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Capacitor loss analysis method for power electronics converters

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ABSTRACT

A capacitor is a major component that contributes to reducing the reliability of high-power density power electronics converters. The lifetime and reliability of capacitors are strongly influenced by temperature. An accurate loss measurement method is necessary to estimate temperature rise. However, practical capacitor loss measurement systems used in power electronics converters have not yet been developed because capacitor loss data provided by the manufacturer is usually measured under sinusoidal excitation, which is different from actual excitations of electronics converters. In this study, a capacitor loss measurement system for power electronics converters is proposed. The proposed measurement system can be used for fast capacitor loss measurement with high accuracy in a real circuit and capacitor loss analysis for each switching period of power electronics converters. To verify the accuracy of the loss measurement, the measured loss value of a filter capacitor used in a pulse width modulated inverter is compared with the calculated value. The experimental results show good agreement with the calculated capacitor loss.

1. Introduction

Advancements in power devices has significantly enhanced the power-density of power electronic converters. However, recent power converters must cope with high-temperature operation because heat dissipation in each power electronics component is increasingly difficult [1].

In power electronics components, capacitors typically have lower heat resistance than other components such as wide-gap semiconductor devices like SiC/GaN. Therefore, a capacitor is a major component that contributes to degrading the reliability of high-power density power converters [1,2].

The lifetime of capacitors can be estimated using the ambient temperature and self-heating temperature [3]. The characteristics of capacitors are usually evaluated under a sinusoidal current waveform, which is provided in the data sheet. However, the actual excitation currents of a capacitor in power electronic converters are complex square and/or triangular waveforms.

Capacitor loss under power electronic converter excitation can be measured using the calorimetric method [4,5]. In this method, the loss is measured from temperature rise in the chamber. Therefore, an insulation between the chamber and the outside air is required to improve the loss measurement accuracy. However, such insulation is very difficult. In addition, since the loss is measured when the temperature inside the chamber reaches steady state, the system requires significant amount of time for each measurement.

In this study, a capacitor loss analyzer (CLA) system is proposed under real power electronic converter excitation condition. The proposed system yields accurate capacitor loss directly measured from a real power electronics converter using current probe and voltage probe, and the capacitor loss is analyzed for each switching period of the power electronics converter.

2. Capacitor loss measurement system

Fig. 1 shows an example of the configuration of the CLA system for filter capacitor loss measurement in a single-phase inverter.

The CLA system is composed of a power electronics circuit, a pulse width modulated (PWM) pulse generator, a high-speed sampling digital recorder, and a computer with loss calculation software. The PWM pulse generator signals are synchronized with the measurement signal and fed into the switching devices; the capacitor current and the capacitor voltage are synchronously detected with the measurement signal.

The measured current and voltage values are stored in a high-speed sampling digital recorder (sampling frequency: 100 MHz, resolution:

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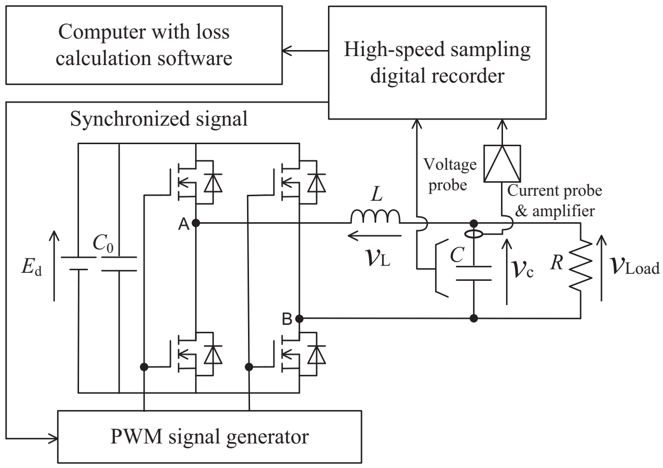

Fig. 1. System configuration of CLA.

16 bits). The values are transferred to the computer, and the capacitor loss during one switching period and the average capacitor loss value in steady state are calculated by the loss calculation software.

This system can be adapted for a DC link capacitor loss measurement system by changing the voltage and current sensor positions.

