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Full Length Research Paper

A new deterioration model for electrolytic capacitors in direct current to direct current (DC-DC) converters

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The output filter aluminum electrolytic capacitor is one of the key components that determine the life of direct current to direct current (DC-DC) converters, and so, establishing a deterioration model for the electrolytic capacitor is the basis for analyzing the impact on the converters' performances. Generally, the main parasitic parameters that indicate the electrolytic capacitor deterioration such as capacitance (C) and equivalent series resistance (ESR) are separately considered when building the model. However, taking the Buck-Boost converter as the research object, this paper discussed the impact of the two kinds of parasitic parameters simultaneous degradation on the DC-DC converters. Firstly, according to the electrolytic capacitor failure mechanisms, a joint degradation model for the C and ESR-a new deterioration model for the electrolytic capacitor was established. On the basis, this paper discussed the impact on the system pole-zero of the parasitic parameters degradation, analyzed the electrolytic capacitor deterioration on how to affect the performances of the DC-DC converter, and verified the theoretical analysis results through the software simulation experiments. The new model provides the theoretical basis for monitoring the health state of DC-DC converters.

Key words: Electrolytic capacitor, deterioration, capacitance, equivalent series resistance (ESR), joint degradation model, pole-zero.

INTRODUCTION

Electronic systems which work in the harsh environments are frequently failures due to a variety of stresses. According to statistics, over 34% of the electronic systems failures are caused by the failure of power supply system (Callan et al., 2002; Rolf et al., 2005). Therefore, the power prognostic health management (PHM) has become the common focus of attention in the international. Direct current to direct current (DC-DC) converter is the main body of power supply system, so, to research its PHM is an urgent subject.

Component failure is the main reason of the DC-DC converter failure. According to statistics, electrolytic capacitor has the highest failure rate in the converter failure (Pang et al., 2010). Military handbook 217F (Department of Defense, 1995) standards made a component failure statistics for two types of DC-DC power supply: nearly 60% of the failures are due to the electrolytic capacitor failure in the filtering unit. Therefore, the electrolytic capacitor is the key component which determines the reliability and life of DC-DC converter. The key component failure analysis is the necessary part of the power supply failure analysis, and this establishes a foundation to realize the technology of the power PHM.

Component failure has two types, fault failure and deterioration failure, and the latter is the main reason which causes the system's life to an end. For the aluminum electrolytic capacitor, the capacitance (C) and the equivalent series resistance (ESR) are the principal parasitic parameters. As the electrolytic capacitor long-term works in high-temperature conditions, the electrolyte

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Abbreviations: DC-DC, Direct current to direct current; **C**, capacitance; **ESR**, equivalent series resistance; **PHM**, prognostic health management; **RHP**, right-half plane.

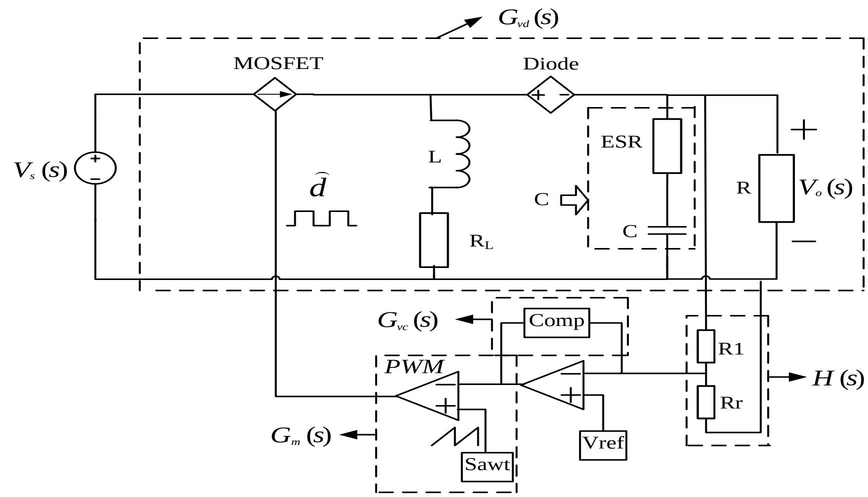

Figure 1. The equivalent circuit of buck-boost power.

