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Prognostics of aluminum electrolytic capacitors using artificial neural network approach

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ABSTRACT

In this work, an effort is being made to monitor the condition of in-circuit aluminum electrolytic capacitor using artificial neural network (ANN). Recent industrial surveys on the reliability of power electronic systems shows that most of faults occur due to the wear out of aluminum electrolytic capacitors and thermal stress is the major cause for its parametric degradation. The condition of target capacitors can be estimated by monitoring variation in equivalent series resistance (ESR) from the initial pristine state value. ANN is used to estimate ESR of pristine and weak target capacitors at the test conditions. The data set for training and testing of proposed back-propagation trained artificial neural network are experimentally obtained from the developed test bed. Using the test bed, target capacitors are subjected to different operating frequency and temperature in the output section of DC/DC buck converter circuit to determine the effect of variation in electrical and thermal stress on ESR value. After off-line training, the proposed ANN is implemented using National Instruments LabVIEW software. A low cost microcontroller is programmed for real time data acquisition of target capacitors and the serial transmission of acquired dataset to the LabVIEW software installed at host computer. The performance of the proposed method is evaluated in real time by comparing the resulting ESR with the experimental values of in-circuit target capacitors. The proposed ANN, once trained properly, can be used for different circuits and in different operating conditions because of its generalization capability.

1. Introduction

Condition monitoring and maintenance is a multidisciplinary field that is gaining importance due to the requirements of high reliability systems for safety-critical applications. Power electronic systems are used for various consumers, industrial and military applications. In order to enhance the service life of reliability-critical components, their real-time condition monitoring is required which will improve the overall reliability of power electronic system. [1] discussed an overview of different condition monitoring techniques to determine the reliability of three different types of capacitors used in dc-link applications that is aluminum electrolytic capacitors, metallized polypropylene film capacitors and high capacitance multi-layer ceramic capacitors. Recent industrial surveys on reliability of power electronic systems shows that most of faults occur due to the wear out of aluminum electrolytic capacitors and thermal stress is the major cause for its parametric degradation [2,3]. Wear-out failure due to parametric degradation of capacitor occurs when its capacitance value fall below 80% or its equivalent series resistance (ESR) increases by 100% of its initial value [4]. Condition monitoring of aluminum electrolytic capacitors in different power converters are done by subjecting them to variable switching frequency [5–8] and temperature [9–14]. ESR varies with both operating frequency and temperature and requires the real-time monitoring of root mean square (rms) voltage and rms current. The aim of this paper is to present ANN approach for determining the real-time in-circuit condition of target capacitors in power electronic systems by considering the effect of both operating frequency and temperature simultaneously. The proposed ANN is trained off-line using training and testing dataset which are experimentally obtained from the developed test bed. Using the test bed, target capacitors are subjected to different operating frequency and temperature in the output section of DC/DC buck converter circuit. Subsequently, weights of trained ANN are used to implement it for estimating ESR of pristine and weak (thermally aged) target capacitors in the real-time using LabVIEW software and data acquisition system. Finally, the implementation is validated in real time using the target capacitors at low pass filter stage for electronic control gear circuit of a compact fluorescent lamp. Real-time temperature and frequency from the test circuit is acquired using low cost

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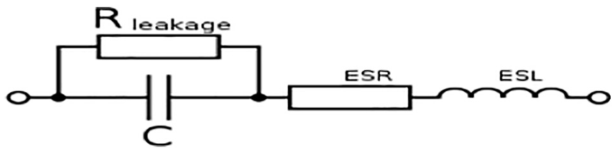

Fig. 1. Equivalent circuit for aluminum electrolytic capacitor.
Where,
$R_{leakage}$ is the leakage resistance;
ESR is the equivalent series resistance; and
ESL is the equivalent series inductance.

microcontroller based data acquisition system. The performance of the proposed method is evaluated by comparing the ANN estimated ESR of target capacitors at resonant frequency with the practical in-circuit ESR values. The proposed ANN based scheme is very useful for in-circuit health monitoring of electrolytic capacitors in power electronics circuits and can be extended for health monitoring of other critical circuit components with suitable training.

2. Parametric degradation failure in aluminum electrolytic capacitor

Degradation failure of aluminum electrolytic capacitor occurs due to increase in the ESR value; decrease in the capacitance value and increase in the dissipation factor (tanδ). The equivalent circuit for an aluminum electrolytic capacitor is shown in Fig. 1.

Neglecting leakage current effect and lead inductance, the simplified equivalent circuit consists of ESR in series with capacitance. ESR is approximated as the impedance value at resonant frequency (≥ 10 kHz) [15]. Volumetric decay in electrolytic solution of capacitor occurs due to increase in its vapor pressure from internal temperature rise over a period of time. A life prediction model based on ESR increase with volumetric decay is proposed by [16]. Volumetric decay of electrolytic solution causes increase in ESR and dissipation factor, as shown in Fig. 2.

