

Full Length Research Paper

Deterioration analysis of aluminum electrolytic capacitor for DC-DC converter

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Aluminum electrolytic capacitor is one of the key components that restrict the life of DC-DC converter. Studying its deterioration analysis has advanced to realizing the prognostics and health management (PHM) technology of DC-DC converter. The main deterioration modes of aluminum electrolytic capacitor include the capacitance decrease and the equivalent series resistance (ESR) increases. These cause the ripple voltage to increase and eventually lead to the DC-DC converter failure. Some parameters of DC-DC converter (such as the ripple voltage, the ripple current, etc.) are selected as the feature signals of the aluminum electrolytic capacitor deterioration. By monitoring the changes of the feature signals, the aluminum electrolytic capacitor deterioration degree can be measured indirectly. Through theoretical analysis, this paper proposed a new idea to predict the remaining useful life (RUL) of DC-DC converter, that is, establishing the curve of the ripple voltage as the aluminum electrolytic capacitor deterioration and setting a warning point in the curve. When the change rate of the ripple voltage reached the warning point, the life of the DC-DC converter will come to an end. So, the RUL of the DC-DC converter can be predicted. In this paper, the buck converter is verified by simulation and physical experiments amid good agreements with the theory.

Key words: Aluminum electrolytic capacitor, DC-DC converter, deterioration, capacitance, equivalent series resistance (ESR), ripple voltage, remaining useful life (RUL), prognostics and health management (PHM).

INTRODUCTION

The modern DC-DC converter has some good characteristics, such as small size, light weight, low power, high efficiency, small ripple, low noise, easy expansion, higher level of intelligence, etc (Meng, 2009; Cai, 2000). It has been widely used in electronics, telecommunications, electrical equipment, control equipment and other areas. As a core power converter, the DC-DC converter's performances directly affect the technical indicators and reliability of power electronic products. With the rapid development of science and technology, the DC-DC converter has some advanced requirements of small and high efficiency that make the working environment of the DC-DC converter to deteriorate. Nonetheless, how to ensure and enhance the reliability of the DC-DC converter, which works in harsh environments, has become a key

technology.

Aluminum electrolytic capacitor is one of the important components of DC-DC converter. It is mainly used in the output filter circuit with the role of energy storage and filtering (Yan et al., 2008). Due to its characteristics, such as poor stability and low reliability, its life is often the weak link in DC-DC converter. So, it determines the life of DC-DC converter. When the deterioration (the capacitance decrease and the ESR increase) of aluminum electrolytic capacitor occurs, the ripple voltage of DC-DC converter will be increased. Eventually, this leads to the failure of DC-DC converter. According to statistics, aluminum electrolytic capacitor occupies about 60% failure rate in the DC-DC converter failure (Pang et al., 2010). Therefore, study on aluminum electrolytic capacitor failure mechanism helps to enhance the reliability of the DC-DC converter, and it is necessary that the Prognostics and Health Management (PHM) of DC-DC converter should be realized. There is more

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Table 1. The failure mechanism of aluminum electrolytic capacitor.

Failure mode	Failure phenomenon	The usage reasons	The manufacturing reasons
Open circuit	Lead and aluminum foil contacts are not fully corroded.	Lead suffered the external stress anomaly, the use of binder, the use of coating agent.	Lead and aluminum foil, bad riveting, mechanical stress imposed.
Short circuit	The insulation effect of oxide film and electrolytic paper was damaged.	Lead suffered the external stress anomaly, higher temperature, long-term use, over-voltage applied, etc.	Attachment of metal particles, glitch on aluminum foil and wire.
The capacitance decrease	Electrolyte dry, the capacitance of anode foil and cathode foil decrease.	Over-voltage applied, larger ripple current, charge and discharge frequently, higher temperature, long-term use, etc.	The capacity of electrolyte is inadequate.
The ESR increase	Internal temperature increases.	Over-voltage applied, larger ripple current, charge and discharge frequently, higher temperature, long-term use, etc.	/

in-depth study about the failure of aluminum electrolytic capacitor, such as the early failure, the failure mode and failure mechanism in the process of using the deterioration course. Considering the impact of the parameters of working environment (such as temperature, voltage, current, frequency, etc.), some papers analyzed the impact of the main parameters of aluminum electrolytic capacitor (such as capacitance, loss angle, leakage current, ripple current, etc.) on its life (Wang et al., 2009; Zhang, 1999; Ji, 2002). For the failure mechanism about the main failure mode of aluminum electrolytic capacitor, the paper (Wang, 2002) made some studies with the method of physical analysis. Some papers discussed the deterioration of aluminum electrolytic capacitor, caused by ESR. The temperature and frequency characteristics have been given in Yaow et al. (2005), Amine et al. (1998), Amaral et al. (2004) and Chetan et al. (2010). Based on the previous studies, this paper derived the relationship between the deterioration of aluminum electrolytic capacitor and the ripple voltage from the principle, and verified the results by specific simulation and physical experiments. We have found the feature signals of aluminum electrolytic capacitor deterioration, and used the signals to monitor the DC-DC converter. Finally, this paper proposed a new idea of predicting the remaining useful life (RUL) of DC-DC converter.

Firstly, this paper describes the main deterioration modes of aluminum electrolytic capacitor, such as the capacitance decrease and ESR increase. Secondly, this paper derives the relationship between the aluminum electrolytic capacitor deterioration and the ripple voltage from the principle, and finds the feature signals of aluminum electrolytic capacitor deterioration. Finally, using MATLAB, this paper implements some simulation experiments for two deterioration modes, and carries out some physical experiments for the ESR deterioration. By

these experiments, we have verified the theoretical result, and proposed a new idea of predicting the RUL of the DC-DC converter.

THE MAIN DETERIORATION MODES OF ALUMINUM ELECTROLYTIC CAPACITOR IN DC-DC CONVERTER

DC-DC converter consists of some reactive components (such as inductor, capacitor, transformer, etc.) and some electronic components (such as MOSFET, diode, etc.) working in the switching mode (Zhang, 2009). It is the core part of modern power electronics, and its quality and reliability directly affect the reliability of power electronics. The main failure mode of DC-DC converter is function failure, and it is characterised as no output voltage, loss of protection, enhanced electrical performance, unable to drive load, etc (Dimitry et al., 2009). The main failure mechanisms are device failure, design defects, functional degradation, etc (Yao, 2005). In DC-DC converter, aluminum electrolytic capacitor is the most prone to failure. Once the aluminum electrolytic capacitor fails, this will lead to the failure of the DC-DC converter.