evaporates, and this leads to the C decrease and the ESR increase. Many people have done a lot of researches on the electrolytic capacitor failure. Michael and Gasperi (1996) studied on the ESR and proposed a method for predicting the ESR value. Chetan et al. (2009) established a thermal model for the electrolytic capacitor. The power loss of the electrolytic capacitor was analyzed by Ahmed et al. (2010) and Sankaran et al. (1997). The C and ESR values could be real-time forecasted by the methods of Z-transform, Taylor series expansion, Fourier transform and power analysis and the life prediction model for electrolytic capacitor was built. All of these were proposed by Karim and Pascal (2010), Gustavo et al. (2010), Fengyan et al. (2010) and Yuege et al. (2011). The above references deeply studied on the failure mechanism of the electrolytic capacitor, but did not analyze the impact of the component failure on the system performances.

Amine et al. (1998), Acacio et al. (2004) and Lifeng et al. (2011) analyzed the relationship between the electrolytic capacitor failure and the output ripple voltage of DC-DC converters, respectively directing at the C and the ESR degradation. However, they did not study the case of the two kinds of parasitic parameters simultaneous degradation. This paper established a new deterioration model for the electrolytic capacitor, which is a joint degradation model for the C and ESR. On this basis, by analyzing the impact on the system pole-zero of the parasitic parameters degradation, discussed the electrolytic capacitor deterioration on how to affect the performances of converter, such as ripple voltage, stability margin and high-frequency anti-jamming capability. Firstly, taking Buck-Boost converter as the research object, this paper establishes a mathematical model for the non-ideal converter, analyzes the important role of the electrolytic capacitor in the converter. Secondly, according to the failure mechanisms the new model is to be built. Then this paper uses it to discuss the influence of the electrolytic capacitor deterioration on the converter performances by analyzing the parasitic parameters on how to affect the system pole-zero in detail. Finally, the correctness of the theoretical analysis results will be verified through the simulation experiments with MATLAB.

MATERIALS AND METHODS

The theoretical basis

In this paper, Buck-Boost converter will be the research object for discussion. With the average model method of switching element to build the model for the Buck-Boost converter (Weiping, 2006), its equivalent circuit is shown in Figure 1. The output filter aluminum electrolytic capacitor is considered non-ideal component and it is equivalent to an ESR in series with an ideal capacitor. The transfer function block diagram of the converter shown is displayed in Figure 2. Where, $H(s)$ is the transfer function of the sampling network, $G_m(s)$ is the transfer function of the PWM regulator, $G_{vc}(s)$ is the transfer function of the compensation network and $G_{vd}(s)$ is the transfer function of the control object. The main work of this paper is to build the relationship between the key component failure and the converter failure by analyzing the ESR and C simultaneous degradation on how to lead the $G_{vd}(s)$ pole-zero to change.

Obtain the transfer functions by small-signal analysis. The transfer function of the control object is:

$$G_{vd}(s) = K_1 \frac{(1+\frac{s}{\omega_{z1}})(1+\frac{s}{\omega_{z2}})}{(1+\frac{s}{\omega_{p1}})(1+\frac{s}{\omega_{p2}})} \quad (1)$$

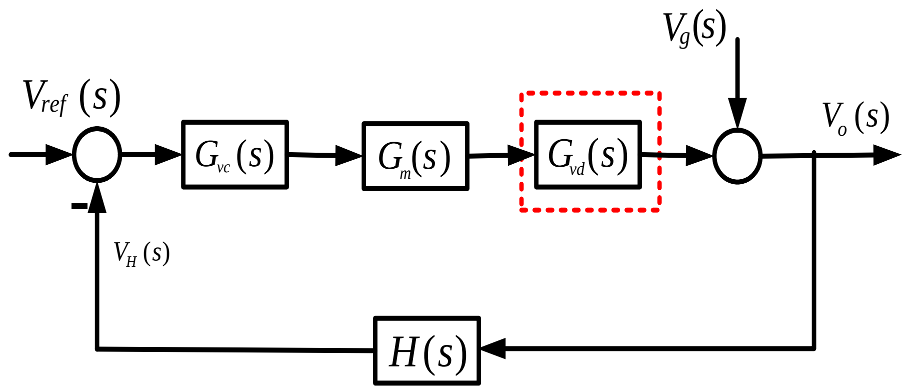

Figure 2. The transfer function block diagram of buck-boost power.

