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Current-sensorless online ESR monitoring of capacitors in boost converter

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Shengxue Tang[1] ✉, Shasha Dong[1], Yajing Liu[1], Qiran Zhang[1]
[1]*State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin, People's Republic of China*
✉ *E-mail: 1793347019@qq.com*

Abstract: boost circuit has been widely used in photovoltaic generation system and electrolytic capacitor is one of the most vulnerable components in the circuit. Equivalent series resistance (ESR) is an important index to reflect the reliability of capacitor. Real-time online monitoring and evaluation of ESR parameter has great significance to improve the reliability of boost circuit. In this study, a non-invasive online method to monitor and evaluate output capacitor's ESR in boost converter in continuous conduction mode is proposed. The ESR is calculated by sampling two specific periods of output voltage in a switching cycle. The calculation method is verified with the boost circuit model. The experimental results demonstrate the effectiveness of this method.

1 Introduction

With the rapid development of power electronic technology, electronic equipment is closely related to people's daily life, and reliable power supply of the electronic equipment is essential to the safety operation of system. Due to the large capacity and high cost performance, the aluminium electrolytic capacitor has become an essential part of switching power and is widely used in electronic circuit. Statistics shows that aluminium electrolytic capacitor is usually the weakest component in switching power supply, and the failure rate is about 60%. The degradation of performance is mainly manifested by an increase of equivalent parameter ESR, when the ESR increases to three times the aluminium electrolytic capacitor fails [1, 2]. So monitoring the change of ESR online is important to improve the reliability of system.

In the past years, some approaches have been developed in order to obtain the capacitors ESR during operation to evaluate their state condition. However, these approaches can only be implemented in a specific circuit. Some offline techniques were presented. In [3], according to the amplitude of AC voltage and capacitor voltage, the ESR and C are calculated by using Newton–Raphson method. The ESR is calculated by discrete Fourier transform by detecting the capacitor current and voltage of the buck circuit driven by the sine-wave pulse-width modulation signal [4–6].

The other is online technique. In [7], ESR can be obtained based on the analysis of the ripple voltage and current by the Hilbert transform. In [8], the switch current and the capacitor voltage ripple are sampled for ESR calculation. By sampling the input current and output ripple voltage of boost converter, ESR is obtained by digital signal processing [9]. In [10–13], the amplitude of the ESR can be obtained by division or by the fast Fourier transformation analysis .ESR can be obtained according to the capacitor voltage and current and by measuring the inner gas pressure and temperature of capacitor.

Most of the above methods rely on the extraction of the capacitor current, and require additional current detection points in the capacitor branch, which increases the cost and complexity of the system, which is not conductive for the improvement of the reliability of system. In [14], the ESR and C are calculated in buck converter by sampling the capacitance voltage values of two specific times without using current sensor to extract current. However, it is only suitable for continuous conduction mode of buck converter.

In this paper, an online monitoring method of ESR without current sensor for boost converter under continuous conduction mode (CCM) mode is proposed by analysing the AC component of output voltage and the expression of capacitor current by sampling two specific periods of output voltage in a switching cycle, and the ESR can also be obtained by analysing the duty cycle parameters. The ESR of electrolytic capacitor in boost circuit was simulated in MATLAB simulation platform, and the validity and feasibility of the method were verified.

2 Parameter online measurement analysis

2.1 Continuous conduction mode of boost converter

Boost converter is a basic DC–DC topology. The main circuit is shown in Fig. 1*a*, in which output electrolytic capacitor is equivalent to ESR and C in series. The working mode of boost circuit can be divided into CCM, discontinuous conduction mode and critical conduction mode according to which the inductor current is continuous. In order to obtain a continuous load current and small ripple voltage, the larger inductance is designed to make the circuit work in the conduction mode. The CCM boost converter without current sensor for online measurement of parameters is described in this paper. The topology and circuit principle are shown in Fig. 1.

In Fig. 1, V_{in}, L, i_{L}, ESR, C, i_{C}, V_{O} represent input voltage, inductance, inductance current, equivalent series resistance, capacitor, capacitance current, and output voltage, respectively.