The main failure modes of aluminum electrolytic capacitor include open circuit, short circuit, capacitance decrease, ESR increase, etc. Table 1 lists the failure phenomenon, manufacturing reasons and usage reasons for each of the failure modes. From Table 1, we can see that over-voltage, high working temperature and longer time of use are the main reasons that caused the failure of aluminum electrolytic capacitor.

Open circuit and short circuit failures belong to the catastrophic failure, and they can be avoided through the aging test in the production process (Ji, 2002). While in the process of usage, the aluminum electrolytic capacitor deterioration is the most frequent failure mode, such as the capacitance decrease and the ESR increase.

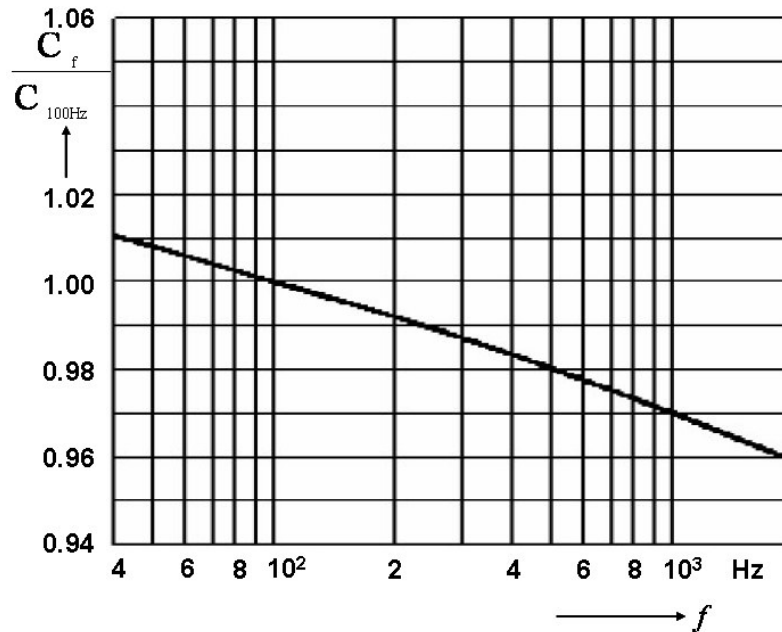


Figure 1. The frequency characteristic of capacitance.

Deterioration failure is determined by the physical properties of the constituent materials from aluminum electrolytic capacitor. It is inevitable, but some detection methods can effectively show some warning.

The capacitance decrease

Capacitance refers to the charge reserves under the given potential difference, with the temperature and frequency (Ji, 2002). Four out of the main reasons caused the capacitance to decrease:

- (1) In the process of usage, the electrochemical reaction that takes place internally in the aluminum electrolytic capacitor has a restorative role to dielectric oxide film. This made the oxide film to be thickened and uneven. Then, the results are the performance of the electrolytic capacitor degradation and the capacitance decrease (Ma and Wang, 2005).
- (2) If the long-term aluminum electrolytic capacitor is used at high temperature, the electrolyte will be evaporated. Besides, the large gases that were generated between the positive and negative capacitance accelerated the evaporation of the electrolyte. All of these made the capacitance to decrease.
- (3) In the high-frequency DC-DC converter, the effective capacitance of the aluminum electrolytic capacitor decreased as the frequency increased. The frequency characteristic of the capacitance is shown in Figure 1 (Zhao, 2010).
- (4) When over-voltage is applied, the leakage current will

increase. This causes an increase in the internal temperature and a decrease in the capacitance. When the capacitance dropped to 20% of the initial value, we believe that the life of aluminum electrolytic capacitors has ended (Ning et al., 2004).

The ESR increase

ESR is one of the major factors that caused recession in the life of the electrolytic capacitor. It is relevant to capacitance, rated voltage, frequency, temperature and other factors, and it is mainly affected by temperature and frequency. There are some main reasons that caused the ESR increase:

- (a) The viscosity of electrolyte is increasing as the capacitance decrease, and this made the ESR to increase.
- (b) The electrolytic capacitor temperature increased due to the ripple current on the ESR, which produced a lot of heat loss. This exacerbates the capacitance decrease. So, the bad cycle and the ESR increase are rapid and this accelerates the failure of the aluminum electrolytic capacitor. Formula (1) on the ESR is given in Amine (1998), Chetan (2009) and Chen and Zhang (2007). Thus, the impact of temperature on ESR is greater.
- (c) When the aluminum electrolytic capacitor works in a cold environment, the viscosity of the electrolyte is too large that the ESR increase becomes transient. The temperature characteristic of ESR is displayed in Figure 2. From Figure 2, we can see that, at low temperature, the

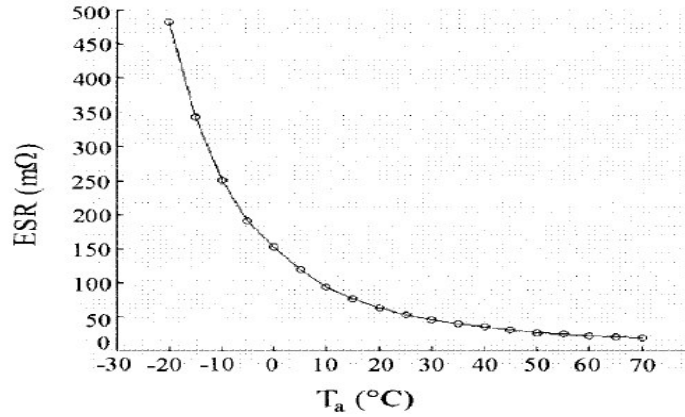


Figure 2. The temperature characteristic of ESR.

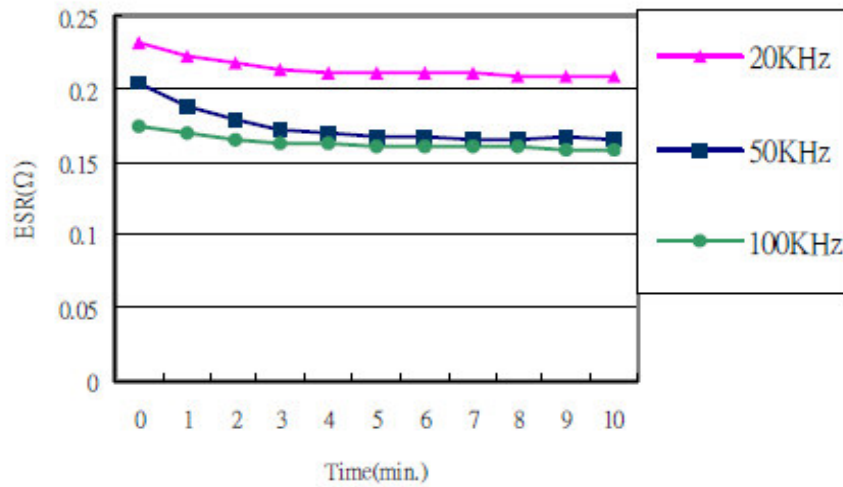


Figure 3. The frequency characteristic of ESR.