Where the RHP (right-half plane) zero:

$$\omega_{z1} = -\frac{R_{e1}}{DL} \tag{2}$$

$(R_{e1} = R(1-D)^2 - R_L(2D-1))$

The high-frequency zero:

$$\omega_{z2} = \frac{1}{C \times ESR} \tag{3}$$

The pole angular frequency:

$$\omega_{p0} = \sqrt{\omega_{p1} \times \omega_{p2}} = \sqrt{\frac{R'}{LC(R+ESR)}} \tag{4}$$

$(R' = R(1-D)^2 + R_L)$

$G_{vd}(s)$ shows that the control object is a second-order system and it has a RHP zero. Therefore, it is necessary to use the controller with double-pole-zero compensation network to compensate. The transfer function of the compensation network is:

$$G_{vc}(s) = K_2 \frac{(1+\frac{s}{\omega_{z3}})(1+\frac{s}{\omega_{z4}})}{s(1+\frac{s}{\omega_{P3}})(1+\frac{s}{\omega_{P4}})} \tag{5}$$

Therefore, the system open-loop transfer function is:

$$T(s) = G_{vc}(s) \times G_m(s) \times G_{vd}(s) \times H(s) \tag{6}$$

The expression of the output signal $V_0(s)$ is:

$$V_0(s) = \frac{V_{ref}(s)T(s)}{H(s)(1+T(s))} \tag{7}$$

The transfer functions, amplitude-frequency characteristics of the control object, the compensation network and the open-loop are shown in Figure 3. By the principle of compensation we know that the system open-loop transfer function can be equivalent to an integral part, and this can basically meet the system requirements of each band's performance. However, the parasitic parameters C and ESR will change when the electrolytic capacitor deteriorates, and this will lead the double-pole ω_{P0} and high-frequency zero ω_{z2} of the control object transfer function to move. Now, the ability to compensate is poor, and the system open-loop transfer function becomes a complex high-level part. Thence, the performances of each band change, such as the steady-state performance at low-frequency, the dynamic stability at middle-frequency and the high-frequency anti-jamming capability at high-frequency. In addition, the output signal $V_0(s)$ will change with the electrolytic capacitor deterioration, and this causes the ripple voltage and the system noise to increase. From the equations (3) and (4), we can see that, the double-pole ω_{P0} and high-frequency zero ω_{z2} are the functions of ESR and C. Moreover, the two parasitic parameters are simultaneously degraded. Therefore, building a joint degradation model for the two parasitic parameters is the premise to analyze the system pole-zero how to change.

The new deterioration model and the analysis method

At present, about the impact of electrolytic capacitor deterioration on the DC-DC converters, the studies are only based on the situation of one of the parasitic parameters degradation. The above analysis shows that all of the ESR and C determine the change of the system pole-zero and they are degraded simultaneously. Therefore, this paper will build a new deterioration model for the electrolytic capacitor of a joint degradation model for the ESR and C. This can help more to accurately analyze the impact on the DC-DC converters performances of the electrolytic capacitor deterioration.

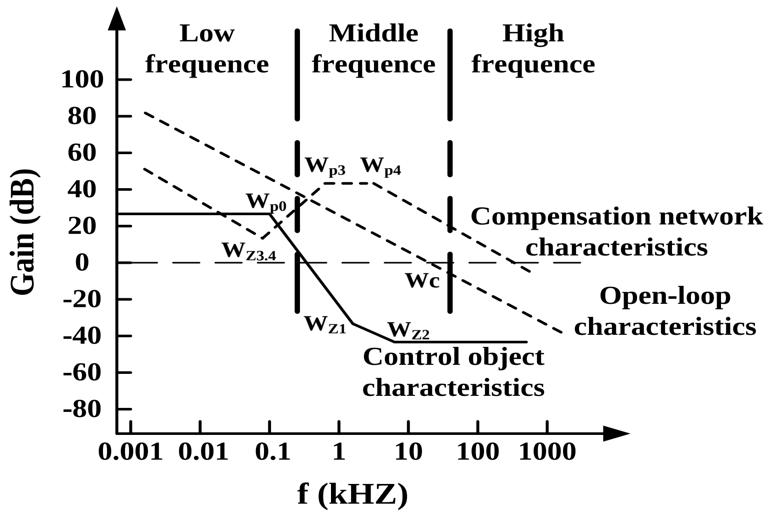

Figure 3. The three log amplitude-frequency characteristic.

