Effect of Electrolytic Capacitors on the Life of SMPS

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Abstract

Aluminum electrolytic capacitors have higher failure rates than other components in Switch Mode Power Supply (SMPS). Degraded Aluminum electrolytic capacitors seriously affect the performance and health of the SMPS, and accelerate the life of SMPS to end. In order to realize the Prognostics and Health Management (PHM) of SMPS, the relationship between Aluminum electrolytic capacitors and the life of SMPS should be established. Firstly, this paper found the key parameters affecting the health of SMPS by studying the various performance characteristics of Aluminum electrolytic capacitor, such as capacitance and equivalent series resistance (ESR). Secondly, this paper gave the relationships of ripple voltage and the key parameters of Aluminum electrolytic capacitors. That is, the ripple voltage increases with the capacitance decrease and the ripple voltage decreases with the ESR decrease. Finally, we have verified the results of simulation experiments by the specific physical experiments.

Keywords: *Prognostics and Health Management (PHM), Switch Mode Power Supply (SMPS), Aluminum Electrolytic Capacitors, Capacitance, ESR, Ripple Voltage*

1. Introduction

With the rapid development of science and technology, the integration and complexity of electronic systems increase, and the working environment is increasingly severe[1][2]. How to ensure and enhance the reliability of electronic systems which works in the harsh environments has becoming a key technology. Power system is a main component of electronic systems, which restricts the reliability of electronic systems and directly affects the working status of the entire electronic systems such as accuracy, reliability, and stability. According to statistics, over 34% electronic systems failures are caused by the failure of the power system[3][4]. Therefore, the realization of SMPS Prognostics and Health Management (PHM) is the urgent subject. Based on the in-depth study on the failure of key components which impact SMPS life, this paper established the relationship between the failure of key components and the output ripple voltage of SMPS, and gave a reference to predict the remaining useful life of SMPS.

2. Life prediction of SMPS

Since the 80s, SMPS has the characteristics of light, small, thin, low-cost. So it has been widely used in electronics, telecommunications, electrical equipment, control equipment, and other fields. SMPS is an energy conversion circuit which uses semiconductor power devices as a switch, transforms a power supply form into another form with protection circuit and automatic control loop stability in output[5]. Fundamental component of SMPS is shown in Figure 1, where DC-DC converter is the core part of the SMPS, whose role is to carry out energy transfer and transformation. DC-DC converter has six basic structures, that is, the Buck, Boost, Buck-Boost, Cuk, Sepic, Zeta[5], and all of them consist of sampling network, controller, pulse width modulation (PWM) link, drive and other control circuit as a closed-loop operation system[6], as shown in Figure 2.

