Evaluation of functional reliability indices for DC-link capacitors in pulse-width modulation converters

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Abstract. The impact of kHz range harmonics on the power losses, thermal stress, and lifetime reduction of the dc-link capacitors in pulse-width modulation (PWM) converters was investigated. Expressions to evaluate the mean time to failure, survival probability, and unavailability of aging failure for dc-link capacitors are presented. The dc-link capacitors failures due to accelerated insulation aging were modeled using Weibull and normal distribution. A case study with the Siemens SINAMICS S120 frequency converter for driving of rolling mill leveler shows that the failures of motor modules due to breakdown of electrolytic dc-link capacitors registered for the time frame from May 2012 to October 2012 can be caused by the increased ambient temperature and additional heating due to high-frequency components of the ripple current. As a possible solution to improve reliability of motor modules, the four AVX FFVE4I0227K film capacitors instead of nine EPCOS B43564 electrolytic capacitors in dc-link were recommended.

1 Introduction

A widespread proliferation of the PWM converters with dc-link in the electric vehicles, uninterruptible power supply, wind turbine and photovoltaic systems, adjustable speed motor drives, etc., causes the increase in the level of current and voltage components with frequencies in the kHz range. The high-frequency harmonic distortion of the current and voltage waveforms in PWM converters is produced by the voltage-source inverter using fast electronic switches which are commutated with very high rate of voltage rise (up to 50 kV/μs) and pulse repetition frequency (about 10-50 kHz) [1, 2]. As an example, Figures 1 and 2 present the distorted current and voltage waveforms generated by LS800-42K2-TD frequency converter with dc-link and registered by digital oscilloscope during laboratory measurements [3]. According to LS800-42K2-TD specification, the space vector PWM (SVPWM) switching frequency for insulated-gate bipolar transistor (IGBT) module can vary from 2 to 16 kHz. The amplitude-time-frequency representation of the distorted current and voltage waveforms registered on the output of the LS800-42K2-TD frequency converter was realized in Wolfram Mathematica using the simplified complex Morlet wavelet [4]. The high-frequency components in the 0.76-97.31 kHz range with the voltage peak values up to 199% and current peak values up to 78% (relative to peak value of the fundamental sinusoidal component) were identified. It was determined that the duration of these high-frequency components reaches up to tens microseconds-only a few milliseconds whereas their pulse edge is similar to square-wave signal one [3].

Fig. 1. Measured output phase current waveform.

Fig. 2. Measured phase-to-phase voltage waveform at the driven motor terminals.

Obtained peak values and durations of the high-frequency components are inherent in the current and voltage switching impulses limited by the International Electrotechnical Commission (IEC) standards. For

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instance, IEC 61800 requires the consideration of overvoltages due to commutation oscillations of up to 150% of the peak value of the fundamental voltage (periodically) or even 250% (non-periodically) for the design of low-voltage converters [5]. The high-frequency components with significant peak values cause accelerated thermal and electrical insulation aging of the driven motor, connecting cable, and dc-link capacitors. Furthermore, the resonant oscillations in the kHz range can appear originating failures of the PWM converter and driven motor elements. In the last few years, the practical examples with problems linked to kHz range harmonics were experienced mainly in the industry. Mostly variable speed drives in industrial environments were found stopping due to dc-link overvoltage. At least in one case investigated, a match between an internal rectifier resonance frequency with the disturbing network frequency contributed to the failure [1, 5].

From the author's experience, two cases with failures of motor modules due to breakdown of electrolytic dc-link capacitors in the Siemens SINAMICS S120 frequency converter for driving of the rolling mill leveler of the PJSC "Azovstal Iron & Steel Works" (Ukraine) were registered for the time frame from May 2012 to October 2012. The power rating of the driven induction motors is 1.5 MW whereas dc-link, consisting of the three separate modules with nine EPCOS B43564 electrolytic capacitors in each one, is an integral part of the motor module. It should be noted that the electrolytic capacitors are sharing 60% of the failure distribution for PWM converter elements as represented in Figure 3 [6].

Fig. 3. Failure distribution for PWM converter elements.

Fig. 4. Failure sources for electronic equipment.

The lifetime of electrolytic capacitors depends on both the rated lifetime at nominal conditions and the actual experienced stresses in the field operation. Long life could be achieved with a large design margin in terms of voltage, ripple current, and temperature. Temperature, vibration, and humidity are the three major stressors that directly or indirectly induce failure in power electronic components. The U.S. Air Force Avionics Integrity Program conducted an investigation into the failure sources of electronic equipment in 1980s and reached the conclusion that temperature is the most dominant stressor as shown in Figure 4 [7].