By controlling the switch tube Q and the diode D, the boost converter operates in the commutation state as shown in Figs. 1*b* and *c*. When the switch Q is turn on, the diode D is reverse cut off, and the input source transfers energy to store in the inductance L, the current of inductance L increases linearly with slope V_{in}/L. At $t = DT_{\text{S}}$, the inductor current rises to peak as shown in Fig. 2. When the switch Q is turn off, the inductance current cannot be mutated, the voltage source and the inductance L release energy to load and capacitor so L releases energy to load. The commutation circuit in this state is shown in Fig. 1*c*, then the current reduces with slope $(V_{\text{in}} - V_0)/L$, the reduce time is $(1 - D)T_{\text{S}}$.

When Q is turn on the inductance voltage is V_{in}. The inductance current increases linearly as follows:

$$i_{\text{L}}(t) = i_{\text{L}}(0) + \frac{1}{L}\int_0^t V_{\text{in}}\text{d}t = i_{\text{L}}(0) + \frac{V_{\text{in}}}{L} \tag{1}$$

where i_{L} represents the inductance current. When $t = DT_{\text{S}}$, i_{L} is

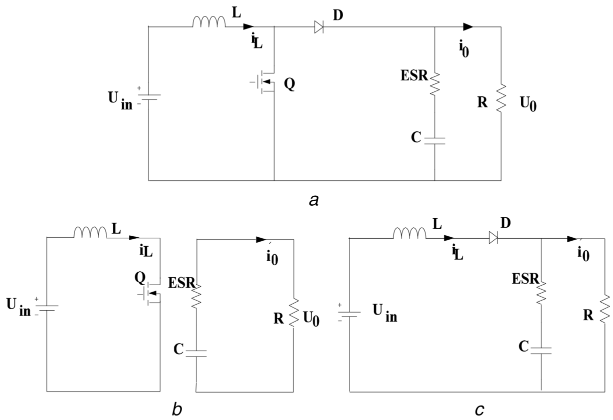

Fig. 1 *Boost main circuit*

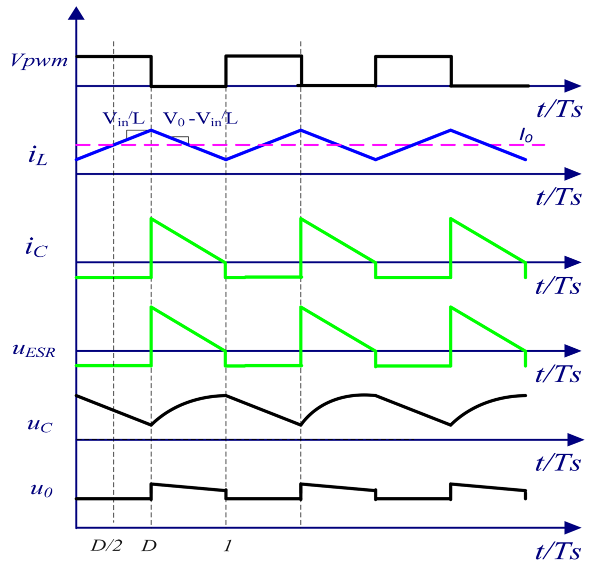

Fig. 2 *Correlation waveforms interrupted*

$$i_L(DT_S) = i_L(0) + \frac{1}{L}V_{in}DT_S \tag{2}$$

When the Q is turn off, the inductor voltage is $V_{in} - V_0$ and current decreases linearly from time $t = DT_S$, the inductance current can be obtained as

$$i_L(t) = i_L(DT_S) + \int_{DT_S}^{t} \frac{V_{in} - V_0}{L}\mathrm{d}t = i_L(DT_S) + \frac{V_{in} - V_0}{L}(t - DT_S) \tag{3}$$

When $t = T_S$, the inductance current i_L is

$$i_L(T_S) = i_L(DT_S) + \frac{1}{L}[(V_{in} - V_O) \times (T_S - DT_S)] \tag{4}$$

When the system reaches steady state, the following will be obtain

$$i_L(0) = i_L(T_S) \tag{5}$$

Then

$$V_0 = \frac{1}{1 - D}V_{in} \tag{6}$$

$$I_0 = \frac{V_0}{R} \tag{7}$$

2.2 Calculation of ESR

In steady state, when the switch is Q turn on, the inductor current increases with the slope V_{in}/L, and the inductor current increases to peak at $t = DT_S$. When the switch Q is turn off, the inductor current starts to decrease linearly from the maximum value with the slope $(V_{in} - V_0)/L$.

