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Online Failure Prediction of the Aluminum Electrolytic Capacitor

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Abstract: ***The aim of this research is to present a simple online condition monitoring system to predict failure of the aluminum electrolytic capacitors used in the output LC filter of the switched mode DC–DC buck converters. Equivalent Series Resistance (ESR) is the best indicator of the failure of the aluminium electrolytic capacitors. The main idea of the proposed method is to monitor the ESR value and predict the failure of the aluminum electrolytic capacitor under operation in switched mode DC–DC buck converter. The proposed method provides a easy and direct way of online failure prediction of the aluminum electrolytic capacitor using a portable device with minimal hardware requirements .***

Keywords: DC-DC buck converter, Electrolytic capacitor, Equivalent series resistance, Failure prediction, Remaining useful life.

1. Introduction

Switched mode power converters has vast industrial applications. The trustworthiness of these power converters is dependent on the electronic components used. Aluminium electrolytic capacitors are one of the most common electronic components used in the switched mode DC-DC buck power converters [1]. Very high volumetric efficiency, low cost, large capacity, very large range of voltage and capacitance ratings, high energy storage and voltage regulation are the main features of aluminium electrolytic capacitors [2]. The limited useful life and high failure rate are the main drawbacks of electrolytic capacitors [3]. Unfortunately, aluminium electrolytic capacitors are responsible for more than 50% of the breakdowns of switched mode power converters [3]. Failure prediction of the electrolytic capacitors has immense importance and practical industrial applications [3].

A practical method of the online failure prediction of aluminum electrolytic capacitor is proposed in this paper. The proposed system is aimed to construct a portable device to predict the remaining useful life of the electrolytic capacitor. A switched mode DC-DC buck converter is constructed. A data acquisition system is used to sense the output voltage ripple of the LC filter and ripple current of the aluminum electrolytic capacitor. The sensed data is used to calculate ESR of the aluminum electrolytic capacitor. The ESR values are then analyzed to predict the failure of aluminum electrolytic capacitor.

2. Aluminum Electrolytic Capacitor

Modern, non-solid aluminum electrolytic capacitors are cylindrical and the structure is shown in Figure 1. An electrochemically etched aluminum anode foil forming the first plate of the capacitor [4]. An oxide layer on the etched aluminum foil that forms the dielectric. Dielectric is the layer of Al_2O_3[4]. A paper spacer impregnated with fluid electrolyte in contact with the oxide layer to form the second plate of the capacitor. A second foil that forms the other contact with the fluid electrolyte [4]. In non-solid aluminum capacitors, the fluid electrolyte forming the second plate of the capacitor penetrates the pores of the anode oxide layer to provide the maximum surface contact and, therefore, ensure high capacitance values [4]. The electrolytic capacitor features a very large foil surface and the very thin dielectric thickness [4]. The structure based equivalent circuit of the aluminum electrolytic capacitor can be realised as shown in Figure 2 [5]. The equivalent circuit of the aluminum electrolytic capacitor is approximated as a series combination of parasitic resistance called as ESR, parasitic inductance called as Equivalent Series Inductance (ESL) and capacitance (C).

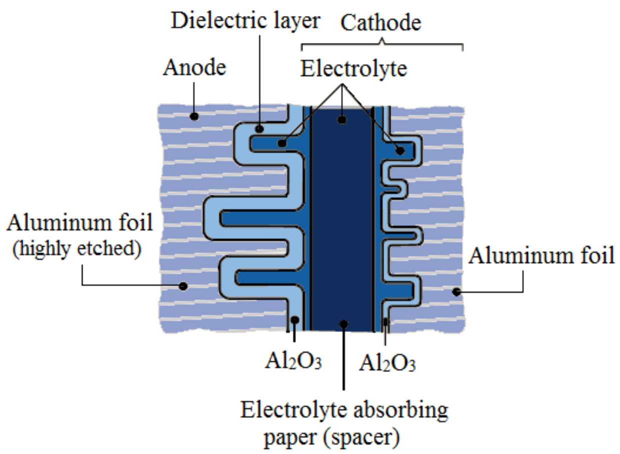

Figure 1: Structure of aluminum electrolytic capacitor [4].

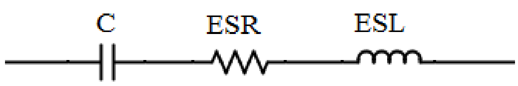

Figure 2 : Approximated equivalent circuit of the aluminum electrolytic capacitors [5].

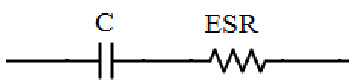

Figure 3: Simplified equivalent circuit of the aluminum electrolytic capacitors [5].