DC-DC converter must be accompanied by some heating measures to ensure that the aluminum electrolytic capacitor work normally.

(d) The modern DC-DC converter continues to increase the operating frequency for high efficiency and then generates a richer high-order harmonic frequency. Therefore, aluminum electrolytic capacitor is required to have a good filtering performance. So, in modern DC-DC converter, the standard that measured the quality of aluminum electrolytic capacitor is not the capacitance, but its impedance frequency characteristic. From the equivalent impedance model of the aluminum electrolytic capacitor (2), we can see that ESR is the main component of the equivalent impedance of aluminum electrolytic capacitor. In order to make the aluminum electrolytic capacitor have a low impedance characteristic at high frequency, its ESR must be reduced. The frequency characteristic of ESR is shown in Figure 3. At high frequency, the ESR decreases, but the ESR would be

caused to increase when the temperature increases, because of the high-frequency harmonics and long-term use. So, at high frequency, the ESR increase is the main reason that caused the aluminum electrolytic capacitor to fail.

$$\frac{1}{ESR(t)} = \frac{1}{ESR(0)} \cdot (1 - k \cdot t \cdot \exp(-\frac{4700}{T + 273})) \tag{1}$$

$$Z = R_{esr} + j\omega L_{esl} - \frac{j}{\omega C} \tag{2}$$

THE PRINCIPLE OF THE IMPACT OF ALUMINUM ELECTROLYTIC CAPACITOR ON DC-DC CONVERTER

According to the aforementioned analysis, the main

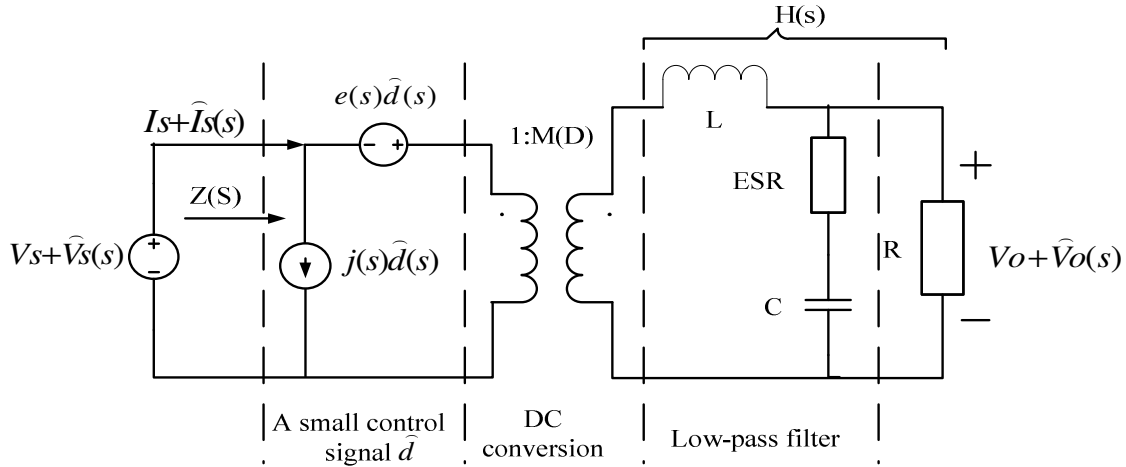


Figure 4. The standard small-signal AC model of the basic converters in CCM.

deterioration modes of aluminum electrolytic capacitor are the capacitance decrease and the ESR increase. The result of the deterioration is that the ripple voltage increases. When the deterioration of aluminum electrolytic capacitor develops to a certain extent, the ripple voltage will exceed the specified maximum allowable range. This means that the DC-DC converter will fail. The paper (Gan and Li, 2007) gave Formula (3) as the ripple voltage in a continuous current mode (CCM). From Formula (3), it can be obtained that, the capacitance and ESR have a certain influence on the ripple voltage, but this formula only applies to Buck converter, and does not have a universal significance. This paper will focus on the standard small-signal circuit mode of DC-DC converter in CCM, and analyze the impact of the aluminum electrolytic capacitor deterioration on the ripple voltage from the view of the system transfer function.

$$\widehat{u}_o = \frac{U\alpha(1-M)TsRe_q + 2U\alpha(1-D)TsLe_q}{2L} + \frac{U\alpha(1-M)Ts^2}{8LC} \quad (3)$$

Although the converter has a variety of different structures and parameters, this research suggests that, for the basic converters (such as Buck, Boost, etc.), they have the same structure with the view of a small signal and equivalent circuit. So, the small-signal AC models of the basic converters can be unified into a standard form, as shown in Figure 4 (Zhang and Cai, 1998; Chen, 2009),

where the voltage source, $e(s)\widehat{d}(s)$, and the current source, $j(s)\widehat{d}(s)$, are used to simulate the role of the small signal, $\widehat{d}(t)$, related to the control variable, $d(t)$ (Chen, 2009). The $e(s)$ and $j(s)$ can be calculated by the four converter transfer functions, such as $\widehat{I}_s(s)$

transfer function of $\widehat{V}_s(s)$, $\widehat{I}_s(s)$ transfer function of $\widehat{d}(s)$, $\widehat{V}_o(s)$ transfer function of $\widehat{V}_s(s)$ and $\widehat{V}_o(s)$ transfer function of $\widehat{d}(s)$.

