Health Monitoring of DC Link Capacitor in Variable Frequency Drives

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Abstract - *DC link capacitor is an intermediate circuit capacitor employed in the converter circuits of different kinds These capacitors are one of the crucial components playing significant roles, such as filters, snubbers, and energy-storage elements. Unfortunately, these capacitors are the most failure-prone component of an electric drive system. Earlier proposed health monitoring techniques were either offline methods or included additional hardware components to estimate the remaining life of capacitor. Hence, an online method for predicting the health of capacitor is put forward using the pre-charge circuit measurement method. The Equivalent Series Resistance (ESR) and Capacitance (C) are considered as the degradation parameters.*

The proposed work presents an health monitoring system for aluminium electrolytic capacitors, used as dc link capacitors in variable frequency drives. The simulation was performed for rectifier fed three-phase inverter using MATLAB-Simulink for a capacitance value of 3300 μF with ESR as 39 mΩ. For the calculation of remaining life has considered the effect of temperature, current and voltage as well. Hence, the complete health monitoring of the DC link capacitor in variable frequency drive was accomplished.

***Key Words*: Electrolytic Capacitors, Equivalent Series Resistance, Capacitance, FFT, MATLAB-Simulink**

1. INTRODUCTION

Power converters are an integral part of many industries because of their undisputed performance in applications, such as motor drives, uninterruptible power supplies, and electrical heating. An electric drive system is one of the important areas, the power converters are used extensively [1]. The major components of variable frequency drives are power devices, capacitors, and inductors. The two converters are linked together with a filter capacitor that is DC link capacitor. The capacitor works along with the rectifier and acts as storage of DC power and filters out the variations of the DC voltage before further processing of the inverter [2].

The circuit design uses different technologies for DC-Link capacitors such as aluminium electrolytic, film, and ceramic types. In common, aluminium electrolytic capacitors (AEC) are employed in power electronics due to their very high power density. The major advantage of an electrolytic capacitor is large capacity in a small package size at a relatively low cost [3]. The electrolytic capacitor provides large energy density and also smaller size while maintaining the range of operating temperature, service life, leakage currents obtainable and tolerance levels with the conventional capacitor [4].

1.1 Capacitor Failure Analysis

Electrolytic capacitors tend to fail time and again frequently than other components of the circuit. These degrade with time and endanger the reliability of power electronic converters [5]. Therefore the capacitor health monitoring system in power electronic converters is required, enabling the indication of future failure occurrences and preventive maintenance. With aging, AEC deteriorate due to various thermal and electrical stresses. Its electrolyte vaporizes and oxide layer decays, leading to significant decrease in capacitance(C) and increase in equivalent series resistance (ESR) values [6]. Prolonged use of aged capacitor leads to open-circuit of DC-link due to complete dry-out of electrolyte. It will increase the accidental maintenance events and shutdown of system, thereby increasing maintenance cost [7].

In order to avoid this uncertain maintenance, reduced downtime of the system and increase the reliability of the system, condition monitoring of AEC is advisable. The major indicators of the degradation for these capacitors are equivalent series resistance (ESR) and capacitance(C)[8].

Health monitoring methods for AECs are classified as (i) Offline, (ii) Online, and (iii) Quasi-online. One of the easiest offline methods is to measure the ESR and C using an LCR meter. Since the ESR value is very low in the range of few milliohms to hundreds of milliohms, high precision instruments are required [9].

The defined industry standards specify the end-of-life of an electrolytic capacitor under thermal stress is- if the capacitance value drops by 10% and the ESR value rises by 250% or more from its initial rated value. Similarly, under electrical stress operations, the end-of-life is expressed by its ESR increasing by 280% - 300% over and capacitance decreasing by 20% below its initial condition values [10]. The criteria vary for electrical and thermal stress conditions because thermal stress conditions are considered for situations while the capacitor is in storage, and not in working condition [11].