The effect of ESL can be considered as negligible. The simplified equivalent circuit of the aluminum electrolytic capacitor is then just a series combination of ESR and C as shown in Figure 3 [5]. Aluminium electrolytic capacitors have limited useful life period [5]. The electrolyte of the operating capacitor will be consumed and volume of electrolyte will decrease with the increase in working hours [6]. Short circuit and open circuit break down occurs in aluminium electrolytic capacitors due to the increase of leakage current and electrolyte vaporization. But the main reason for degradation of the aluminum electrolytic capacitor is the vaporization of electrolyte [7]. When the volume of electrolyte decreases, the value of ESR will increase and C will decrease. The increasing value of ESR will results in additional power loss, increasing internal temperature and accelerated evaporation of the electrolyte [7]. The electrolytic capacitor is considered as failed when its 40% of the electrolyte is consumed [6]. Previous researches have stated that when the 40% of the electrolyte is consumed then the ESR will become about 2.8 to 3 times of the initial value of ESR and capacitor is considered as failed [5]. Therefore, ESR is a good indicator for the failure of aluminum electrolytic capacitor [6].

3. Methodology

In DC-DC buck converters there is always a ripple current induced in the output of inductor as a result of inductor charging and discharging [2]. For high inductance value the inductor can be treated as a constant current source [6]. The inductor current I_L has two components, a dc current, I_{Ldc}, and an ac current, I_{Lac}, which can be expressed as in (1) [6].

$$I_L = I_{Ldc} + I_{Lac} \tag{1}$$

The aluminum electrolytic capacitor will act as an open circuit for dc source and only ac component of the inductor current will surge through the capacitor [6]. Inductor ac current and electrolytic capacitor ripple current I_C are considered as equal and given in (2) [1].

$$I_C = I_{Lac} \tag{2}$$

Capacitance value of the electrolytic capacitor used in the LC filter of switch mode DC-DC converter is greater than hundreds of microfarads for switching frequency higher than 20 kHz [6]. Ohmic losses in the electrolytic capacitor are responsible for the output voltage ripple (V_R). Therefore, the output voltage ripple can be determined as given in (3) [6].

$$V_R = ESR \times I_C \tag{3}$$

In this way output voltage ripple of the dc-dc buck converter is related to the ERS of the electrolytic capacitor. The ESR value must be smaller for a regulated output voltage. Failure of the electrolytic capacitor of a DC-DC converter will result in unregulated output and may lead to the failure of complete system dependent on the DC-DC buck converter [5].

The Block diagram of the proposed method is shown in Figure 4. A DC-DC converter with an LC filter is constructed. The initial value of the ESR is taken from datasheet of the electrolytic capacitor denoted as ESR_i. The output voltage ripple V_R and ripple current of the electrolytic capacitor I_C are sensed using data acquisition system. The present ESR value of the electrolytic capacitor is calculated using (3) and it is denoted as ESR_p. When ESR value becomes 2.8 to 3 times of ESR_i then electrolytic capacitor is considered as failed [5] and ESR value is denoted by ESR_f . ESR_f is calculated using (4).

$$ESR_f = 2.8 \cdot ESR_i \tag{4}$$

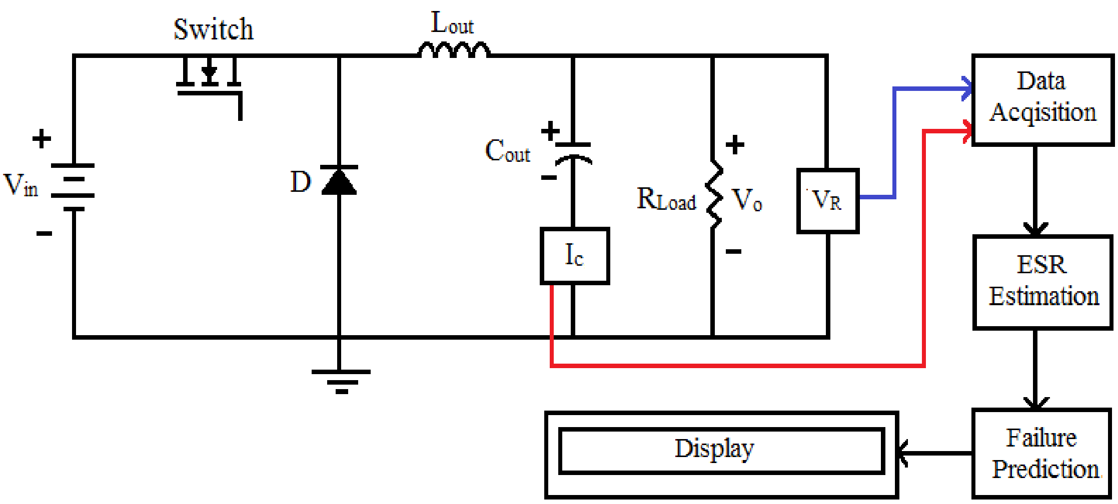

Figure 4: Block diagram of proposed method.