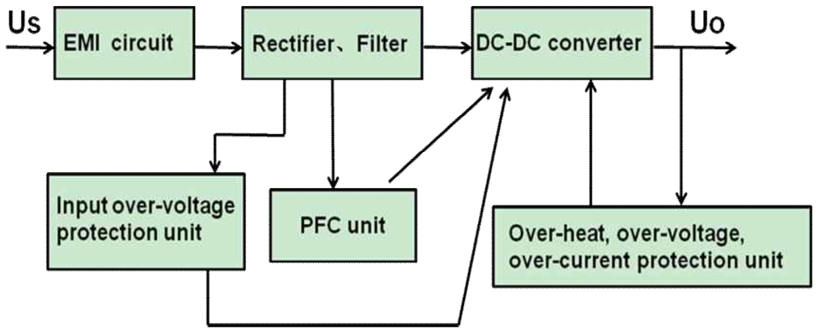

Figure 1. Fundamental component of SMPS

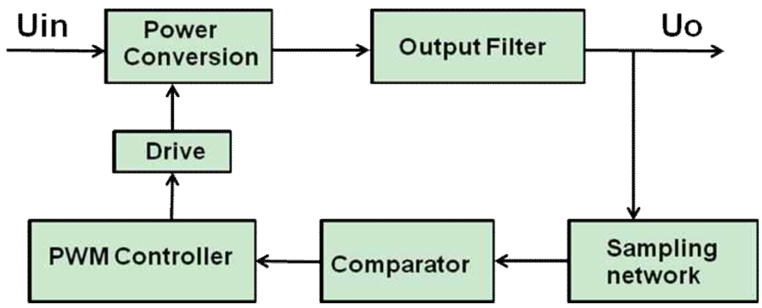

Figure 2. Fundamental component of DC-DC converter

The main failure mode of SMPS is function failure, such as no output voltage, loss of protection, enhanced electrical performance, unable to drive load and so on[7]. The main failure mechanisms have device failure, design defects, functional degradation, etc[8]. There are two basic ways to predict the life of SMPS. The first one, SMPS as a machine, it is consistent with the life cycle of the bathtub curve. So, we can use the derating, stress and other analysis methods for the analysis of the failure mechanism, and then estimate the remaining useful life. The disadvantage of this method is that the confidence is lower. The second one, SMPS is composed of many components of whole system, so its life is basically linked to the life of used devices. Therefore, we can first predict the life of components by analysis the failure mechanism of them, and then predict the remaining useful life of SMPS synthetically. Because the analysis methods of component failure mechanisms have been very mature, so this approach is feasible and the confidence is higher.

3. Failure mechanism of Aluminum electrolytic capacitor

The key devices that impact the life of SMPS are electrolytic capacitors, switching transistors, high-speed power diode, fans, optical couplers, switches, impulse current protection resistance and thermal power resistors. According to statistics, electrolytic capacitors have a high failure rate in the SMPS failure[9]. Study on Aluminum electrolytic capacitor failure mechanism is necessary for predicting the life of SMPS.

3.1. The main failure mechanism of Aluminum electrolytic capacitor

The main parameters of electrolytic capacitors include capacitance, equivalent series resistance (ESR), ripple current, temperature rise. By monitoring changes of key parameters, we can analyze the main failure mechanism of Aluminum electrolytic capacitors.

1）The capacitance decrease

Capacitance refers to the charge reserves under the given potential difference, with the temperature and frequency[10]. When Aluminum electrolytic capacitors work under high temperature a long time, it causes electrolyte evaporation and capacitance decreases. In addition, because the ripple current on ESR generates a large amount of heat loss, that increases the temperature ascent and accelerates the capacitance decrease. When the capacitance dropped to 20% of the initial value, we believe that the life of Aluminum electrolytic capacitors has been end[11].

2）The ESR increase

ESR is one of the major factors that caused electrolytic capacitor life recession due to the ripple current on the ESR produced a lot of heat loss to bring about the electrolytic capacitors temperature rise. ESR is relevant to capacitance, rated voltage, frequency, temperature and other factors, and mainly affected by temperature and frequency. For purposes of Aluminum electrolytic capacitor, ESR consists of the electrolyte resistance, the Aluminum oxide resistance of negative plates and the resistance between Aluminum and anode foil[12]. The electrolyte resistance is the main component of ESR, which decreases with increasing temperature. However the Aluminum oxide resistance of negative plates and the resistance between Aluminum and anode foil increase with increasing temperature. Integrating all the factors, the result is that the ESR of Aluminum electrolytic capacitors will decrease with increasing temperature. When the low frequency, ESR decreases stability in inverse proportion curve with increasing frequency. When it reached the resonant frequency (which typically less than 10 KHz)[13], the ESR curve will become a straight line with increasing frequency. Generally, the resonant frequency of large-capacity electrolytic capacitor is lower, so its ESR basically unchanged with increasing frequency. When the high frequency, ESR is almost unchanged with increasing frequency, its value is only concerned with the volume of electrolytic capacitors. Due to the operating frequency of SMPS higher and higher and has a wealth of high-order harmonic voltage and current, and due to electrolytic capacitors are inductive in high-frequency, electrolytic capacitors are required to have low impedance in high-frequency[13]. In addition, ESR and capacitance has a certain relationship that ESR increases with lower capacitance. That causes greater heat loss and accelerates the Aluminum electrolytic capacitors failure.

