Condition monitoring for DC-link capacitors based on artificial neural network algorithm,” IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives, IEEE Press, pp. 587-591, 2015, doi:10.1109/PowerEng.2015.7266382.

[11] M. Hao and W. L. Guo. “Degradation analysis and failure prediction of aluminum electrolytic capacitors,” Industrial Electronics Society 2005, vol. 29, pp. 68-74, Nov. 2005, doi:10.1109/IECON.2005.1569014.

[12] S. Bo, F. X. Jun, C.A. Yuan, and Q. Cheng. “A degradation model of aluminum electrolytic capacitors for LED drivers,” International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, 2015.

[13] A. Lahyani, P. Venet, G. Grellet, and P.J. Viverge. “Failure prediction of electrolytic capacitors during operation of a switchmode power supply,” IEEE Transaction on Power Electronics, vol. 13, pp. 1199-1207, Aug. 2002, doi:10.1109/63.728347.

[14] M. L. Gasperi. “Life prediction model for aluminum electrolytic capacitors,” Industry Applications Conference, Thirty-First IAS Annual Meeting, vol. 3, pp. 1347-1351, 1996, doi:10.1109/IAS.1996.559241.