Methods for predicting the effect of ripple current stress on the power losses, temperature rise, and expected lifetime of the dc-link capacitors used in the variable-frequency drives, power converters, rectifiers, electric vehicle drive systems, photovoltaic inverters, wind turbine and fuel cell power converters have been presented in [8-17]. But so far none of the recognized approaches has been applied for evaluating the functional reliability indices of the dc-link capacitors, such as the probability to aging failure (a conditional probability that capacitor will fail in a subsequent period t after having survived for T operating hours) and the unavailability of aging failure (average probability that capacitor is found not available due to aging failure).

This paper presents an approach to evaluate the effect of high-frequency components of the ripple current on the additional heating, loss of lifetime, and functional reliability indices reduction of the dc-link capacitors in PWM converters. The effectiveness of the proposed approach was demonstrated using case study with the dc-link capacitors of the Siemens SINAMICS S120 frequency converter for driving of the rolling mill leveler of the PJSC "Azovstal Iron & Steel Works" (Ukraine). Based on the comparative analysis, the four AVX FFVE4I0227K film capacitors instead of nine EPCOS B43564 electrolytic capacitors in dc-link were recommended to mitigate the negative impact introduced by the increased ambient temperature and additional heating due to kHz range harmonics of the ripple current.

2 Capacitor models and characteristics

The electrical model parameters, a ripple current spectrum, and the thermal model parameters are needed to evaluate the effect of high-frequency components of the ripple current on the reduction of dc-link capacitor functional reliability indices due to accelerated thermal insulation aging. Equivalent series resistance (ESR) and ripple current are the main parameters for electrical model. Ripple current is the root-mean-square (RMS) value of the alternating current (AC) caused by the ripple voltage. The ripple current value depends on dissipation factor (also known as the tangent of the loss angle $\tan \delta$) which in turn is defined by ESR. Dissipation factor depends on the supply voltage frequency, therefore a ripple current depends on frequency also. The permissible maximum ripple current values are commonly given by the manufacturer datasheets for frequencies 100 or 120 Hz (sometimes for frequencies

10 or 20 kHz). In addition, manufacturer often provides generic curves to determine the ripple current for other operating frequencies.

The ESR model of an electrolytic capacitor is shown in Figure 5 [8, 11], where the resistance R_0 accounts for the sum of resistances of foil, tabs, and terminals, R_1 represents the electrolyte resistance, C_1 represents the terminal capacitance, and the parallel combination of R_2 and C_2 represents the dielectric losses. According to Figure 5, the complex impedance of the capacitor is described as

$$Z_{\text{cap}} = \frac{1}{\frac{1}{R_2} - j2\pi f C_2} + R_1 + R_0 - \frac{j}{2\pi f C_1}, \quad (1)$$

where f is the frequency.

Only the real part of this impedance is needed to estimate the additional power losses and heating caused by the ripple current:

$$\text{ESR} = \text{Real}(Z_{\text{cap}}), \quad (2)$$

$$\text{Real}(Z_{\text{cap}}) = R_1 + R_0 + \frac{R_2}{1 + (2\pi f R_2 C_2)^2}. \quad (3)$$

Increasing temperature causes a decrease in ESR because the resistance R_1 is reduced due to the increased conductivity of electrolyte. The effect of temperature on R_1 is described by the following expression [8, 11]:

$$R_1 = R_{1\text{base}} \exp\left(\frac{T_{\text{base}} - T_{\text{core}}}{F}\right), \quad (4)$$

where $R_{1\text{base}}$ represents the value of R_1 at the base temperature T_{base} (27 °C), T_{core} is the capacitor core temperature, °C, and F is the temperature sensitivity factor, K⁻¹.

Fig. 5. ESR model of an electrolytic capacitor.

Parameters of the EPCOS B43564 electrolytic capacitor used in dc-link of the Siemens SINAMICS

S120 frequency converter driving the rolling mill leveler are given in Table 1 [11, 18].

Table 1. Parameters of the EPCOS B43564 electrolytic capacitor.