We think that the DC component is zero for all variables in the standard model, and so, we only discuss the dynamic characteristic of the AC small signal. We can obtain Formula (4) by analyzing Figure 4.

$$\widehat{V}_o(s) = [M(D)\widehat{V}_s(s) + M(D)e(s)\widehat{d}(s)]H(s) \quad (4)$$

This paper does not consider the roles of the AC small signals, \widehat{V}_s and \widehat{d} , and this means that $M(D)\widehat{V}_s(s)$ and $M(D)e(s)\widehat{d}(s)$ are a constant value. Hence, Formula (4) is simplified by introducing the new variables as $G1 = M(D)\widehat{V}_s(s)$ and $G2 = M(D)e(s)\widehat{d}(s)$, and then Formula (4) becomes

$$\widehat{V}_o(s) = [G1 + G2]H(s) \quad (5)$$

Where, $H(s)$ is the transfer function of the output low-pass filter. When the aluminum electrolytic capacitor is seen as the ideal device (not considering the ESR), it can be expressed as:

$$H(s) = \frac{R \parallel \frac{1}{sC}}{sL + R \parallel \frac{1}{sC}} = \frac{R}{s^2RLC + sL + R} \quad (6)$$

So, Formula (5) becomes:

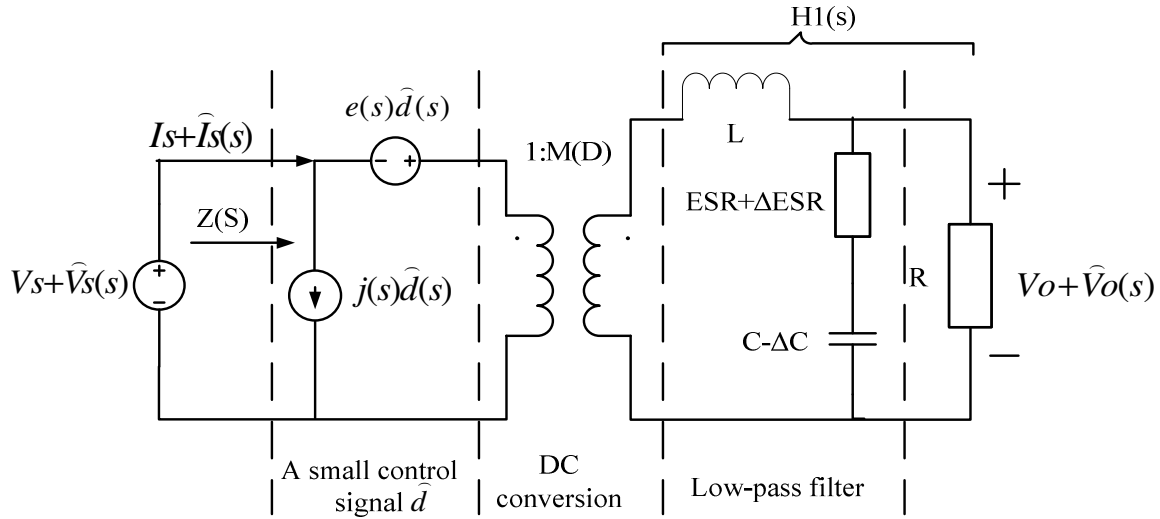


Figure 5. The standard small-signal AC model when the aluminum electrolytic capacitor deterioration occurs.

$$\widehat{V}_o(s) = [G_1 + G_2] \cdot \frac{R}{s^2 RLC + sL + R} \quad (7)$$

When the aluminum electrolytic capacitor is seen as the non-ideal device (considering the ESR), it can be expressed as:

$$H(s) = \frac{R // (ESR + \frac{1}{sC})}{sL + R // (ESR + \frac{1}{sC})} = \frac{R(1 + sC \cdot ESR)}{s^2(RLC + LC \cdot ESR) + s(L + RC \cdot ESR) + R} \quad (8)$$

So, Formula (5) becomes:

$$\widehat{V}_o(s) = [G_1 + G_2] \cdot \frac{R(1 + sC \cdot ESR)}{s^2(RLC + LC \cdot ESR) + s(L + RC \cdot ESR) + R} \quad (9)$$

Comparing Formulas (7) and (9), the converter system adds a high-frequency zero due to ESR, and reduces the pole frequency. The zero changes the high frequency performance, weakens the anti-jamming capability, and increases the ripple voltage. The pole frequency decrease although improves the dynamic performance of the system, but increases the adjustment time and reduces the system response speed. So, when the aluminum electrolytic capacitor deterioration takes place, the ripple voltage will increase, as the capacitance decreases and the ESR increases. Figure 5 shows the standard small-signal AC model when the aluminum electrolytic capacitor deterioration occurs, where ΔESR is the increment of ESR and ΔC is the decrement of capacitance. Now, the transfer function, H1(s), of the low-pass filter can be expressed as:

$$H1(s) = \frac{R // (ESR + \Delta ESR + \frac{1}{s(C - \Delta C)})}{sL + R // (ESR + \Delta ESR + \frac{1}{s(C - \Delta C)})} = \frac{R(1 + sC \cdot ESR + sRC \cdot \Delta ESR - \Delta C \cdot ESR - \Delta C \cdot \Delta ESR)}{s^2(RLC + LC \cdot ESR + s(L + RC \cdot ESR) + R + s^2[LC \cdot \Delta ESR - \Delta C \cdot (R + ESR) - \Delta C \cdot \Delta ESR] + sRC \cdot \Delta ESR - \Delta C \cdot ESR)} \quad (10)$$

Ignoring the impact of ΔC·ΔESR, Formula (10) can be simplified as:

$$H1(s) = \frac{R(1 + s(C \cdot ESR + C \cdot \Delta ESR - \Delta C \cdot ESR))}{s^2\{(RLC + LC \cdot ESR + [LC \cdot \Delta ESR - \Delta C \cdot (R + ESR)] + s(L + RC \cdot ESR + RC \cdot \Delta ESR - \Delta C \cdot ESR)\} + R} \quad (11)$$

When Formula (11) was compared with Formula (9), due to the ESR increase, the distance between the zero and imaginary axis decreased. Therefore, the overshoot of the system increases. This leads to the significant increase of the ripple voltage. In addition, the capacitance decreases the dynamic performance of the system better, but at the same time, it deduces the filter performance and makes the ripple voltage to increase. Generally considering the capacitance, the impact of ESR on the ripple voltage is greater than the impact of capacitance. This is consistent with Formula (3). This shows that the conclusions of the two methods are the same.