Electrolyte evaporation is the root reason that causes the electrolytic capacitor to deteriorate. With the electrolyte evaporation, the concentration of electrolyte increases. This leads to the ESR increase and the C decrease at the same time. The relationship between the ESR and the volume of electrolyte which was proposed by Michael and.Gasperi (1996) is:

$$\frac{ESR_t}{ESR_0} = \left(\frac{V_0}{V_t}\right)^2 \quad (8)$$

Where, ESR_0 is the initial value of ESR, ESR_t is the value of ESR at time t, V_0 is the initial volume of the electrolyte, V_t is the volume of the electrolyte at time t.

For the cylindrical electrolytic capacitor, the volume of electrolyte is calculated as:

$$V = \pi r^2 h \quad (9)$$

Where r is the radius of the electrolytic capacitor, h is the height of the electrolyte.

We consider that the electrolyte evaporation can be equivalent to the height h reducing. So, the degradation model of ESR can be established as:

$$\frac{ESR_t}{ESR_0} = \left(\frac{h_0}{h_t}\right)^2 \quad (10)$$

Where h_0 is the initial height of the electrolyte, h_t is the height of the electrolyte at time t.

The original formula of C is:

$$C = 8.855 * 10^{-12} * \frac{\varepsilon S}{d}(F) \quad (11)$$

Where ε is ihe dielectric constant of the electrolyte, d is the thickness of the electrolyte, its relationship with the voltage-resistant is: 1V is corresponding to 14~15A°, S is the electrode area.

Because the structure of the electrolytic capacitor is wound, so we can equate it with a flat capacitor after the commencement. Therefore, the electrode area S is the sum of surface area on each floor. Assuming the electrolytic capacitor consists of n layers and the thickness of each layer is x.

So, S can be calculated as:

$$S = \sum_{n=1}^{n} 2\pi h[r-(n-1)x] = 2\pi hx[nr - \frac{n(n-1)}{2}] \quad (12)$$

Because of

$$x * n = r.$$

So,

$$S = 2rh(r^2 - \frac{n-1}{2}r) \quad (13)$$

Therefore, the degradation model of the C can be established as:

$$\frac{C_0}{C_t} = \frac{h_0}{h_t} \quad (14)$$

Therefore, the joint degradation model of the new deterioration model can be built as:

$$\frac{ESR_t}{ESR_0} = \left(\frac{h_0}{h_t}\right)^2 \quad \frac{C_0}{C_t} = \frac{h_0}{h_t}$$

The degradation models of the ESR and C show that, the rate of ESR degradation is higher than that of the C. When the ESR increases to four times of the initial value, the C decreases to only 50% of the initial value. However, the electrolytic capacitor has failed at this time. Therefore, ESR is the key parameter which determines the life of the electrolytic capacitor.

According to the joint degradation model, the equations (3), (4) and (7) can be rewritten as:

$$\Delta\omega_{z2} = f_1(\Delta ESR^2, \Delta C) \tag{15}$$

$$\Delta\omega_{p0} = f_2(\Delta ESR^2, \Delta C) \tag{16}$$

$$\Delta V_0(s) = f_3(\Delta ESR^2, \Delta C) \tag{17}$$

These show that, when the electrolytic capacitor deteriorates, the absolute value of the high-frequency zero ω_{z2} reduces. That means the zero moves to the imaginary axis, at the same time, the pole angular frequency increases. By respectively analyzing the real and the imaginary parts of the poles ω_{P1}、ω_{P2} it can be known that, all of the absolute values of their real and imaginary parts increase with the electrolytic capacitor deteriorating. This means the poles move away from the real axis and the imaginary axis. Besides, with the electrolytic capacitor deteriorating, the output signal $V_0(s)$ increases. Its growth rate is proportional to ΔESR^2, but inversely to ΔC. This is consistent with the relationship between the ripple voltage, the ESR and C which are proposed by GAN and LI (2007), such as what is been shown in the equation (18).