Parameters	Value
ESR at 100 Hz (mΩ)	23
Maximum impedance at 10 kHz (mΩ)	28
Resistance of foil, tabs, and terminals R_0 (mΩ)	5.03
Resistance of electrolyte at the base temperature $R_{1\text{base}}$ (mΩ)	6
Temperature sensitivity factor F (K ⁻¹)	21
Dielectric losses resistance R_2 (mΩ)	20
Terminal capacitance C_1 (μF)	4700
Dielectric losses capacitance C_2 (μF)	11.6
Capacitor core temperature T_{core} (°C)	40
Maximum permissible current (A)	37

Let's consider a possibility to use the film capacitors instead electrolytic ones in dc-link of the Siemens SINAMICS S120 frequency converter. For this purpose, the four AVX FFVE4I0227K film capacitors instead of nine EPCOS B43564 electrolytic capacitors were selected in each dc-link module.

When the operating frequency is higher than 1 kHz, the ESR value of the film capacitor can be modeled as a function of frequency by means of such equation [11]:

$$\text{ESR}(f) = (R_s - A_s) + K(f) \cdot A_s, \quad (5)$$

where R_s is the base resistance, A_s is a given by the manufacturer value depending on the capacitor size, $K(f)$ is the predefined function showing the effect of frequency which is usually given by plots in manufacturer datasheets. $K(f)$ is mathematically expressed as a cubic polynomial function as follows

$$K(f) = k_3 \cdot f^3 + k_2 \cdot f^2 + k_1 \cdot f + k_0, \quad (6)$$

where the coefficients k_0 - k_3 can be established by using the least square curve fitting.

In contrast with the electrolytic capacitor, the ESR value of film capacitor increases with the frequency. Its temperature-sensitivity is less than that of electrolytic capacitor because the ESR of film capacitor results mainly from the tabs and contact resistances, but not from the electrolyte [11]. Parameters of the AVX FFVE4I0227K film capacitor are presented in Table 2 [19].

Since the ESR values of electrolytic and film capacitors show frequency-dependent characteristics, a ripple current multiplier M_f is defined in (7) to characterize the ripple current at a given frequency [11]:

$$M_f = \frac{I_f}{I_{100}} = \sqrt{\frac{\text{ESR}_{100}}{\text{ESR}_f}}, \quad (7)$$

where I_{100} and ESR_{100} are the rated ripple current and ESR value at 100 Hz, respectively, I_f and ESR_f represent ripple current and ESR at frequency f .

Table 2. Parameters of the AVX FFVE4I0227K film capacitor.

Parameters	Value
ESR at 100 Hz (mΩ)	0.9
Base resistance R_s (mΩ)	0.9
Terminal capacitance C_1 (μF)	220
Parameter defined by height A_s	0.23
Coefficient k_3	$3.173 \cdot 10^{-7}$
Coefficient k_2	-0.000124
Coefficient k_1	0.02369
Coefficient k_0	1.014
Maximum permissible current (A)	100

The dc-link capacitor ripple current frequency spectra analysis realized in [11] for different operating conditions and modulation strategies shows that SVPWM gives the largest kHz range harmonics in mode when modulation index $M = 0.625$ and load power factor $\cos \varphi = 0.954$. In this case, amplitude of 20 kHz component is equal to 52% from the output phase current amplitude, amplitude of 40 kHz component – 14%, amplitude of 60 kHz component – 9.9%, and amplitude of 80 kHz component – 9%. Let's define the power losses in the considered electrolytic and film capacitors for this ripple current frequency spectrum because SVPWM is used for the Siemens SINAMICS S120 frequency converter. These power losses can be represented as the sum of power losses from the individual frequency current components:

$$P_{\text{cap}} = \sum ESR_{f_i} \cdot (I_{\text{cap } f_i})^2 = ESR_{100} \sum \left(\frac{I_{\text{cap } f_i}}{M_f} \right)^2, \quad (8)$$

where ESR_{f_i} is the ESR value at frequency f_i , $I_{\text{cap } f_i}$ is the RMS current of the frequency f_i component.

Table 3 shows the power losses for considered electrolytic and film capacitors. Capacitor hot-spot temperature

$$T_{h \text{ core}} = P_{\text{cap}} R_{th} + T_a, \quad (9)$$

where T_a is the ambient temperature, °C, R_{th} is the capacitor thermal resistance (for film capacitor $R_{th} = 7.2$ °C/W [19], for electrolytic one pressed against a large metal plate or chassis $R_{th} = 1.02$ °C/W [20]).

For Siemens SINAMICS S120 frequency converter $T_a = 40$ °C so $T_{h \text{ core}} = 52.3$ °C for electrolytic capacitor and $T_{h \text{ core}} = 62.9$ °C for film one were obtained by (9).