Comparing Formulas (9) and (11), H1(s) can be expressed as:

$$H1(s) = H(s) + \Delta H(s) \quad (12)$$

Where, ΔH(s) is expressed as:

$$\Delta H(s) = \frac{[s^2(RLC + LC \cdot ESR) + sL + R] \cdot [sR(C \cdot \Delta ESR - \Delta C \cdot ESR)]}{s^2(RLC + LC \cdot ESR) + s(L + RC \cdot ESR) + R + s^2[LC \cdot \Delta ESR - \Delta C \cdot (R + ESR)] + sRC \cdot \Delta ESR - \Delta C \cdot ESR} \cdot \frac{1}{[s^2(RLC + LC \cdot ESR) + s(L + RC \cdot ESR) + R]} \quad (13)$$

Then, the ripple voltage can be shown as:

$$\widehat{V}_o(s) = [G_1 + G_2]H1(s) = [G_1 + G_2]H(s) + [G_1 + G_2]\Delta H(s) \quad (14)$$

Using the time-domain differential characteristic of

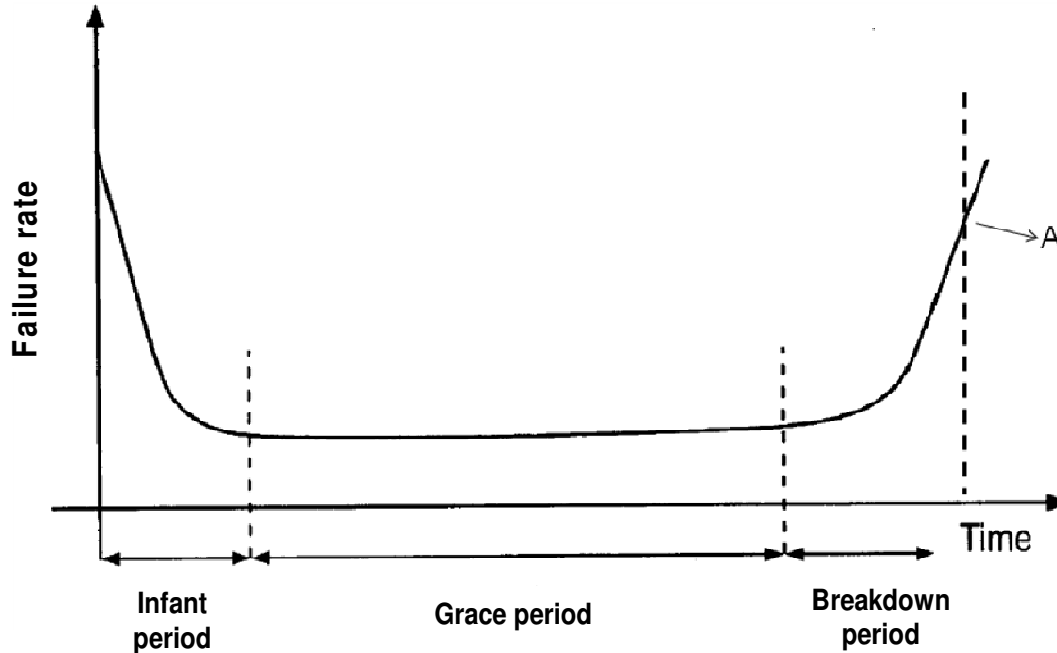


Figure 6. The life curve of the DC-DC converter.

Laplace transform, as shown in Formula (15), the derivatives of Formula (14) are taken on both sides, as displayed in Formula (16). Thus, the curve of the ripple voltage can be obtained with the aluminum electrolytic capacitor gradual deterioration. The curve is similar to the bathtub curve, as shown in Figure 6 (United States Patent No. US 2008/0036487 A1; Jason et al., 2006). Set a

warning point A in the curve, so that when $L^{-1}[s\widehat{V}o(s)]$ reached the warning point, it means that the life of the DC-DC converter will come to an end. Using this method, we can predict the RUL of the DC-DC converter as:

$$L\left[\frac{d(f(t))}{dt}\right] = sF(s) - f(0) \tag{15}$$

$$L^{-1}[s\widehat{V}o(s)] = [G1 + G2]L^{-1}[s\Delta H(s)]$$

$$\frac{d(\widehat{V}o(t))}{dt} = [G1 + G2] \frac{d(\Delta H(t))}{dt} \tag{16}$$

THE FEATURE SIGNALS OF ALUMINUM ELECTROLYTIC CAPACITOR DETERIORATION

The aluminum electrolytic capacitor deterioration can not be directly measured, but can be indirectly measured by monitoring the changes in the output signals of the DC-DC converter. From Formula (12), we can know that, the capacitance and ESR have a certain effect on the ripple voltage. When the capacitance and ESR change,

the ripple voltage must change. However, the change of the ripple voltage should be monitored and the relationship between the ripple voltage and the aluminum electrolytic capacitor deterioration should be established, when the aforementioned two deterioration models are injected respectively into the DC-DC converter.

Buck (step-down) converter is one of the most basic topology in DC-DC converter. We take it as the object of study, generating a simulation model in MATLAB (2008a), as displayed in Figure 7. For the two deterioration modes, the simulation experiments were done. In the simulation circuit, the parameters are set as follows: input voltage VDC = 30 V, initial capacitor value C = 150 μF, inductance L = 75 μH, load R = 3 Ω, the initial ESR value ESR = 1 mΩ, switching frequency F = 25 KHz, and duty cycle D = 0.5; while in the buffer circuit, switches L and C are 0.5 and 2 μF, respectively.

The simulation experiments about the capacitance decrease

Set the initial value of aluminum electrolytic capacitor as 150 μF, and set the ESR as 1 mΩ (taking the aluminum electrolytic capacitor as the ideal component, and the ESR as almost non-existent). Reduce the capacitance to the initial value of 80, 60, 40 and 20%, respectively and carry out the simulation experiments. Figure 8 shows the response curve of the output voltage, and Figure 9 shows the response curve of the inductor current. From the two curves, it can be seen that as the capacitance decrease, the ripple voltage and the volatility of inductor current

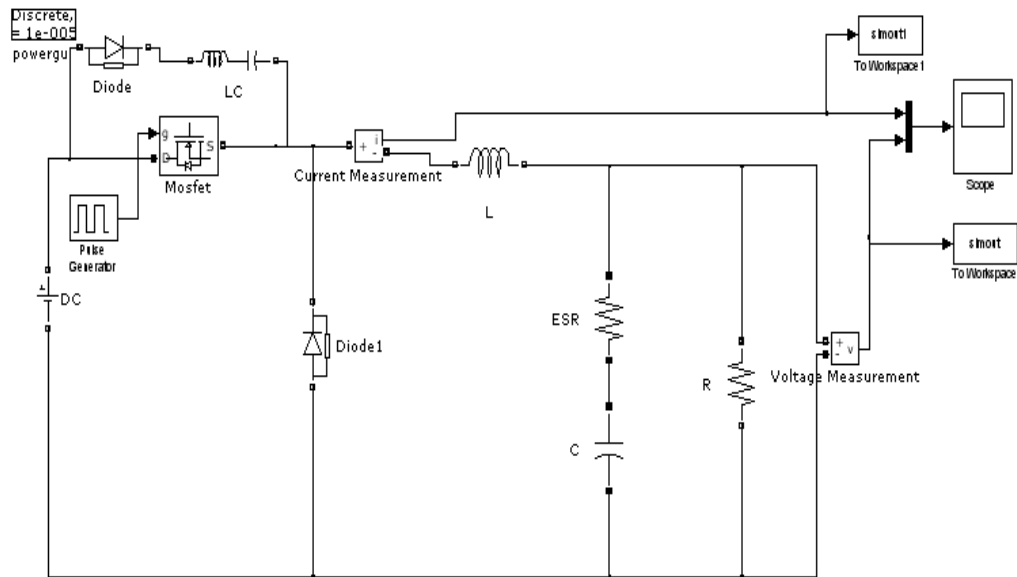


Figure 7. The simulation model of buck converter.