3.2. Aluminum Electrolytic Capacitor on the impact of SMPS

Aluminum electrolytic capacitor is one of the important components in the first and second filter circuit of SMPS[13]. The main impact of SMPS is that generated ripple voltage at the output and produced high frequency oscillation when working in the current state of discontinuous. Because of the characteristics of Aluminum electrolytic capacitor, such as poor stability and low reliability, its life is often the weak link in the entire power system[14]. According to the main failure mechanisms of Aluminum electrolytic capacitor, monitor the changes in the main parameters. We found that capacitance has some connections with the ripple voltage, so do ESR. The following will be discussed through simulation experiments and the corresponding physical experiments.

4. The relationship between capacitance and ripple voltage

4.1. Simulation experiments

Buck (step-down) converter is one of the most basic topology in DC-DC converters. We take it as an object of study, generating a simulation model in MATLAB 2008a.

The equivalent circuit of Buck converter is shown in Figure 3. We can think of the switch transistor, diode and inductors as ideal components. Then we created the SIMULINK model of Buck converter in MATLAB, as displayed in Figure 4. In the simulation experiments, the parameters of Buck converter are set as follows: input voltage VDC = 30V, in the buffer circuit for switch L, C, 0.5uH, 2uF, respectively, the ideal filter capacitor value C = 1320uF, inductance L = 3.3uH, load R = 3Ω, switching frequency F=125 KHz, duty cycle D=0.5.

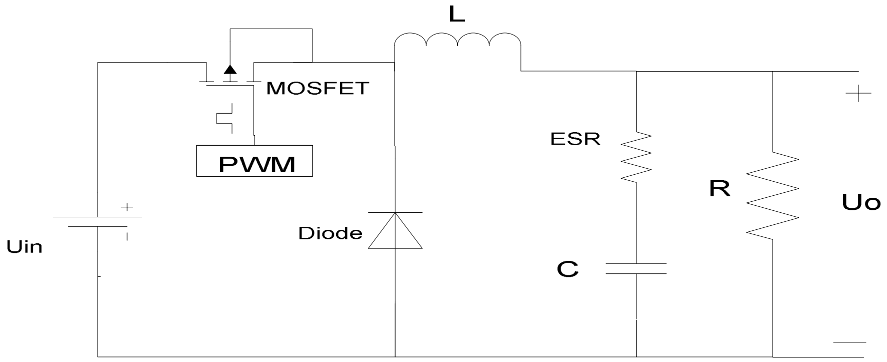

Figure 3. Buck Converter Equivalent Circuit

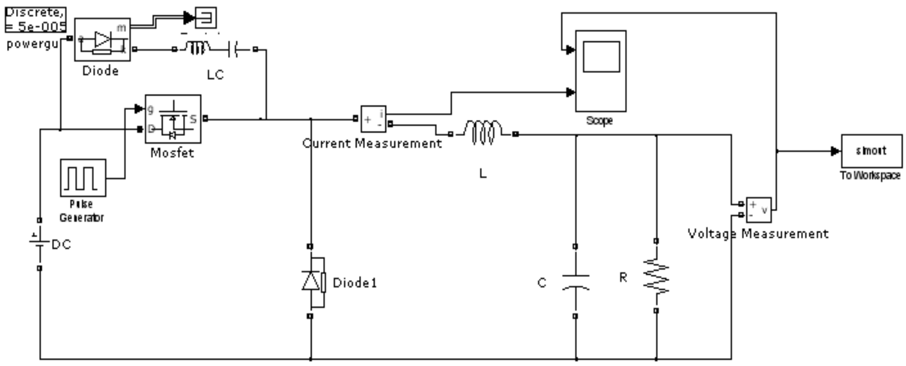

Figure 4. Buck Converter Simulink Model

The purpose of the simulation experiment is to observe the changes in output voltage by changing the value of the Aluminum electrolytic capacitor. Change the capacitor's value from 1320uF to 264uF by the rate of 20% and simulate under the different capacitance respectively. The simulation results (the ouput voltage waveforms) are illustrated in Figure 5. Calculate the ripple voltage peak – peak by analysing and processing the simulation data. The Table 1 lists the ripple voltage peak – peak corresponding to capacitance values. Fitting the simulation data, we obtain the curve of capacitance and ripple voltage peak - peak, as shown in Figure 6. It is clear that with the capacitance decreases, the ripple voltage increases. When the capacitor's value reduces to 60% of the ideal value, the ripple voltage's change is not obvious relatively. When the capacitor's value is down to 20% of the ideal value, the ripple voltage increases nearly 5 times, which means the capacitor failure.