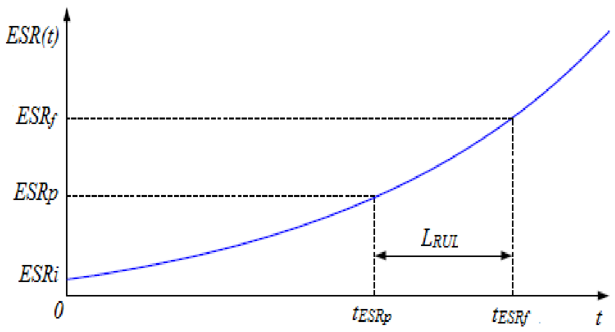

Figure 5: Exponential variation of the ESR value of electrolytic capacitor with respect to time [3].

There is a exponential relationship between ESR of the electrolytic capacitor and time (t) is as shown in Figure 5 and can be given in mathematical form as in (5) [3].

$$ESR(t) = \alpha \cdot \exp(\beta \cdot t) \tag{5}$$

The experimental parameters α and β are calculated with experimental data using the recursive least square fitting method. The remaining useful life (L_{RUL}) of the electrolytic capacitor can be calculated using following equations (6), (7) and (8) [3].

$$t_{ESRp} = \frac{1}{\beta}(\ln ESR_p - \ln \alpha) \tag{6}$$

$$t_{ESRf} = \frac{1}{\beta}(\ln ESR_f - \ln \alpha) \tag{7}$$

$$L_{RUL} = t_{ESRf} - t_{ESRp} \tag{8}$$

The predicted L_{RUL} of the electrolytic capacitor will be displayed on the screen. In this way failure prediction of the electrolytic capacitor is done. If an aged electrolytic capacitor is used then it will show higher ESR value and if that ESR value is greater than or equal to 2.8 times ESR_i then result will be displayed as FAILED.

4. Experimental Setup and Results

A DC-DC buck converter with an LC filter is constructed and specifications are mentioned in Table 1. A data acquisition system is constructed using dsPIC33FJ64GS406. dsPIC33FJ64GS406 has 10 bit ADC, high conversion rate and strong DSP engine. The aluminum electrolytic capacitor selected for the LC filter of DC-DC converter is C_{out} = 220 µF, 35 V, 85 °C [8]. The V_R and I_C of the electrolytic capacitor are acquired using data acquisition system. The acquired data of V_R and I_C is processed further to estimate the ESR value. The value of ESR is monitored for specific period to calculate experimental parameters α and β. After evaluating experimental parameters the present ESR value is acquired that is ESR_p.

ESR_p is used with the experimental parameters to calculate t_{ESRp} as in (6). ESR_f is calculated using ESR_i as mentioned in (4). ESR_f with the experimental parameters is applied in (7) to calculate t_{ESRf}. Finally L_{RUL} is calculated as stated in (8) and result is displayed on LCD. There is also provision of serial communication with personal computers for the purpose of data transfer.

The proposed method is employed to find L_{RUL} of the selected electrolytic capacitor and obtained experimental result is given in Table 2. Result is reasonable to validate the proposed method. Higher accuracy of online failure prediction of the electrolytic capacitors can be achieved under constant operating temperature.

Table 1: DC-DC buck converter specifications

Specification	*Symbol*	*value*
Input Voltage	V_{in}	48 V
Output Voltage	V_o	30 V
Output Current	I_{out}	2 *A*
Switching frequency	F_s	12.5 kHz
Output capacitor	C_{out}	220 µF
Output inductor	L_{out}	9 mH

Table 2: Experimental Result

Parameter	*value*
ESR_i	0.2Ω
ESR_f	0.56Ω
ESR_p	0.31Ω
L_{RUL}	54583.4Hrs

5. Conclusion

The aluminum electrolytic capacitors features a limited useful life. Equivalent series resistance is the best indicator of the failure in aluminum electrolytic capacitors. The proposed method is implemented practically to predict the remaining useful life based on the equivalent series resistance of the electrolytic capacitor of an LC filter in the switched mode DC-DC buck converter. Results obtained is satisfactory and aiming towards more research in this field.

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