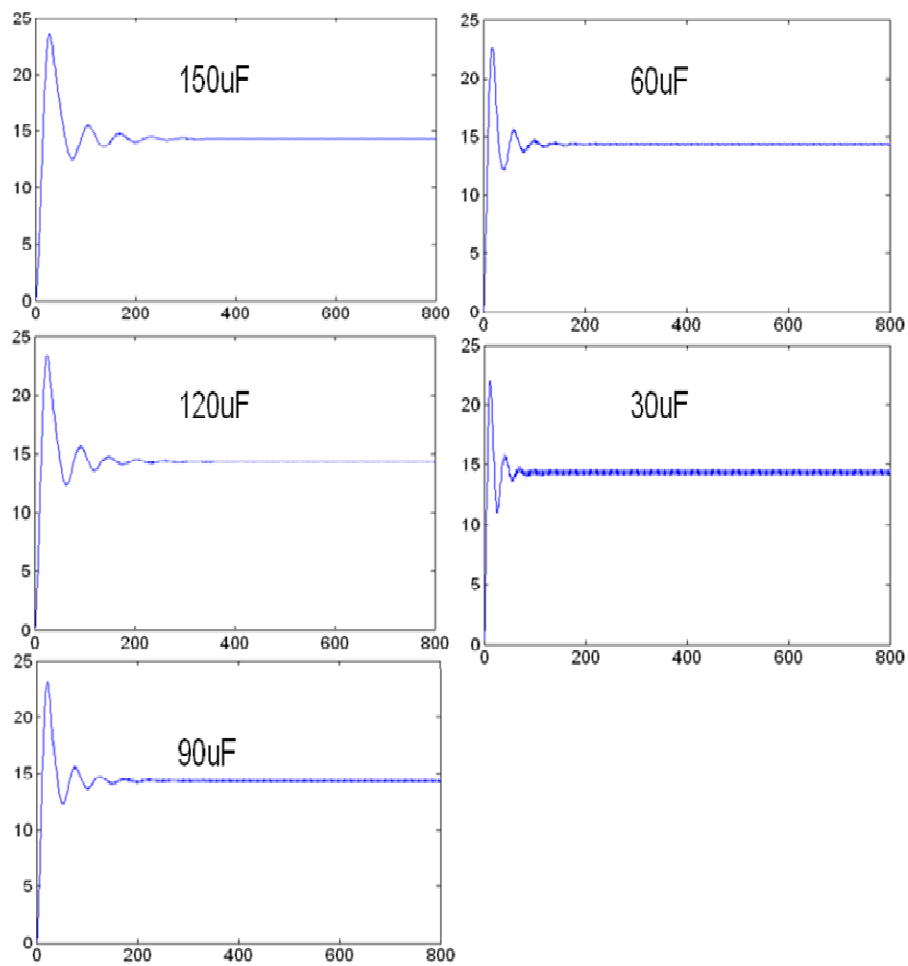


Figure 8. The response curve of output voltage when the capacitance decreases.

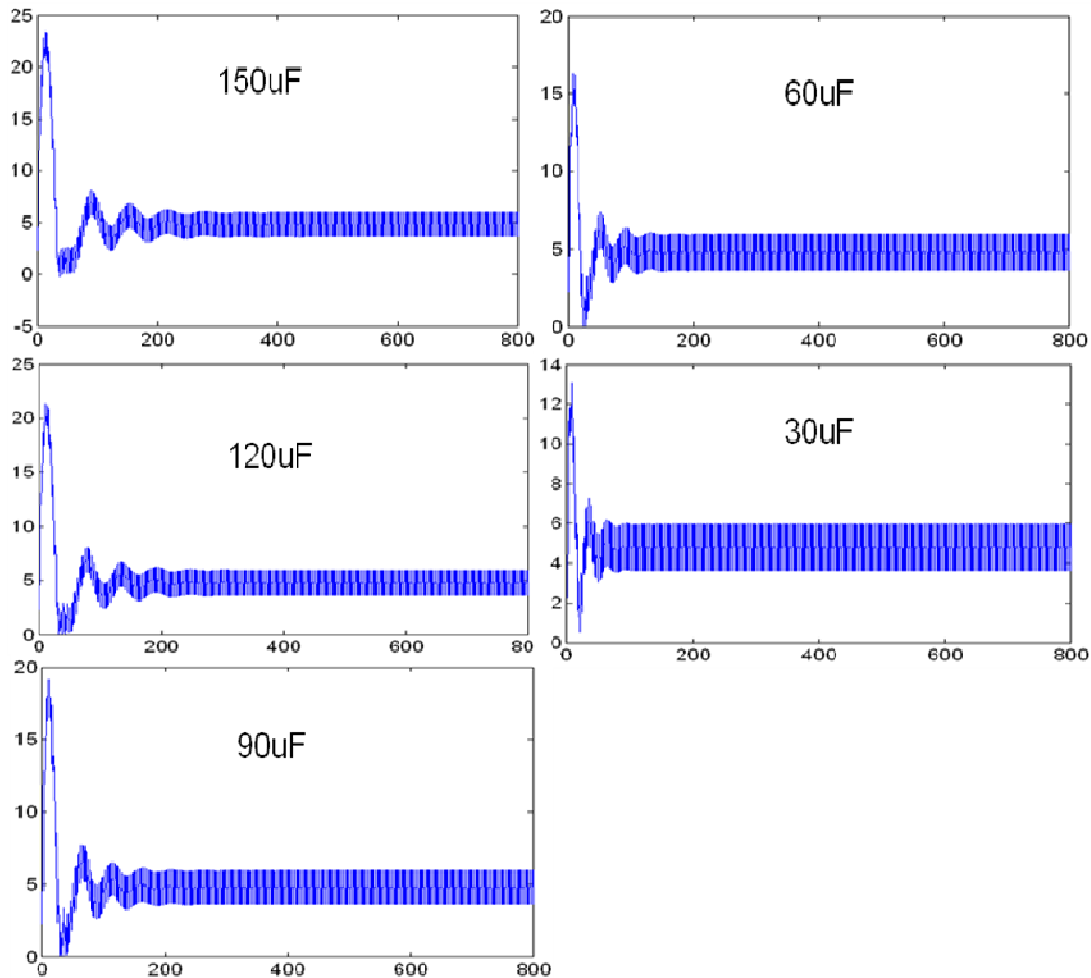


Figure 9. The response curve of inductor current when the capacitance decreases.