2. DEGRADATION OF DC LINK CAPACITOR

The Fig-1 shows electrical equivalent circuit of a practical aluminium electrolytic capacitor. Here, C is the actual capacitance value, Rc is the leakage resistance of the dielectric, Ra is the series resistance due to the terminals, tabs, and electrolyte. It is also known as ESR that represents overall loss components of a practical capacitor [5]. The ESL models the equivalent series inductance due to the loop formed by the terminals and tabs depicted by L1. The diode D1 models the overvoltage and reverse voltage behavior of the electrolytic capacitor.

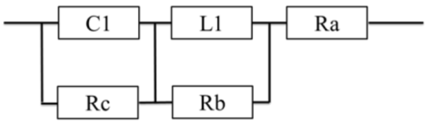

Fig -1: Equivalent Circuit of Capacitor

The degradation of AEC is modelled as a function of time (t) and temperature (T). For the operation at constant core temperatures, C and ESR at any time t is written as

$$C(t) = CAP_0(1 - A[T].t) \quad (1)$$

$$ESR(t) = ESR_0.e^{C[T].t} \quad (2)$$

Here, CAP(t) and ESR(t) are the instantaneous values of capacitance and ESR. CAPo and ESRo are the initial values of capacitance and ESR. A[T] and C[T] represent temperature dependent degradation rates of capacitor as follows

$$A[T] = A_0.e^{\frac{-E_{a1}}{KT}} \quad (3)$$

$$C[T] = C_0.e^{\frac{-E_{a2}}{KT}} \quad (4)$$

Ao and Co are the base degradation rates. Ea1 and Ea2 are the activation energies of Capacitance and ESR. K is the Boltzmann constant; T is the Temperature and t is the ageing time. The values of all these parameters are summarized in the Table-1.

Table -1: Specifications of Degradation Model

Sl.no	Parameter	Value
1	Activation energy (Ea_1)	0.68 eV
2	Activation energy (Ea_2)	0.7 eV
3	Boltzmann constant (K)	1.38e-23 J/K
4	Temperature (T)	25 °C
5	A_0	5.2e6
6	C_0	12e6

The lifespan of electrolytic capacitors is majorly dependent on the application conditions: environmental factors (temperature, humidity and vibrations), along with the electrical factors (operating voltage, ripple current and charge-discharge). While the capacitors are employed for filtering purpose, ambient temperature and heating caused due to ripple current are vital factors for determining the lifetime of the capacitors. Therefore, the primary factors affecting the lifetime of electrolytic capacitors in the power applications are the operating temperature, the ripple current and the operating voltage. Other factors have less affect to the lifetime and are ignored in the estimation.

The complete equation of the lifetime estimation model for electrolytic capacitors is based on earlier described factors. The remaining useful life of capacitor (in hours) is written as,

$$L_x = L_o K_T K_i K_v \quad (5)$$

$$L_x = L_o * 2^{\left(\frac{T_o - T_a}{10}\right)} * K_r^{\left(1-\left(\frac{I_a}{I_o}\right)^2\right)\frac{\Delta T_o}{10}} * \left(\frac{V_a}{V_r}\right)^n \quad (6)$$

Where, L_o- Specified rated life
K_T- Temperature factor
K_i- Ripple current factor
K_v- Voltage factor
Kr – empirical safety factor [11].

3. PROPOSED HEALTH MONITORING SYSTEM

Fig-2 shows the basic flowchart of the project work. At the first step, initial values of C and ESR are measured using the LCR meter at the time of installing them in the inverter. The first step is performed only once at start. In the second step DC link current is measured using the hall sensor present in the pre-charge circuit.