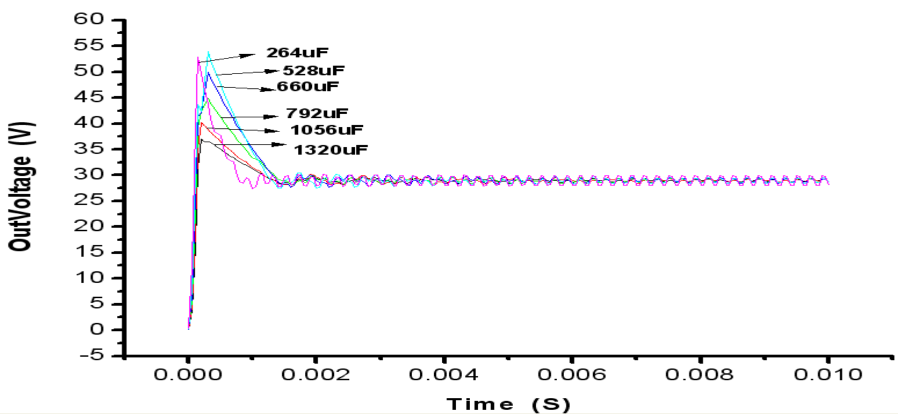

Figure 5. The output voltage waveforms corresponding to capacitance values

Table 1. The ripple voltage corresponding to capacitance values

Capacitance （uF）	Ripple Voltage （V）
1320	0.87
1056	1.26
792	1.17
660	1.39
528	1.43
264	1.89

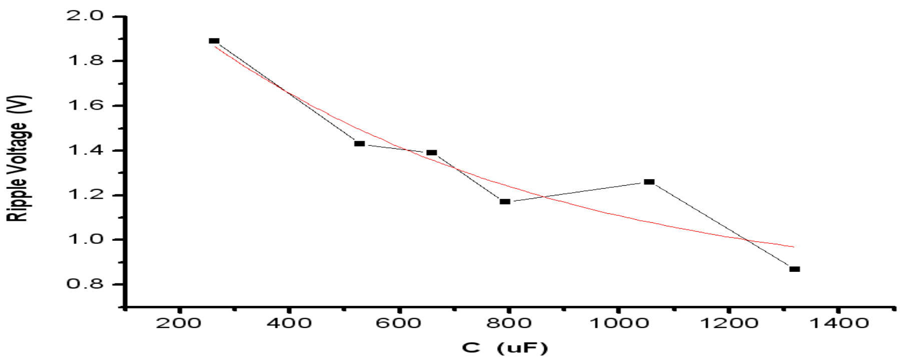

Figure 6. Capacitance and ripple voltage of the curve for simulation experiments

4.2. Physical experiments

The DC-DC converter is displayed in Figure 7. The test system consists of a SMPS whose specifications for the DC-DC 5V/2A 10W and a Tektronix oscilloscope DPO7254.