Therefore, the inductance current in a switching period can be expressed as

$$i_L(t) = \begin{cases} \dfrac{V_{in}t}{L} - \dfrac{V_{in}D}{2Lf_s} + I_0 & (0 < t < DT_S) \\ -\dfrac{V_0 - V_{in}}{L}t + \dfrac{(V_0 - V_{in})(1 + D)}{2Lf_s} + I_0 & (DT_S < t < T_S) \end{cases} \tag{8}$$

where V_{in} represents the input voltage V_0 is the average output voltage, L is the inductance, f_s is the switching frequency of the boost converter, and T_S is the switching cycle of the boost converter.

When Q is conducting, only capacitor transfers energy to R and when Q is shut off, the capacitance current is equal to the inductance current minus the average value of the output current

$$i_C(t) = \begin{cases} -I_0 & (0 < t < DT_S) \\ -\dfrac{V_0 - V_{in}}{L}t + \dfrac{(V_0 - V_{in})(1 + D)}{2Lf_s} & (DT_S < t < T_S) \end{cases} \tag{9}$$

The voltage waveform of $u_{ESR}(t)$ on the ESR is consistent with the waveform of $i_C(t)$ and the expression is (see (10)) . The voltage $u_C(t)$ on the capacitor C is expressed as

$$u_C(t) = V_C(0) + \frac{1}{C}\int_0^{DT_S} i_C(t)\mathrm{d}t$$

$$\begin{cases} V_C(0) + \dfrac{1}{C}\displaystyle\int_0^t (-I_0)\mathrm{d}t = V_C(0) - \dfrac{I_0}{C}t & (0 \le t < DT_S) \\ V_C(DT_S) + \dfrac{1}{C}\displaystyle\int_{DT_S}^t \left[-\dfrac{V_0 - V_{in}}{L}t + \dfrac{(V_0 - V_{in})(1 + D)}{2Lf_s}\right]\mathrm{d}t \\ = V_C(0) - \dfrac{V_0 - V_{in}}{2LC}t^2 + \dfrac{(V_0 - V_{in})(1 + D)}{2LCf_s}t \\ -\dfrac{(V_0 - V_{in})D}{2LCf_s^2} - \dfrac{I_0D}{Cf_s} & (DT_S \le t < T_S) \end{cases} \tag{11}$$

where $V_C(0)$ represents the initial value of the capacitor voltage.

The average value V_0 of output voltage in a switching period is expressed as follows:

$$V_0 = \frac{1}{T_S}\int_0^{T_S} u_{ESR}(t)\mathrm{d}t + \frac{1}{T_S}\int_0^{T_S} u_C(t)\mathrm{d}t \tag{12}$$

$$u_{ESR}(t) = \mathrm{ESR} \times i_C(t) = \begin{cases} \mathrm{ESR} \times (-I_0) & (0 \le t < DT_S) \\ \mathrm{ESR} \times \left[-\dfrac{V_0 - V_{in}}{L}t + \dfrac{(V_0 - V_{in})(1 + D)}{2Lf_s}\right] & (DT_S \le t < T_S) \end{cases} \tag{10}$$

As the DC component of ESR current is zero, the average voltage in a switching cycle is zero

$$\frac{1}{T_S}\int_0^{T_S} u_{ESR}(t)dt = 0 \tag{13}$$

Then,

$$V_O = \frac{1}{T_S}\int_0^{T_S} u_C(t)dt = \frac{1}{T_S}\left\{\begin{array}{l}\int_0^{DT_S}\left(V_C(0) - \frac{I_0}{C}t\right)dt + \\ \int_{DT_S}^{T_S} \begin{array}{l}(V_C(0) - \frac{V_0 - V_{in}}{2LC}t^2 + \frac{(V_0 - V_{in})(1 + D)}{2LCf_s}t \\ -\frac{(V_0 - V_{in})D}{2LCf_s^2} - \frac{I_0D}{Cf_s})dt\end{array}\end{array}\right.$$
$$= V_C(0) + \frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} + \frac{D^2 - 2D}{2CR}V_0 \tag{14}$$