Table 3. Power losses for electrolytic and film capacitors.

f (kHz)	$I_{\text{cap } f_i}$ (%)	EPCOS B43564	AVX FFVE4I0227K
		$I_{\text{cap } f_i}$ (A)	$I_{\text{cap } f_i}$ (A)
10	2.1	0.777	2.1
20	52	19.24	52
30	5	1.85	5
40	14	5.18	14
50	3	1.11	3
60	9.9	3.663	9.9
70	1.5	0.555	1.5
80	9	3.33	9
90	1.5	0.555	1.5
100	3	1.11	3
P_{cap} (W)		12.099	3.185

3 Capacitor functional reliability indices

The lifetime for both electrolytic and film capacitors can be derived from the "lifetime doubles in every 10 °C" rule as follows [9, 11, 14]:

$$L = L_0 \cdot 2^{-\frac{\Delta\tau}{10}} = L_0 \cdot \exp(-\beta\Delta\tau), \quad (10)$$

where L and L_0 are the lifetimes under the real operating conditions and maximum permissible temperature of the hottest spot, respectively, $\Delta\tau$ is the additional insulation heating, °C, $\beta = 0.0693$ °C⁻¹ is the insulation aging factor.

Based on the assumption of normally distributed random variable $\Delta\tau$, the mean value and standard deviation of the capacitor lifetime, respectively

$$m_L = L_0 \exp(-\beta m_{\Delta\tau} + 0.5\beta^2 \sigma_{\Delta\tau}^2), \quad (11)$$

$$\sigma_L = m_L \sqrt{\exp(\beta^2 \sigma_{\Delta\tau}^2) - 1}, \quad (12)$$

where $m_{\Delta\tau}$ and $\sigma_{\Delta\tau}$ are the mean value and standard deviation of the additional insulation heating.

Weibull or normal distribution can be used to model the aging failures of dc-link capacitors caused by accelerated thermal insulation aging. Practical experience shows that the same historical reliability data can be successfully approximated by the both distributions.

In the case of Weibull distribution, the reliability function is

$$R(t) = \exp \left[- \left(\frac{t}{a} \right)^b \right], \quad (13)$$

where a and b are the scale and shape parameters.

The probability to aging failure (a conditional probability that capacitor will fail in a subsequent period t after having survived for T operating hours) is

$$P_f = F(t|T) = \frac{\exp\left[-\left(\frac{T}{a}\right)^b\right] - \exp\left[-\left(\frac{t+T}{a}\right)^b\right]}{\exp\left[-\left(\frac{T}{a}\right)^b\right]}. \quad (14)$$

The corresponding survival probability is

$$P_r = R(t|T) = 1 - F(t|T). \quad (15)$$

The unavailability of aging failure (average probability that capacitor is found not available due to aging failure) can be obtained using the concept proposed in [21, 22]. For this purpose, the period t is divided into N equal intervals, each having a length $\Delta t = t/N$. The following equations can be expressed:

$$U_a = \sum_{i=1}^N \left(1 - \frac{2i-1}{2N}\right) P_i, \quad (16)$$

$$P_i = \frac{\exp\left[-\left(\frac{(i-1)\frac{t}{N} + T}{a}\right)^b\right] - \exp\left[-\left(\frac{i\frac{t}{N} + T}{a}\right)^b\right]}{\exp\left[-\left(\frac{T}{a}\right)^b\right]}, \quad (17)$$

where U_a is the unavailability of capacitor aging failure. The availability is

$$A_a = 1 - U_a. \quad (18)$$

From the mathematical expression of the Weibull density distribution function, the following equations can be obtained for evaluating the mean value and standard deviation of the capacitor lifetime:

$$m_L = a\Gamma(1+1/b), \quad (19)$$

$$\sigma_L^2 = a^2[\Gamma(1+2/b) - \Gamma^2(1+1/b)], \quad (20)$$

where $\Gamma(1+1/b)$ and $\Gamma(1+2/b)$ are the gamma functions depending on the shape parameter b .

As only m_L and σ_L values were defined by using (11) and (12), the shape parameter b can be calculated by

$$\frac{\Gamma(1+2/b)}{\Gamma^2(1+1/b)} = 1 + \left(\frac{\sigma_L}{m_L}\right)^2. \quad (21)$$

Then scale parameter a is found from (19) using a known shape parameter b .