$$\hat{u}o = \frac{Uo(1-M)Ts\,\mathrm{Re}\,q + 2Uo(1-D)TsLeq}{2L} + \frac{Uo(1-M)Ts^2}{8LC} \tag{18}$$

In short, with the electrolytic capacitor deteriorating, the high-frequency zero of the control object transfer function moves to the imaginary axis, but its poles move away from the real axis and the imaginary axis. Due to the zero changes, the high-frequency anti-jamming capability is worse. Due to the poles changes, the low-frequency performances are worse and possibly generate steady-state error. All the changes of the zero and the poles cause the crossover frequency of the system open-loop transfer function to increase. While this accelerates the transient response, it increases the system overshoot and reduces the system's stability margin. Besides, due to the crossover frequency increase, some high-frequency harmonics cannot be filtered. This leads the output ripple voltage to increase.

RESULTS

The simulation experiments

Set the values of the parameters in the converter for Vin=24V, D=0.6, R=10Ω, L=320uH, C=160uF, ESR=150mΩ, RL=140mΩ, Vo=35V. Set up the power frequency for fs = 100 KHZ, the crossover frequency for fc = 10 KHZ, the reference voltage of the compensator for Vref = 2.5 V, the output peak value of the PWM for VM = 3 V. Then, put these values into the expression of each transfer function:

$$G_{vd}(s) = \frac{1.223(s+4.167\times10^4)(s-8188)}{s^2+1127s+3.348\times10^6}.$$

$$G_{vc}(s) = \frac{1.8\times10^5\times(s+914.9)^2}{s(s+8188)(s+4.167\times10^4)}$$

$$G_m(s) = \frac{1}{V_M} = \frac{1}{3}$$

$$H(s) = \frac{R_r}{R_1+R_r} = 0.07$$

So, the system open-loop transfer function is:

$$T(s) = G_{vc}(s)\times G_m(s)\times G_{vd}(s)\times H(s)$$
$$= \frac{5136(s+4.167*10^4)(s-8188)(s+914.9)^2}{s(s+8188)(s+4.167*10^4)(s^2+1127s+3.348*10^6)}$$

Using MATLAB as the simulation software, simulate the aluminum electrolytic capacitor deterioration on how to affect the converter performances through the Bode diagram and the Pole-Zero map of the system open-loop transfer function. According to the joint degradation model, set the values of the ESR and C that are listed in Table 1. The simulation results are shown in Figures 4 and 5.

DISCUSSION

From the simulation results, we can see that: with the electrolytic capacitor deteriorating, the frequency of the double-pole increases, the frequency of the high-frequency zero decreases, and the crossover frequency of the system open-loop transfer function increases. These results are consistent with the above analysis results. The double-pole frequency increase causes the system steady-state error to increase, and in severe the system may be in an unstable state. The changes of the zero and the poles have a uniform role that causes the crossover frequency of the system open-loop transfer function to increase. While this accelerates the transient response, it reduces the stability margin and weakens the high-frequency anti-jamming capability. Consequently, the ripple voltage increases and the lifetime declines. By the time ESR increased to three times than the initial value, the crossover frequency has already exceeded the allowable upper limit (one-sixth of the switching frequency). At this moment, a great quantity of high-

Table 1. The values of equivalent series resistance (ESR) and capacitance © in the simulation experiments.

The new deterioration model of electrolytic capacitor		The values of ESR and C in the simulation experiments	
ESR_t/ESR_0	C_t/C_0	ESR(mΩ)	C(μF)
1.0	1.0	150	160
1.2	0.9129	180	146.064
1.5	0.8165	225	130.64
1.8	0.7454	270	119.264
2.0	0.7071	300	113.136
2.2	0.6742	330	107.872
2.5	0.6325	375	101.2