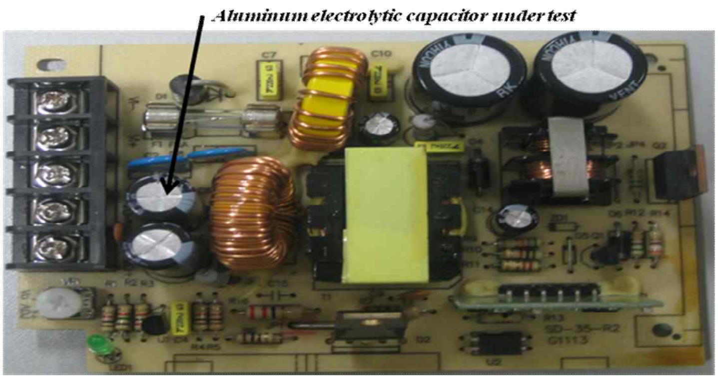

Figure 7. DC-DC converter hardware used for the experiments

First, we change the value of the output electrolytic capacitor, and then observe the changes of the ripple voltage waveform. The results are illustrated in Figure 8. It shows the ripple voltage waveforms when the capacitor's values were 1320uF, 660uF, 330uF, respectively. We can clearly see that the ripple voltage increases with the capacitance decrease. By calculating the RMS (root mean square) of waveform area, we obtain the curve of ripple voltage and capacitance, as shown in Figure 9. Comparing Figure 6 and Figure 9, the two curves are basically the same trend and rate of change. The simulation results are verified.

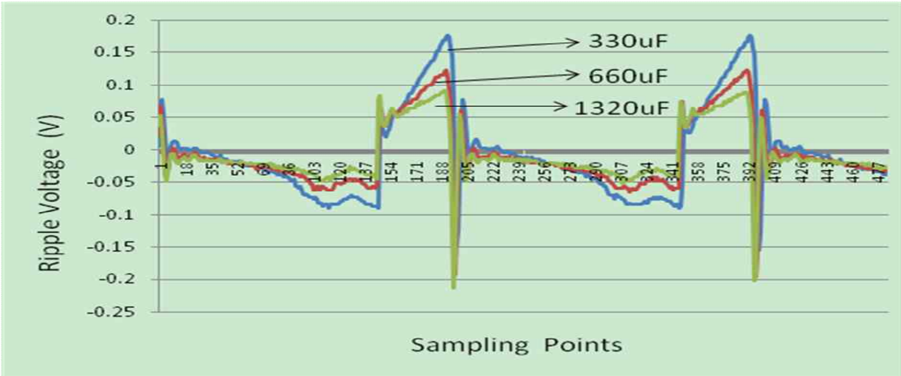

Figure 8. The ripple voltage waveforms corresponding to capacitance values

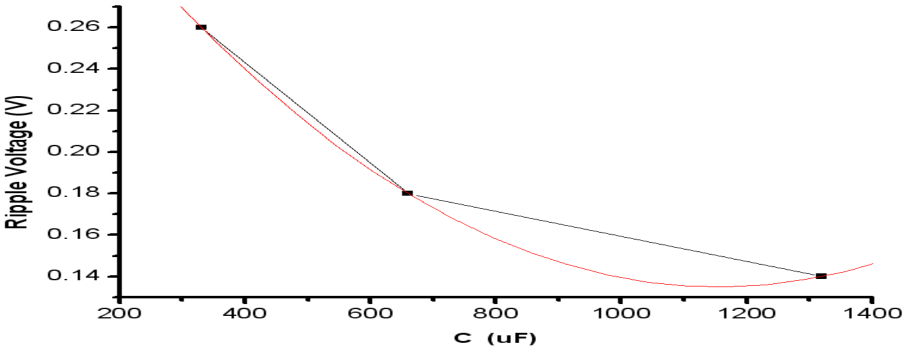

Figure 9. Capacitance and ripple voltage of the curve for physics experiments

5. The relationship between ESR and ripple voltage

5.1 Simulation experiments

The simulation model is displayed in Figure 10, and the device parameters are same to that simulation experiments in the above. Change the value of the ESR, and then observe the changes of the output voltage waveform. Make the ESR from 100mΩ to 20mΩby the rate of 20%, record the experimental data each time and process the data preliminary. The simulation results (the output voltage waveforms) are illustrated in Figure 11. From the simulation results we can see visually that the ripple voltage decreases significantly with the ESR decrease. According to the above simulation, we use the same data processing method to obtain the ripple voltage peak- peak corresponding to the various ESR values, as listed in Table 2. Fitting the simulation data, we obtain the curve of ESR and ripple voltage peak - peak, as shown in Figure 12. It can be seen, ESR is proportional to ripple voltage, and the curve basically becomes linear. When ESR is more than 60mΩ, the ripple voltage is rising rapidly. When ESR is greater than 80mΩ, the ripple voltage is too large and the SMPS is close to failure.