increase, but the DC output voltage did not almost change. When the capacitance fell to 20% of the initial value, the ripple voltage was significantly larger, and then the converter was unstable. This means that the converter failed.

The simulation experiments about the ESR increase

Set the value of aluminum electrolytic capacitor as 150 μF and the initial value of ESR as 50 $\text{m}\Omega$, and increase the value of ESR twice. For the different ESR values, implement the simulation experiments. Figure 10 shows the response curve of the output voltage, and Figure 11 shows the response curve of the inductor current. It can be seen that as the ESR increase, the ripple voltage and the volatility of the inductor current increase, but the DC output voltage did not almost change. When the value of ESR is 1600 $\text{m}\Omega$, the ripple voltage approaches 2V; then, the converter completely fails. As such, it can not work normally.

From the results of the aforementioned simulation

experiments, it can be seen that, when the aluminum electrolytic capacitor deterioration occurs, the output signals of the DC-DC converter will change. Thus, we can regard the ripple voltage and the ripple current as the feature signals of the aluminum electrolytic capacitor deterioration. By monitoring the changes in the ripple voltage or the ripple current, we can measure the degree of the aluminum electrolytic capacitor deterioration.

THE VERIFICATION INSTANCE

Build the test platform and verify the simulation results about the ESR increase failure. As shown in Figure 12, the test system consists of a converter (whose specifications are for the DC-DC 5V/2A 10W), a Tektronix oscilloscope DPO7254, a power supply, a relay controller PCI2307 and a experiment board used to simulate the process of the aluminum electrolytic capacitor deterioration.

In the aluminum electrolytic capacitor, connect the

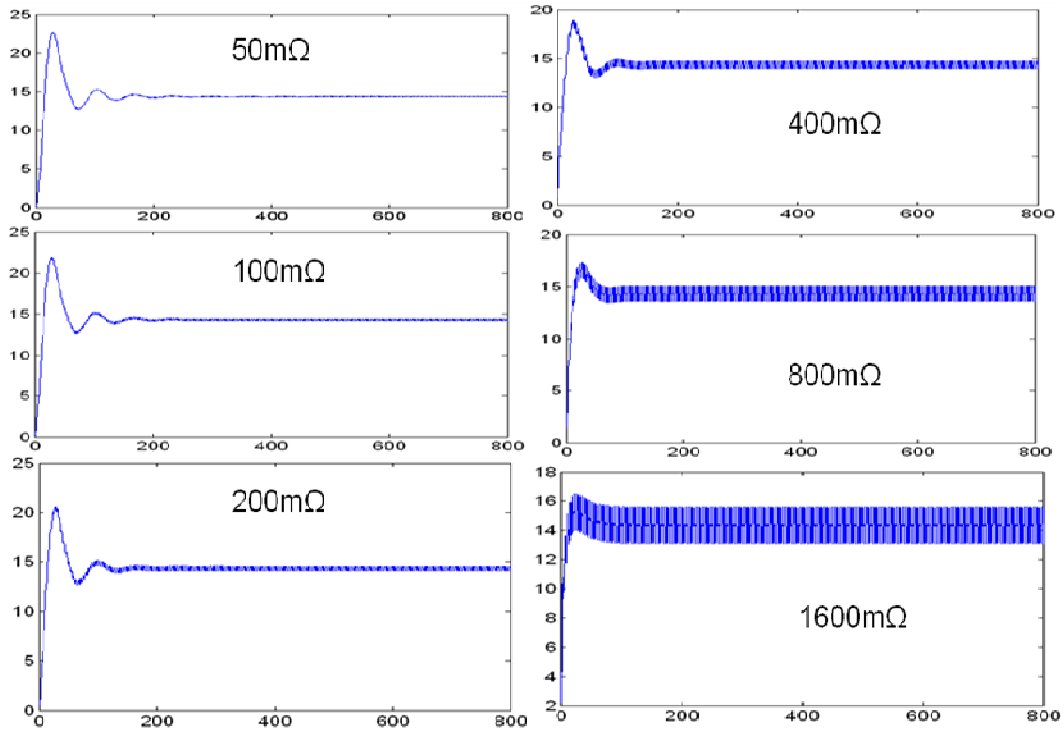


Figure 10. The response curve of output voltage when the ESR increases.