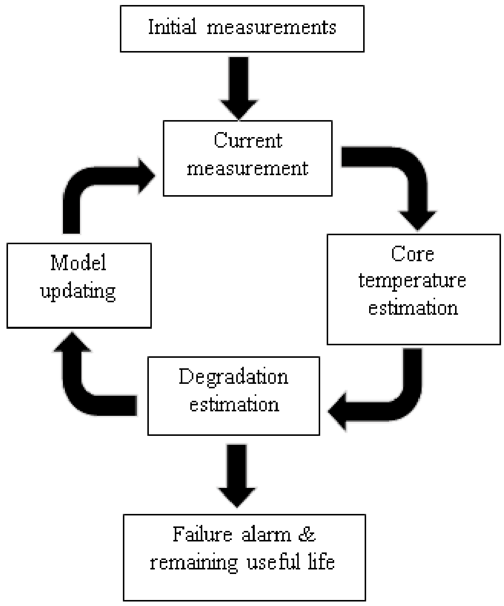

Fig -2: Methodology for Health Monitoring System

Using the current value and the ambient temperature value, core temperature is estimated. In the next step, degradation parameters are estimated. The capacitance is estimated using the charge value and the DC link current. The ESR is estimated using the switching frequency components extracted from the band pass filter. In order to improve the accuracy of the method, the error is optimized in the model updating stage. Using the temperature, current and voltage value, remaining life of capacitor is estimated. The failure status as well as the remaining life is displayed on the LCD.

4. SIMULATION MODEL

The drive simulation model includes the three-phase source, diode rectifier, capacitor model subsystem, band pass filter, three-phase inverter, induction motor, voltage and current measurement blocks. The inverter uses MOSFET as switching device. SPWM switching pulses are generated at the switching frequency of 4 kHz. Since the ESR estimation scheme is based on extracting the switching frequency components, the BPFs are tuned to extract the required harmonic components.

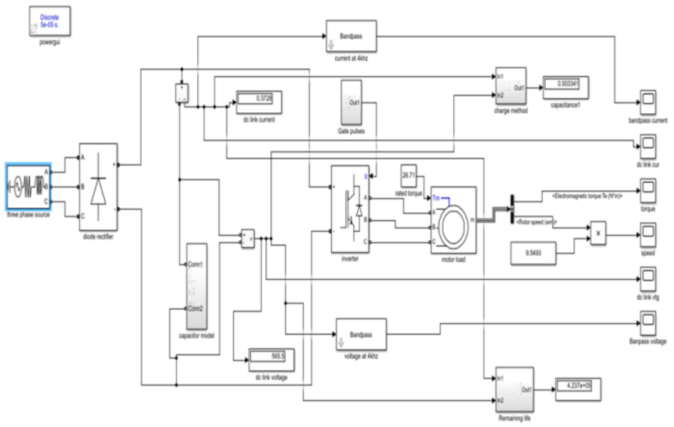

Fig -3: Drive Simulation Model

The capacitor model subsystem consists of capacitor equivalent circuit as mentioned in the earlier section. The simulation model of front end rectifier fed inverter is shown in Fig- 4. The waveforms of DC link voltage, DC link current, band pass voltage, band pass current and the motor parameters that is torque and speed are observed using the scope.

5. RESULTS AND DISCUSSION

The DC link voltage and current waveform are analyzed to understand the capacitor behavior. The voltage and current waveforms are obtained as shown in Fig- 4(a) and 4(b) respectively. The voltage is near to 580 V and current of 4 A is obtained for full load. For an unhealthy capacitor, these waveforms have high amount of ripple content compared to healthy capacitor.