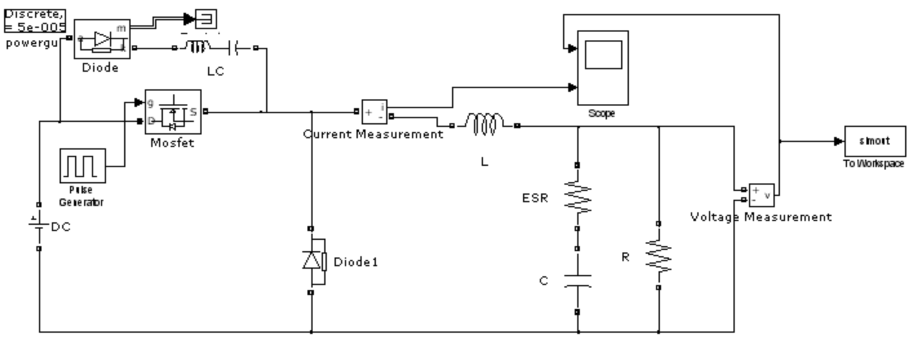

Figure 10. The simulation model of ESR change

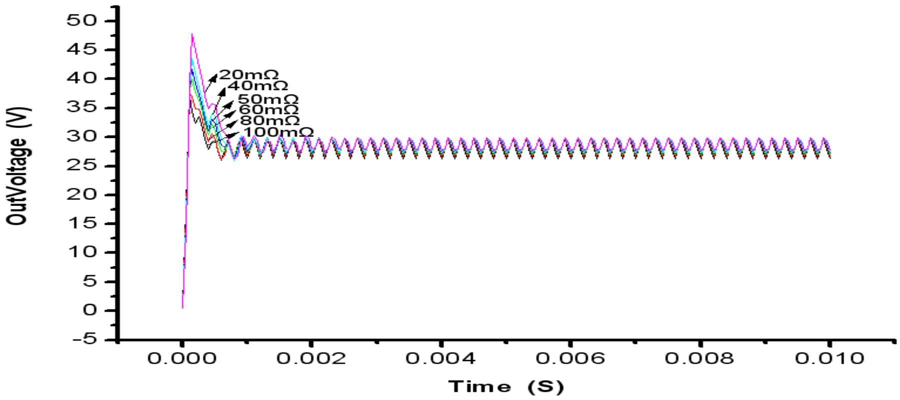

Figure 11. The output voltage waveforms corresponding to ESR values

Table 2. The ripple voltage corresponding to ESR values

ESR (mΩ)	Ripple Voltage(V)
100	3.50
80	3.23
60	2.90
50	2.74
40	2.56
20	2.24

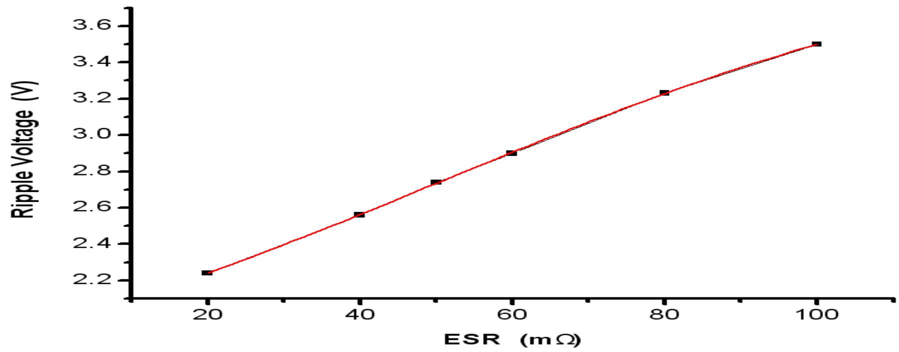

Figure 12. ESR and ripple voltage of the curve for simulation experiments

5.2. Physical experiments

Change the value of the ESR of electrolytic capacitor, and then observe the changes of the ripple voltage waveform. In the electrolytic capacitors in series a resistance, with the initial value of 87mΩ. Decrease the resistance to 8.7mΩ following by the proportion of 20%, and then measure the ripple voltage waveform under each length of the wire. The results are illustrated in the Figure 13. It can be seen that the ripple voltage is significantly reduced with the ESR decrease. According to the above physical experiments, we use the same data processing method to obtain the ripple voltage peak- peak corresponding to the various ESR values. Fit the experimental data and obtain the relationship between ESR and ripple voltage, as shown in Figure 14. Comparing Figure 12 and Figure 14, first, the two curves are basically the same trend and rate of change, second, the two curves are close to linear. That is, the simulation results are verified.

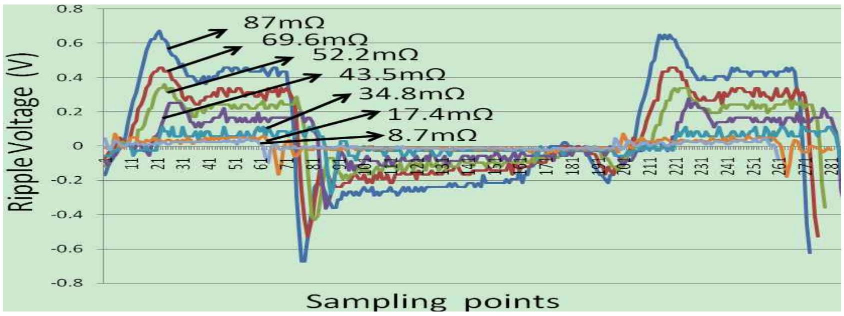