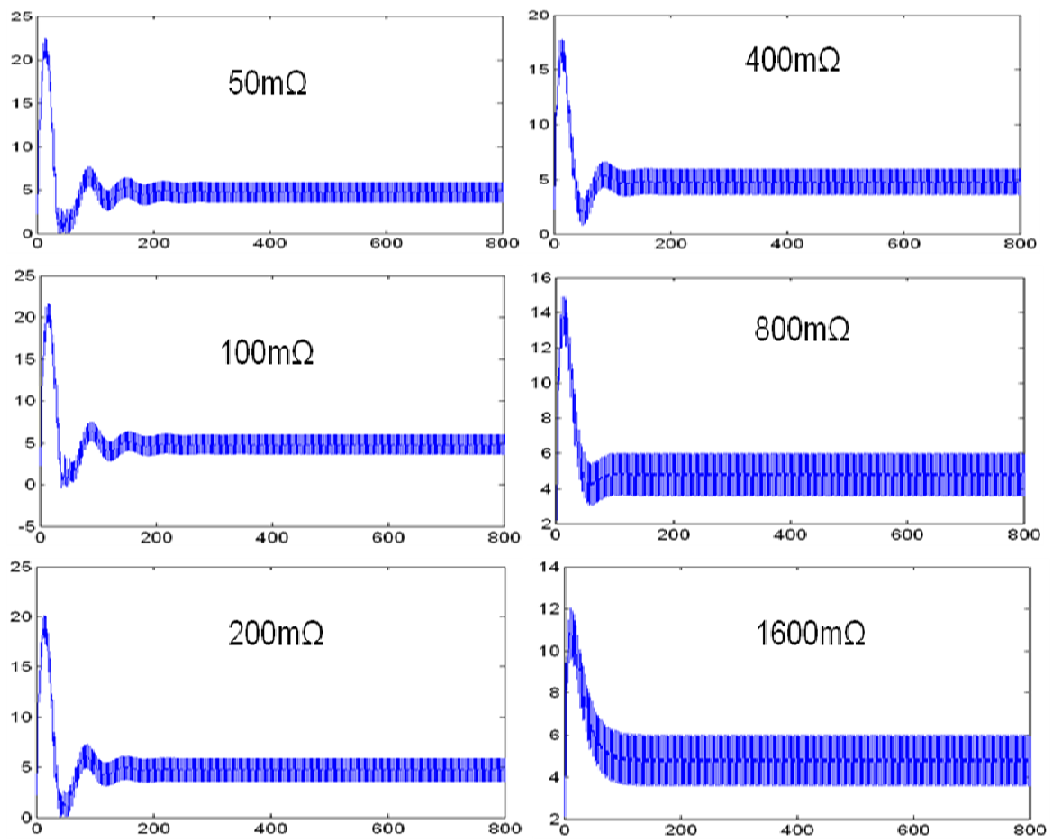


Figure 11. The response curve of inductor current when the ESR increases.

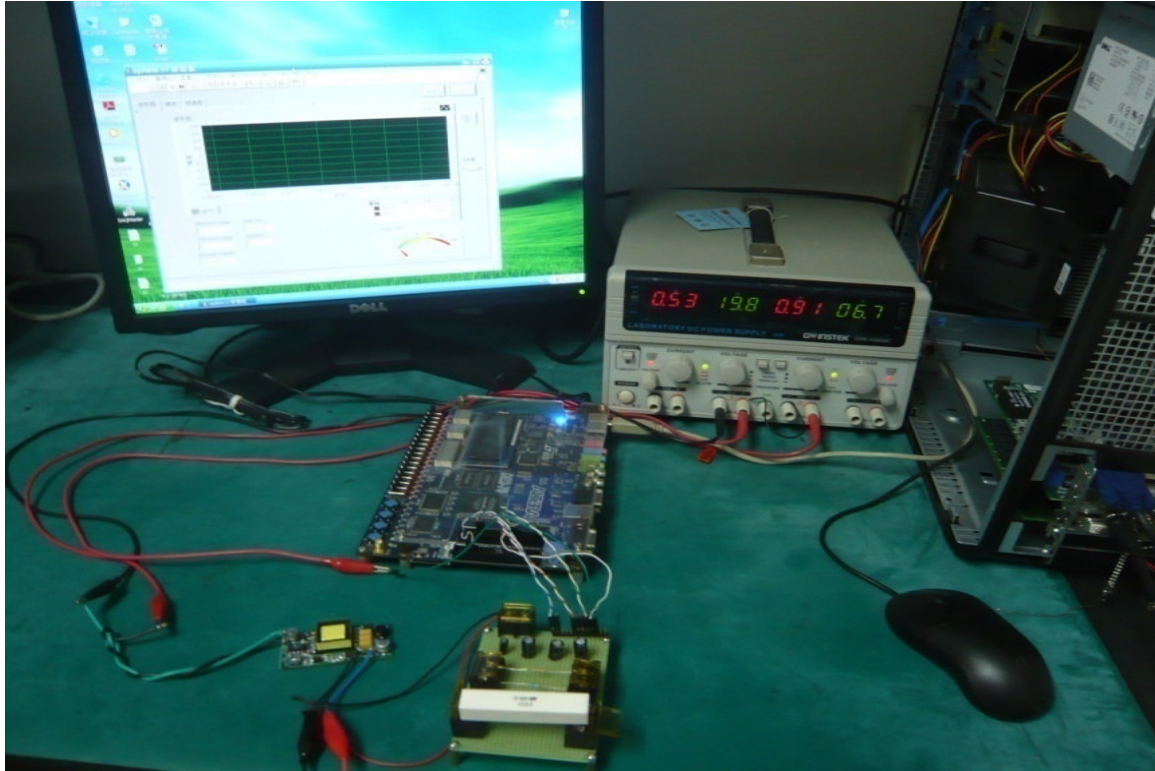


Figure 12. The test system.

series to the resistance, with the initial value of 20 m Ω , and gradually increase the ESR value to 100 m Ω . For the different ESR values, respectively measure the ripple voltage of the converter, and calculate the peak-peak value of the ripple voltage. The results are shown in Table 2. From the results, we can see that the ripple voltage obviously increases as the ESR increases. By comparing it with the simulation results, it can be seen that the test results are basically consistent with the simulation results. Thus, the conclusions of simulation experiments are verified.

CONCLUSIONS

The simulation and test results indicate that the capacitance decrease and the ESR increase can cause the ripple voltage to increase. That is, the result of the aluminum electrolytic capacitor deterioration caused the ripple voltage to increase. This is consistent with Formula (12). Therefore, the principal conclusions have been verified. The ripple voltage and the ripple current are regarded as the feature signals of the aluminum electrolytic capacitor deterioration. By monitoring the changes in the feature signals, we can indirectly measure the degree of the aluminum electrolytic capacitor deterioration.

When the aluminum electrolytic capacitor deterioration

Table 2. The ripple voltage value when the ESR increases.

ESR (m Ω)	Ripple voltage (V)
20	0.03
40	0.08
60	0.21
80	0.35
100	0.54

occurs, the DC output voltage does not change significantly, but this does not mean that the DC-DC converter is still in the healthy state. In DC-DC converter, the ripple voltage has a certain range of requirement. So, when the ripple voltage exceeds the specified range, the DC-DC converter fails. Therefore, the aluminum electrolytic capacitor deterioration finally leads the DC-DC converter into failure. Through setting up a warning point in the curve of the ripple voltage, with the aluminum electrolytic capacitor gradual deterioration, we can predict the RUL of the DC-DC converter. This established the foundation for realizing the PHM technology of the DC-DC converter. The future work, as regards this study, is considering the effect of the environment in obtaining the exact curve of the ripple voltage with the aluminum electrolytic capacitor deterioration by a large number of physical experiments. The aim is to enable the study

predict, more accurately, the RUL of the DC-DC converter.

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