Then, the initial value of the capacitor voltage can be obtained as

$$V_C(0) = V_O - \frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} - \frac{D^2 - 2D}{2CR}V_0 \tag{15}$$

The synthetic voltage of $u_C(t)$ and $u_{ESR}(t)$ is the instantaneous value of output voltage. According to (10) and (11), the resultant voltage can be obtained (see (16)) . The AC component of the output voltage $\hat{u}_0(t)$ is

$$\hat{u}_0(t) = u_0(t) - V_0 \tag{17}$$

Substitution the formulae (15), (16) into (17), the formula (18) can be obtained as

$$\hat{u}_0(t) = \left\{\begin{array}{ll}\mathrm{ESR}(- I_0) + - \frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} \\ -\frac{D^2 - 2D}{2CR}V_0 - \frac{I_0}{C}t & (0 \le t < DT_S) \\ \mathrm{ESR}\left(-\frac{V_0 - V_{in}}{L}t + \frac{(V_0 - V_{in})(1 + D)}{2Lf_s}\right) \\ -\frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} - \frac{D^2 - 2D}{2CR}V_0 - \frac{V_0 - V_{in}}{2LC}t^2 \\ +\frac{(V_0 - V_{in})(1 + D)}{2LCf_s}t - \frac{(V_0 - V_{in})D}{2LCf_s^2} - \frac{I_0D}{Cf_s} & (DT_S \le t < T_S)\end{array}\right. \tag{18}$$

The AC component of the output voltage at time DT_S and T_S are, respectively, expressed as (see (19))

(see (20)) . By formulae (19) and (20), the following equation is obtained:

$$\hat{u}_0(T_S) - \hat{u}_0(DT_S) = \mathrm{ESR}\frac{(V_0 - V_{in})(D - 1)}{Lf_s} \tag{21}$$

Then, ESR is expressed as

$$\mathrm{ESR} = Lf_S\frac{\hat{u}_0(T_S) - \hat{u}_0(DT_S)}{(V_0 - V_{in})(D - 1)} \tag{22}$$

$$u_0(t) = u_{ESR}(t) + u_C(t) = \left\{\begin{array}{ll}\mathrm{ESR}(- I_0) + V_0 - \frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} \\ -\frac{D^2 - 2D}{2CR}V_0 - \frac{I_0}{C}t & (0 \le t < DT_S) \\ \mathrm{ESR}\left(-\frac{V_0 - V_{in}}{L}t + \frac{(V_0 - V_{in})(1 + D)}{2Lf_s}\right) + V_0 \\ -\frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} - \frac{D^2 - 2D}{2CR}V_0 - \frac{V_0 - V_{in}}{2LC}t^2 \\ +\frac{(V_0 - V_{in})(1 + D)}{2LCf_s}t - \frac{(V_0 - V_{in})D}{2LCf_s^2} - \frac{I_0D}{Cf_s} & (DT_S \le t < T_S)\end{array}\right. \tag{16}$$

$$\hat{u}_0(DT_S) = \mathrm{ESR}\frac{(V_0 - V_{in})(1 - D)}{2Lf_s} - \frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} - \frac{D^2 - 2D}{2CR}V_0 - \frac{I_0D}{Cf_s} \tag{19}$$

$$\hat{u}_0(T_S) = \mathrm{ESR}\frac{(V_0 - V_{in})(D - 1)}{2Lf_s} - \frac{(V_0 - V_{in})(- D^3 + 3D^2 - 3D + 1)}{12LCf_s^2} - \frac{D^2 - 2D}{2CR}V_0 - \frac{I_0D}{Cf_s} \tag{20}$$