Figure 13. The ripple voltage waveforms corresponding to ESR values

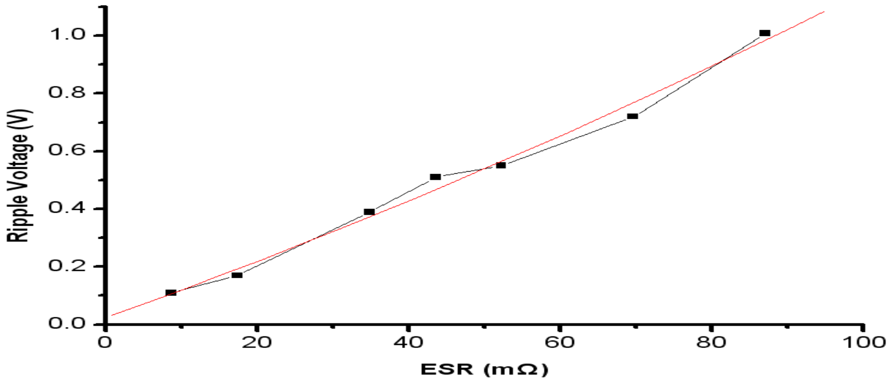

Figure 14. ESR and ripple voltage of the curve for physics experiments

6. Conclusion

This paper discussed the impact of capacitance and ESR on the life of SMPS. By the simulation experiments, we get two curves (one is the relationship between capacitance and ripple voltage, the other is the relationship between ESR and ripple voltage). By the physical experiments, we verify the results of the simulation experiments. With our experiments we get the following conclusions. First, with the capacitance decrease, the ripple voltage increases. The relationship between them is inversely proportional. Second, with the ESR decrease, the ripple voltage decreases. The relationship between them is directly proportional. Third, the impact of ESR on ripple voltage is much greater than that of the capacitance on the ripple voltage. The degradation failures of electrolytic capacitor are related to the capacitance decrease and the ESR decrease. In addition, the capacitance decrease and the ESR decrease cause the change of the ripple voltage. Therefore, by monitoring the change of the ripple voltage, we can know the health status of SMPS, and then predict the remaining useful life of SMPS. In future we plan to conduct experiments at different conditions, and obtain the mathematical relationship about the two curves.

7. Acknowledgements

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