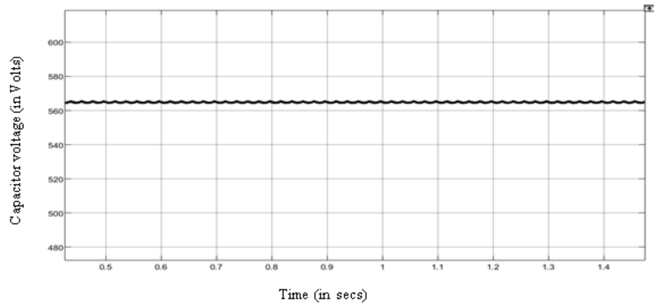

Fig -4 (a): DC Link Capacitor Voltage

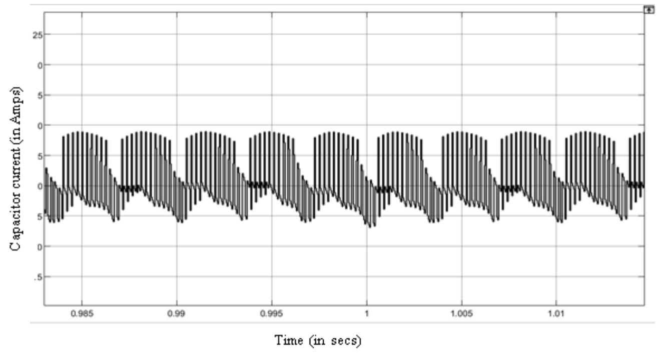

Fig -4 (b): DC Link Capacitor Current

The electromagnetic torque waveform is as shown in Fig- 5 (a). The torque values obtained is 27 N-m for full load. The speed waveform is as shown in Fig- 5 (b). The rated motor speed is 1430 rpm, and the obtained speed value is 1428 rpm for full load. As the capacitor degrades with passage of time, the ripples in the torque and speed increases.

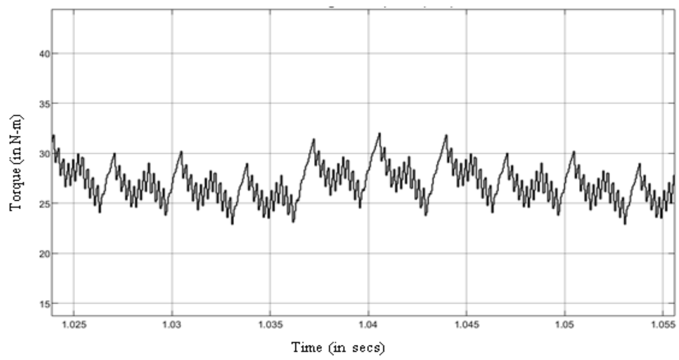

Fig -5 (a): Electromagnetic Torque

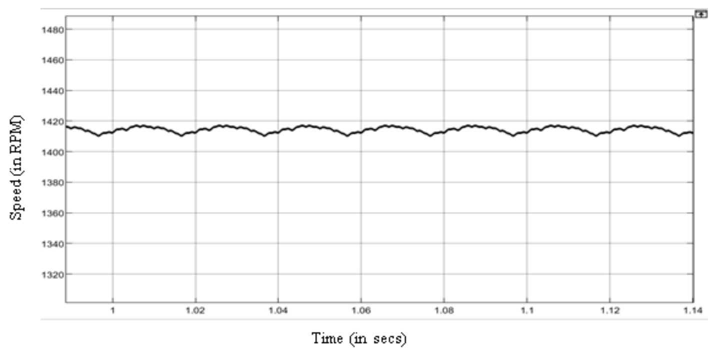

Fig -5 (b): Motor Speed

The FFT analysis of DC link capacitor voltage and current indicate that the dominant higher frequency harmonics are distributed mainly around switching frequency and its multiples. Hence, 4 kHz components are extracted using the band pass filter. The cut-off frequencies are 3.5 and 4.5 kHz. Since switching frequency components are sinusoidal quantities, peak value of these components is used for calculation of ESR. The band pass filter output- voltage and current are as shown in Fig-6 (a) and 6 (b) respectively.