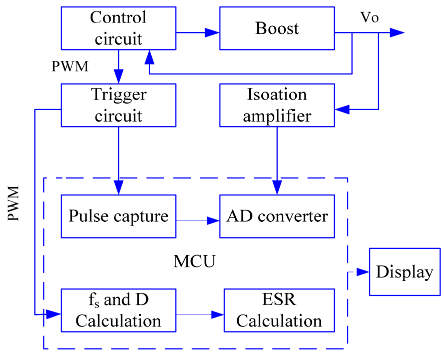

Fig. 3 *Schematic of the online identification system*

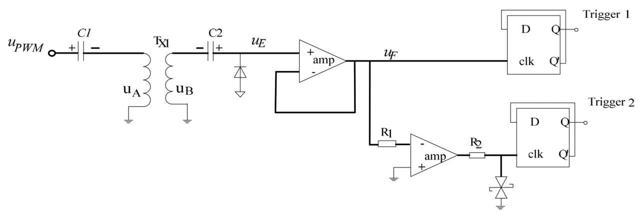

Fig. 4 *Trigger circuit*

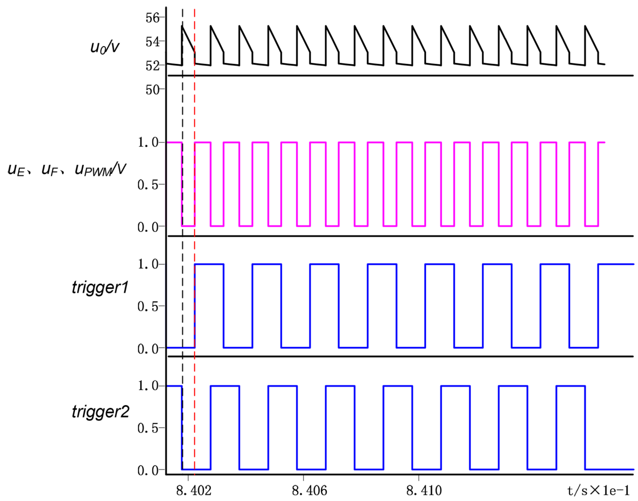

Fig. 5 *Waveforms of the trigger circuit*

3 Design of the online identification system

From the above analysis, we can design a schematic of the online identification system for ESR. As shown in Fig. 3, which includes boost power and control circuit, trigger circuit, isolated amplification circuit, and micro-control unit (MCU). The trigger circuit is shown in Fig. 4, which generates the trigger signal at DT_S and T_S by using pulse width modulation (PWM) signal from the control circuit. The AD conversion of MCU captures the output voltage at the action moment of trigger signals. Combining with the frequency f_S and D got from the MCU, the calculation model of ESR is compiled based on (22). Thus the ESR is obtained and displayed in real time [14–17].

3.1 Trigger circuit

The trigger circuit and its main waveforms are shown in Fig. 4 and 5, respectively. For boost converter, PWM signal amplitude is equal to V_S. The capacitor C_1 is used to eliminate the DC component of the PWM signal and the voltage across C_1 equals to DV_S. By the transformer T_{X_1} with the turns ratio of n, the trigger of the PWM signal transfers from point A to B, whose positive and negative amplitudes are $V_{A\_h} = (1-D)V_S$, $V_{A\_l} = -DV_S$, $V_{A\_h} = (1-D)V_S/n$, $V_{A\_h} = -DV_S/n$. The voltage on C_2 is DV_S/n. The waveform of V_E is same as PWM signal, set $C_1 = C_2 = 10\,\mu$F, $n = 1$.

Also signal V_F can be obtained by V_E though a voltage follower and sent it to D flip–flip, then trigger1 is generated on positive edge of V_F. When trigger1 is in action, that is to say both positive edge and negative edge, which corresponds to DT_S time of a switching cycle. Then V_F is fed into the zero-crossing comparator, when system operates in stable state *trigger*2 action on falling edge of V_F. The trigger2 signal T_S can be obtain in a similar way.