For the case of weak capacitor, the evaporation of electrolytic solution becomes more as compare to pristine capacitor and therefore its deterioration rate is faster. Simple thermal model of capacitor shows that core temperature is related to ambient temperature, power dissipation and thermal resistance [17] as,

$$T_{elcap} = P_{dis} \times (R_{thCoC} + R_{th}) + T_{amb} \quad (1)$$

Where,

P_{dis} is Power dissipation in Watts;
T_{elcap} is Core temperature in °C;
R_{thCoC} is Core to Case thermal resistance in °C/W;
R_{th} is Case to Ambient thermal resistance in °C/W; and,
T_{amb} is Ambient temperature in °C.

It is reported by [18], that core-case thermal resistance (R_{thCoC}) is negligible in comparison to case-ambient thermal resistance (R_{th}). So, core-ambient temperature change is approximated as case-ambient temperature change in capacitor which is directly related to the increase in ESR value in capacitor. [19] show that during the aging process, the change in the ESR value is more prominent than capacitance value. Therefore ESR is an important failure signature parameter for aluminum electrolytic capacitor in determining its health at different operating conditions in power electronic system. Based on case-ambient temperature rise, real-time in-circuit remaining useful life (RUL) of capacitors is monitored and the enhancement of its RUL is analyzed using Peltier cooling for 96 h at thermal stress based accelerated aging condition [20]. It is reported by [21] that the resulting heating of capacitor due to the Ohmic losses occurring from the ESR increase can be reduced by controlling the rise in the ripple current through it and therefore its RUL can be enhanced.

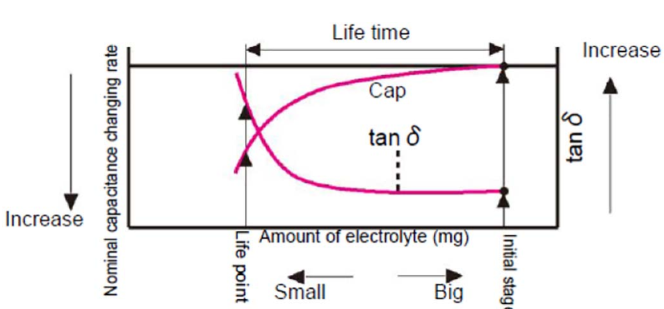

Fig. 2. Parametric degradation due to volumetric decay of electrolyte.

3. Experimental measurement of in-circuit ESR of test capacitors

For obtaining the variations in ESR value of target capacitors at different switching frequency and temperature, a simple and low-cost microcontroller based test bed is developed. Using the test bed, target capacitors (10 μF/450 V, 105 °C from Rubycon BXA and G.Luxon 708D series) are subjected to different operating frequency and temperature in the output section of DC/DC buck converter circuit. The internal timer of the microcontroller is programmed to obtain variable frequency square pulses of 10, 15, 20 and 35 kHz at 50% duty ratio using the corresponding frequency selector switch from switch array. The pulses are isolated using opto-isolator and amplified to drive gate of MOSFET in DC/DC buck converter. Fig. 3 shows the schematic diagram of test bed.

3.1. Measurement of ESR at variable frequency and constant temperature

At different switching frequency, the average values of impedance (Z) for 8 samples of target capacitors is monitored at a constant case temperature of 40 °C in the output section of DC/DC buck converter circuit. The voltage and current waveforms for pristine and weak target capacitors are captured at varying frequencies on digital storage oscilloscope (DSO). Average ESR values (approximated as Z at ≥ 10 kHz) for target capacitors at variable frequencies are obtained experimentally by dividing the root mean square (rms) value of the voltage across capacitors with rms value of current through it at every half hour interval of test. The measured ESR values for pristine and weak target capacitors are compared with reference values of impedance analyzer (AGILENT 4294) and are listed in Tables 1 and 2 respectively for Rubycon BXA and G.Luxon 708D series.

From Tables 1 and 2, the percentage relative error in experimental ESR values is very small that verifies accuracy of developed test bed that is used for analyzing thermal variation of ESR. Variation in ESR of strong and weak 10 μF/450 V, 105 °C G.Luxon (708D) capacitor with frequency is shown in Fig. 4.

3.2. Measurement of ESR at variable temperature and constant frequency

Using the test bed, the average impedance values for eight samples of pristine and weak state of target capacitors are monitored at different operating case temperature of 55 °C, 65 °C, 75 °C and 85 °C at constant frequency of 10 kHz. The test assembly consists of temperature controlled oven; digital thermometer; test bed with the electrolytic capacitor placed inside the oven with an temperature sensor glued on top of can and an DSO. The test assembly is shown in Fig. 5.

Using test bed, the ESR value at different temperature is obtained from the rms voltage and current waveforms that are acquired at every half hour interval. ESR variations with temperature for pristine and weak state of target capacitors at 10 kHz are shown in Table 3.