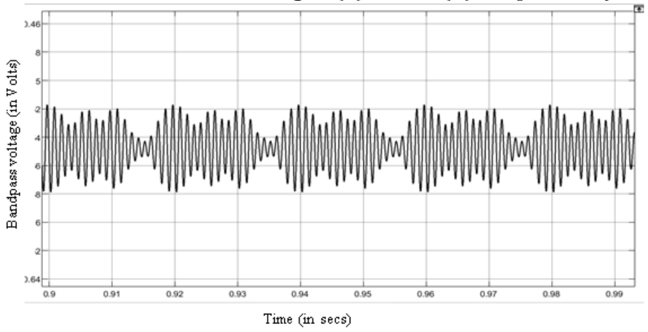

Fig -6 (a): Band pass Voltage

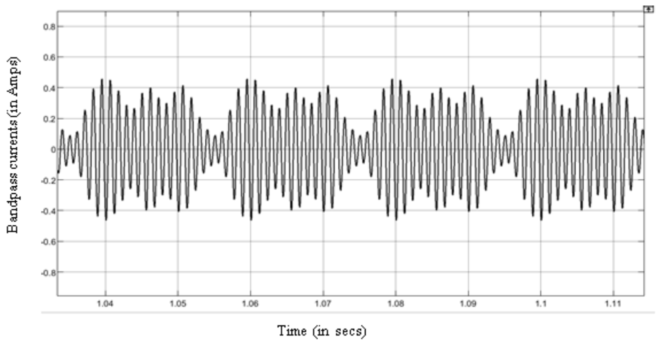

Fig -6 (b): Band pass Current

5.1 ESR Estimation

The ESR estimation using band pass filter requires the peak values of extracted harmonic components and the phase difference between them. The average of peaks over 10-ms period is used to account for the intrinsic variations in peak values. From Fig-7 the zero crossings of extracted capacitor voltage and current are obtained. The time interval is converted to corresponding phase difference θ in radians.

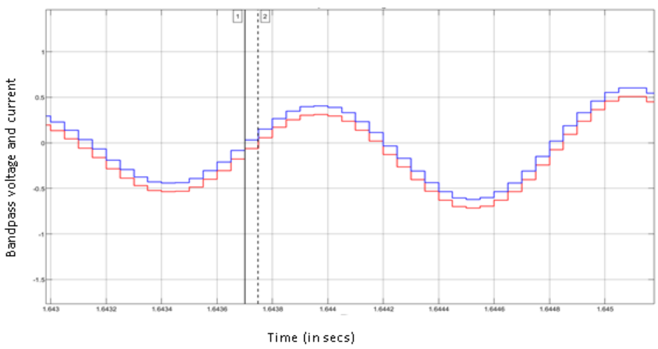

Fig -7: Phase Difference Measuremnet

Using the cursor measurements, the time interval obtained is, ΔT=47.163μs

Therefore, Phase difference is

Θ = 360*f* ΔT= 360*4000* 47.163μs=67.91 degrees

In radians, phase difference Θ = 1.185 rad

$$ESR_{4k} = \frac{(0.303) * 0.1 * \cos(1.185)}{(0.7842)} = 38.63\ m\Omega \quad \text{...... (7)}$$

Error = 0.27 mΩ or 0.98 %

5.2 Capacitance Estimation

Capacitance estimations play a very important role in the health monitoring system of capacitor. The capacitance is estimated using the charge and the voltage value. The charge value is obtained by integrating the current over a time interval same as the simulation time.

Actual value of capacitance = 3300 μF

$$C = \frac{Q}{V} = \frac{\int idt}{V} = 3341\ \mu F \quad \text{..........................(8)}$$

Error = 41 μF or 1.24 %

6. CONCLUSION

In the proposed work, the ESR estimation circuit required only a current sensor employed in the pre-charge circuit and an ATmega microcontroller to estimate the ESR. An equivalent capacitor model is selected to operate in all conditions. Capacitor degradation model is simulated to study the variation of capacitance and ESR with ageing time. Capacitance is estimated directly using the charge value obtained from the integration of DC link current and voltage. ESR is estimated using the extracted components from the band pass filter.

The health monitoring system for variable frequency drive based on capacitance and ESR estimation was proposed in this project work. For a capacitance value of 3300 μF and ESR of 39 mΩ used as DC link capacitor in the drive, the estimated value of capacitor was 3341 μF and 38.63 mΩ. In this case, the error obtained was less than 2 %, it depicted the good accuracy of the proposed system. The remaining life estimated of the capacitor was 45000 hours; the calculation of remaining life had considered the effect of temperature, current and voltage as well. Hence, the overall health monitoring of the DC link capacitor in variable frequency drive was performed.

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