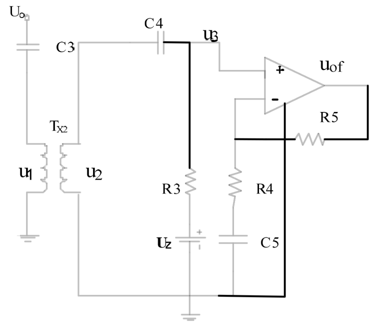

Fig. 6 *Isolation and amplification*

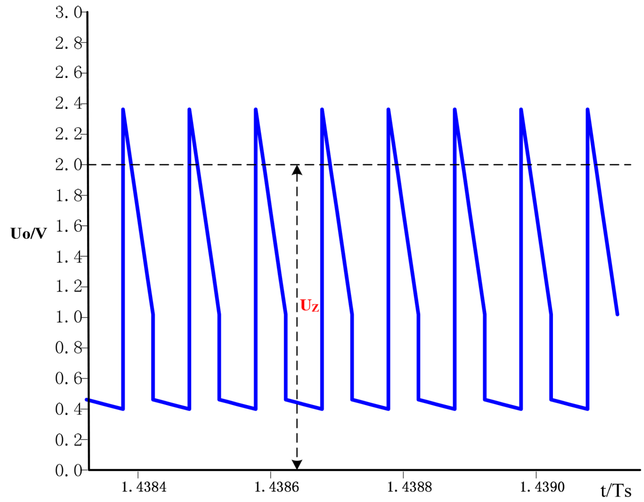

Fig. 7 *Waveform of the isolation and amplification circuit*

3.2 Voltage isolation and amplification

Figs. 6 and 7 show the schematic and waveforms of the isolation and amplification circuit for the output voltage ripple. The output voltage of boost converter is u_o with the average value of V_0. The DC component of u_o is blocked by the capacitor C_3, that is $V_{C3} = V_0$. The transformer T_{X2} with the turns ratio of 1 is adopted for the isolation between the amplification and main power circuit, thus the secondary-side voltage is the AC component of output voltage.

AD conversion module allows the input range to be 0–3.3 V, and u_3 needs to be offset. The AC voltage across C_4 and C_5 should be as low as possible so that it can be considered negative, that is, $1/2\pi f_s C_4 \ll R_3$ and $1/2\pi f_4 C_5 \ll R_4$. Then we can set up $C_4 = C_5 = 10\,\mu$F, $R_3 = R_4 = 1$ k, $R_5 = 200\,\Omega$. $f_s = 10$ kHz, $u_z = 2$ V is selected, the value of output voltage ripple is shown in Fig. 6.

4 Experiment and analysis

4.1 Simulation results and analysis

The approximate expressions of ESR in actual electrolytic capacitor with the operating temperature and time for simulation are given as follows:

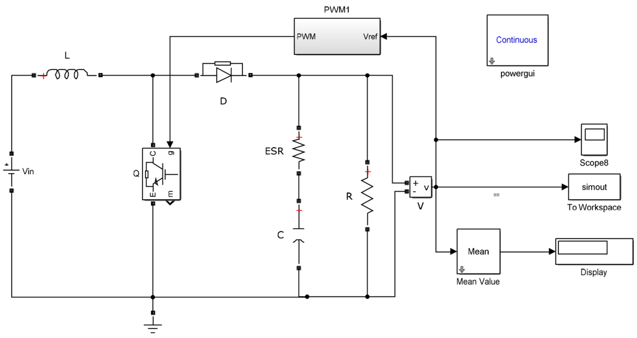

Fig. 8 *Converter emulation circuit of CCM boost*

Table 1 Simulation circuit parameters set

V_{in}, V	L, mH	ESR, Ω	C, μF	V_0, V
17	1	2	220	31.52

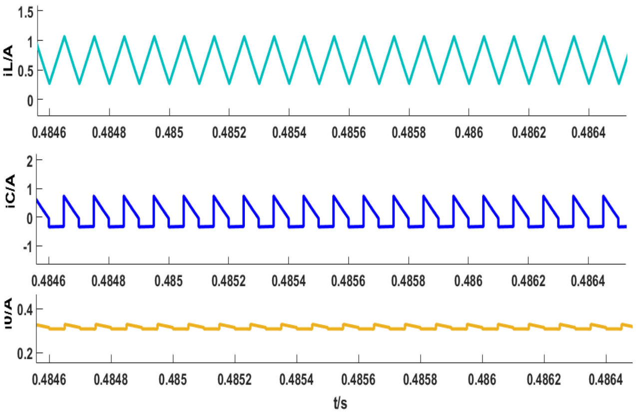

Fig. 9 *Inductance capacitance and load current*

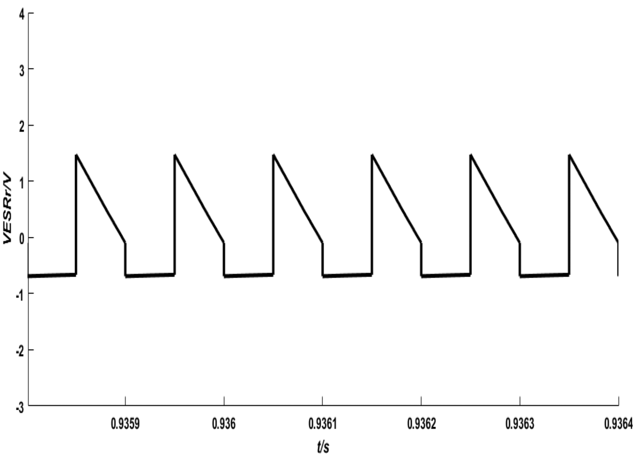

Fig. 10 *Average value of output voltage on ESR*

$$\frac{1}{\mathrm{ESR}(t)} = \frac{1}{\mathrm{ESR}(0)} \times \left(1 - k \times t \times e^{-\frac{4700}{T+273}}\right) \quad (23)$$

In this paper, the simulation is implemented on MATLAB/Simulink platform. The model is given in Fig. 8 and the parameters are given in Table 1 and equivalent model of an actual capacitor is expressed by ideal capacitor and resistor ESR in series. Using type (23), establish the model of ESR within 30 and 49 h. Set $T = 40$ °C, ESR initial value is ESR(0) = 2 Ω.

When input voltage is given 25 V and output voltage is 31.52 V, the inductor current, capacitor current and output current waveform are shown in Fig. 9. The average voltage waveform of the ESR in real time is shown in Fig. 10, the output voltage waveform can be seen in Fig. 11 and the average is about 31.52 V, the capacitance voltage can be seen in Fig. 12.

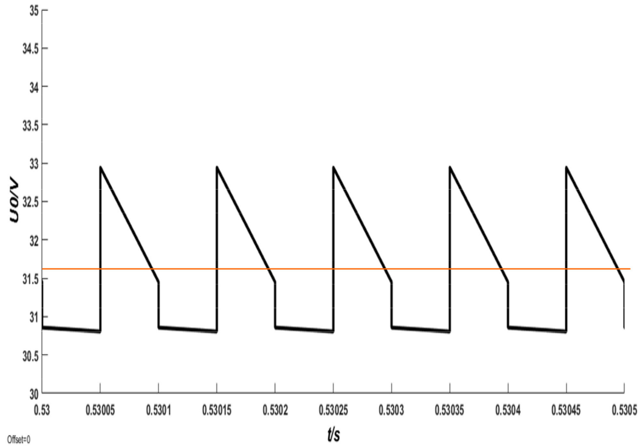

Fig. 11 *Output voltage waveform*

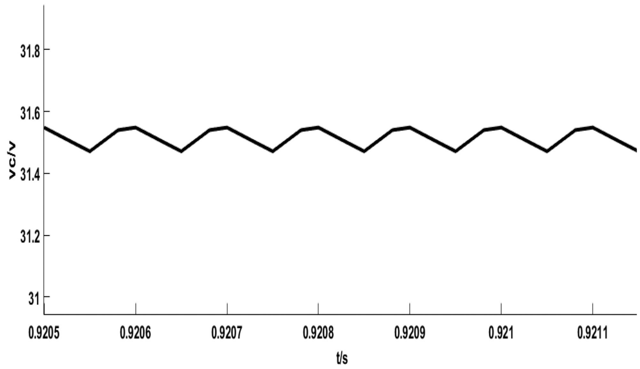

Fig. 12 *Capacitance voltage waveform*

4.2 Tested results and analysis

ESRs, calculated from $t = 30$h to $t = 49$ based on the formula (23), are used as actual values in the simulation model, and $V_{in} = 25$ V, $f_S = 10$ kHz are selected. The tested ESRs are calculated by sampling output ripple voltage value combine with D obtained by trigger circuit, and actual values of ESR are obtained based on the formula (23). The tested data of each group are shown in Table 2.

As shown in Table 2, the relative error of results is between 1.92 and 3.54%, all of those within 5% the proposed method can obtain ESR. When the value of ESR value exceeds 6 Ω (three times of 2 Ω), the capacitor is faulty at that moment.