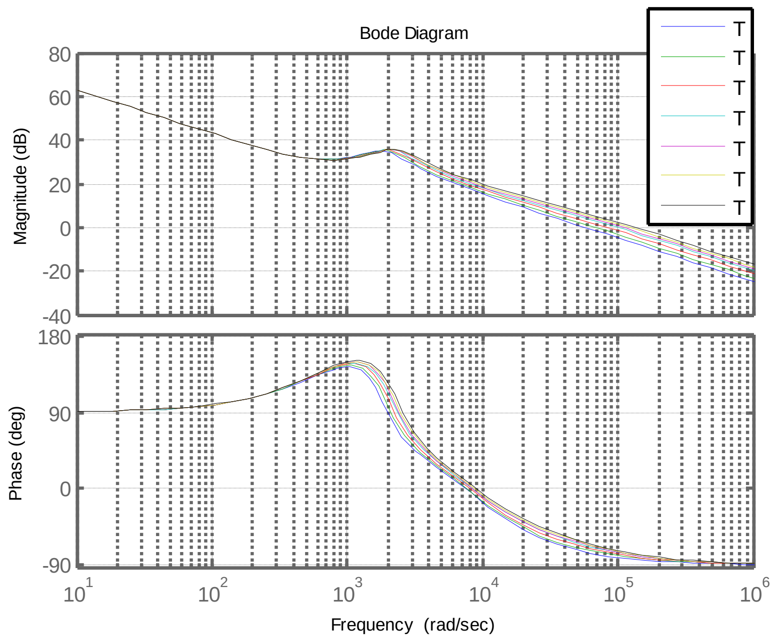

Figure 4. The Bode diagram of T(S) when capacitor deteriorats.

frequency harmonics cannot be filtered, and this results in the ripple voltage increase. When the ripple voltage exceeds the rating value, it means that the converter is to failure and its life is to an end.

Conclusions

The main deterioration mode of the electrolytic capacitor is the degradation of the parasitic parameters such as ESR and C. This paper established a joint degradation model for the ESR and C by analyzing the relation of the parasitic parameters and the electrolyte. Then, analyzed the electrolytic capacitor deterioration on how to affect the system performances (ripple voltage, stability margin and high-frequency anti-jamming capability) from the perspective of the system pole-zero. The simulation results show that the main consequences caused by the aluminum electrolytic capacitor deterioration are the crossover frequency increase, the stability margin decrease and the high-frequency anti-jamming capability decline and these lead the ripple voltage to increase and lead the life of the converter to drop. Comparing with the simulation results and the theoretical analysis results, their conclusions are consistent, and the theoretical analysis has been verified. According to the analysis results, we can estimate the converter health state by monitoring the converter’s output signals. The analysis results presented by this paper establish a foundation for realizing the PHM of DC-DC converter.

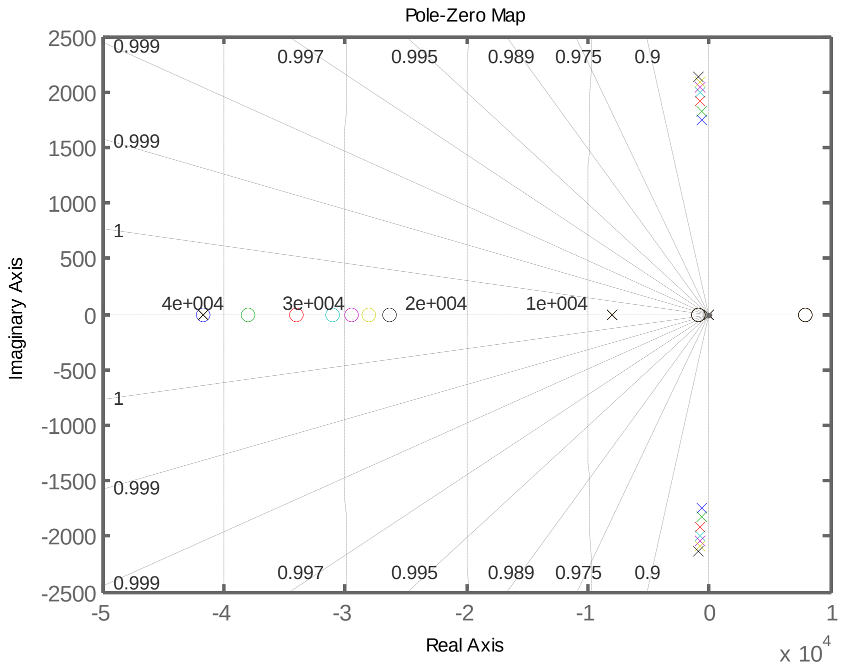

Figure 5. The Pole-Zero map of T(S) when capacitor deteriorats.

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