The differences between the normal distribution and Weibull distribution are not significant if the shape parameter $b \geq 3.9$. In case of normal distribution the reliability function is given by

$$R(t) = \frac{0.5 + P\left(\frac{m_L - t}{\sigma_L}\right)}{0.5 + P\left(\frac{m_L}{\sigma_L}\right)}, \quad (22)$$

where $P(t) = \frac{1}{\sqrt{2\pi}} \int_0^t e^{-t^2/2} dt$ is the probability integral.

The probability to aging failure

$$P_f = F(t|T) = \frac{P\left(\frac{t+T-m_L}{\sigma_L}\right) + P\left(\frac{m_L-T}{\sigma_L}\right)}{0.5 + P\left(\frac{m_L-T}{\sigma_L}\right)}. \quad (23)$$

The corresponding survival probability is found from (15).

The unavailability of aging failure can be derived from (16) where P_i is defined as

$$P_i = \frac{P\left(\frac{i\frac{t}{N} + T - m_L}{\sigma_L}\right) - P\left(\frac{(i-1)\frac{t}{N} + T - m_L}{\sigma_L}\right)}{0.5 + P\left(\frac{m_L - T}{\sigma_L}\right)}. \quad (24)$$

The availability can be obtained from (18). To demonstrate the effectiveness of the proposed approach, it has been assumed that $m_{\Delta\tau} = 12.3^\circ\text{C}$, $\sigma_{\Delta\tau} = 3^\circ\text{C}$ for electrolytic capacitor whereas $m_{\Delta\tau} = 22.9^\circ\text{C}$, $\sigma_{\Delta\tau} = 5^\circ\text{C}$ for film capacitor (these values are based on the results of $T_{h\text{core}}$ estimation). Table 4 presents the performance comparison and functional reliability indices for both electrolytic and film capacitors at the $T = 4000$ hrs, $t = 1000$ hrs.

Based on the obtained results it can be concluded that the functional reliability indices for both electrolytic and film capacitors are approximately similar if the aging failures are modeled by either Weibull or normal distribution. Both manufacturers have designed quite competitive capacitors with good characteristics and high reliability. However, it is better to use the four AVX FFVE4I0227K film capacitors instead of nine EPCOS B43564 electrolytic capacitors in dc-link because the film capacitors have the maximum permissible temperature which is 20°C higher than that for electrolytic ones. At the increased ambient temperature, such solution mitigates the negative impact introduced by the additional heating due to kHz range harmonics of the ripple current. Furthermore, the quantity, dimensions, and cost of the film capacitors are much lower.

Table 4. Performance comparison and functional reliability indices.

Parameters	EPCOS B43564	AVX FFVE410227K
Capacitor type	Electrolytic	Film
Quantity	9	4
Capacitance (μF)	4700	220
Total capacitance (μF)	42300	880
Dimensions (d×h, mm)	76.9×105.7	84.5×51
Maximum permissible current (A)	37	100
Rated voltage (V)	400	400
Maximum permissible temperature (°C)	85	105
Lifetime at 85 °C (hrs)	15000	35000
Cost (\$)	112	86
Total cost (\$)	1008	344
Functional reliability indices (Weibull distribution)		
P_f	0.101	0.091
P_r	0.899	0.909
U_a	0.043	0.043
A_a	0.957	0.957
Functional reliability indices (normal distribution)		
P_f	0.104	0.082
P_r	0.896	0.918
U_a	0.043	0.038
A_a	0.957	0.962
Mean time to failure, hrs	6500	7600

4 Conclusions

The main goal of the paper was to present an approach to evaluate the functional reliability indices for dc-link capacitors in PWM converters. A case study with the dc-link capacitors of the Siemens SINAMICS S120 frequency converter for driving of rolling mill leveler was used to demonstrate the effectiveness of the proposed approach. The dc-link capacitors failures due to accelerated thermal insulation aging were modeled using both Weibull and normal distribution. The results indicate that the failures of motor modules due to breakdown of electrolytic dc-link capacitors, registered for the time frame from May 2012 to October 2012, can be caused by the increased ambient temperature and additional heating due to high-frequency components of the ripple current. Based on the comparative analysis, the four AVX FFVE410227K film capacitors instead of nine EPCOS B43564 electrolytic capacitors in dc-link were recommended to improve reliability of motor modules.

The presented approach can be used to evaluate the functional reliability indices reduction of the driven motor and connecting cable, which is caused by the accelerated thermal and electrical insulation aging due to high-frequency components. Other practical applications of the proposed methodology include the estimation of the economical damage due to the kHz range harmonics

of the ripple current, and comparative analysis of cost-effectiveness of the passive and active filters to suppress ones.

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