In order to verify the correctness of the formula with different conditions, input voltage is changed with a constant duty cycle and frequency. Duty cycle with constant input voltage, changing frequency with constant input voltage and constant duty cycle, and changing frequency under input voltage and duty cycle are fixed, and tested in the paper.

In this experiment, the input voltage is set from 15 to 24 V, and duty cycle is selected as $D = 0.5$, frequency is set to $f_s = 10$ kHz, ESR default value is 2 Ω. The tested data is given in Table 3.

As shown in Table 3, the relative error of calculated results is between 0.74 and 3.70%. Keep the input voltage to 15 V unchanged, and change duty cycle from 0.1 to 0.9. The frequency at $f_s = 10$ kHz and $f_s = 100$ kHz are selected, respectively. The tested data is given in Tables 4 and 5.

The relative error of calculated results in Tables 4 and 5 under D change from 0.4 to 0.9 is between 0.29% and 4.45%. All of those are within 5%, and when D is between 0.1 and 0.3, the relative error is over 5% and even up to 71.6%, in which D is too small and boost circuit^^ cannot work at normal station.

5 Conclusion

In this paper, a non-invasive online technique that is able to estimate the ESR of the output capacitor for boost converter is proposed. It can be implemented online and in real time without

Table 2 Experimental results for $T = 40\,°C$

Time, h	V_0, V	ESR actual value, Ω	ESR calculate value, Ω	Relative error, %
30	46.94	2.496	2.560	2.56
31	46.93	2.517	2.572	2.18
32	46.92	2.538	2.587	1.92
33	46.91	2.559	2.612	2.07
34	46.90	2.581	2.648	2.59
35	46.89	2.604	2.677	2.80
36	46.88	2.626	2.683	2.16
37	46.86	2.649	2.726	2.91
38	46.85	2.673	2.746	3.40
39	46.84	2.697	2.770	2.70
40	46.83	2.721	2.787	2.42
41	46.82	2.746	2.818	2.62
42	46.81	2.771	2.863	2.65
43	46.80	2.796	2.887	3.32
44	46.78	2.823	2.912	3.11
45	46.77	2.849	2.930	2.84
46	46.76	2.876	2.972	3.33
47	46.74	2.904	3.001	3.34
48	46.73	2.932	3.035	3.51
49	46.72	2.961	3.066	3.54

Table 3 Experimental results for test parameters ($D = 0.5$)

V_{in}, V	V_0/V	Calculate ESR, Ω	Relative error, %
15	27.60	2.074	3.70
16	29.56	2.070	3.52
17	31.52	2.056	2.80
18	33.47	2.051	2.54
19	35.43	2.043	2.19
20	37.39	2.039	1.96
21	39.35	2.034	1.72
22	41.30	1.986	0.74
23	43.26	2.031	1.52
24	45.22	2.021	1.04

Table 4 Experimental results ($f_s = 10\,kHz$)

D	V_0, V	Calculate ESR, Ω	Relative error, %
0.1	21.17	3.433	71.6
0.2	23.81	2.321	16.3
0.3	27.08	2.173	8.68
0.4	31.40	2.059	4.45
0.5	37.39	2.039	1.96
0.6	46.23	2.006	0.29
0.7	60.59	1.980	1.00
0.8	88.01	1.956	2.21
0.9	161.1	1.931	3.41

using current sensor. To apply it, we analyse the working condition of boost converter under CCM and derive the expression of ESR only by using two specific periods of output voltage in a switching cycle combine with two trigger signals. The experimental results from many aspects show that the ESR estimation error is <5% except when the duty cycle is too small. So it can be considered that the accuracy and validity of proposed method are verified.

Table 5 Experimental results ($f_s = 100\,kHz$)

D	V_0, V	Calculate ESR, Ω	Relative error, %
0.1	21.26	3.183	59.1
0.2	23.81	2.365	18.3
0.3	27.08	2.173	8.65
0.4	31.40	2.081	4.09
0.5	37.39	2.028	1.39
0.6	46.23	2.006	0.31
0.7	60.59	1.979	1.04
0.8	88.01	1.956	2.22
0.9	161.1	1.914	4.23

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7 References

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