2.1. Accuracy of the capacitor loss measurement system

According to [6], using current probe and voltage probe degrades the loss measurement accuracy due to the phase error between the measured voltage and current signals. It has been shown that the error of the measured loss of low power factor device, such as inductor and capacitor, due to inaccurate measurement of the voltage and current phase displacement can be expressed as follows [6]:

$$k = \frac{\cos(\theta + \Delta\varphi(f)) - \cos\theta}{\cos\theta} \times 100\ [\%] \tag{1}$$

where k is the relative error as a percentage of the measured capacitor loss, θ is the actual phase angle between the voltage and current, and $\Delta\varphi(f)$ is the phase error of the voltage sensor and current sensor.

Fig. 2 shows the loss measurement error caused by the phase error, $\Delta\varphi(f)$. The relative error of the capacitor loss, k increases rapidly as the actual phase angle, θ approaches $-90°$, and the larger the phase error, $\Delta\varphi(f)$, the greater the increase in the measured capacitor loss error, k. For instance, when the phase angle of a film capacitor (Shizuki: TME 4.7 uF) is $-89.22°$, the loss measurement error reaches 38%, even though the phase error is only 0.3°.

In the case of the original phase characteristic in the CLA, the maximum phase error is 10.01° at 1 MHz. In the CLA, to compensate for the phase error between the measured voltage and current, the capacitor current, $i_C(t)$ is compensated by using Fourier series expansion (FSE). If the capacitor current, $i_C(t)$ is given and expressed in FSE, such as Eq. (2), the capacitor current, $i_C(t)$ can be compensated to $i_C^*(t)$ as given in Eq. (3).

$$i_C(t) = \sum_{n=1}^{k} \{a_n \cos(n\omega t) + b_n \sin(n\omega t)\}. \tag{2}$$

$$i_C^*(t) = \sum_{n=1}^{k} \{a_n \cos(n\omega t + \Delta\varphi(nf)) + b_n \sin(n\omega t + \Delta\varphi(nf))\} \tag{3}$$

where $i_C^*(t)$ is the compensated capacitor current.

Note: After phase compensation, the maximum phase error of the CLA is less than 0.013° in the frequency band from 1 kHz to 1 MHz. This indicates that the measurement error of the CLA is less than 1.67% at a capacitor phase angle of $-89.22°$.

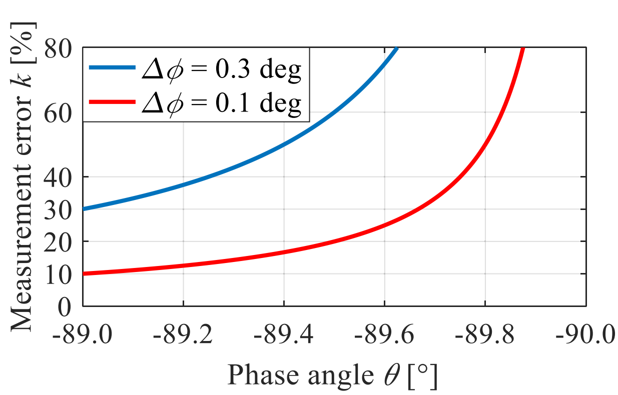

Fig. 2. Loss measurement error ratio.

2.2. Capacitor loss measurement method

In this study, the capacitor loss of an ac filter capacitor used in an inverter with PWM is calculated.

First, the switching period is detected from the PWM pulse generator signals. The definition of one switching period in unipolar PWM filter capacitor current is shown in Fig. 3. One switching period corresponds to one capacitor ripple current period. Once the switching period is identified, the instantaneous capacitor loss, $Q_{(n)}$ during the n-th switching period of the PWM inverter is calculated using the following equation:

$$Q_{(n)} = \int_{t_{(n)}}^{t_{(n+1)}} i_C^*(t) v_C(t) dt \tag{4}$$

where $v_C(t)$ is the capacitor voltage.

Note: the unit of $Q_{(n)}$ is Joule.

Then, taking the average of the summed values of the instantaneous capacitor losses, $Q_{(n)}$ during 1 cycle of the output frequency, T, the average capacitor loss, $P_{Capacitor}$ is calculated as follows:

$$P_{Capacitor} = \frac{1}{T} \sum_{n=1}^{n} Q_{(n)} \tag{5}$$

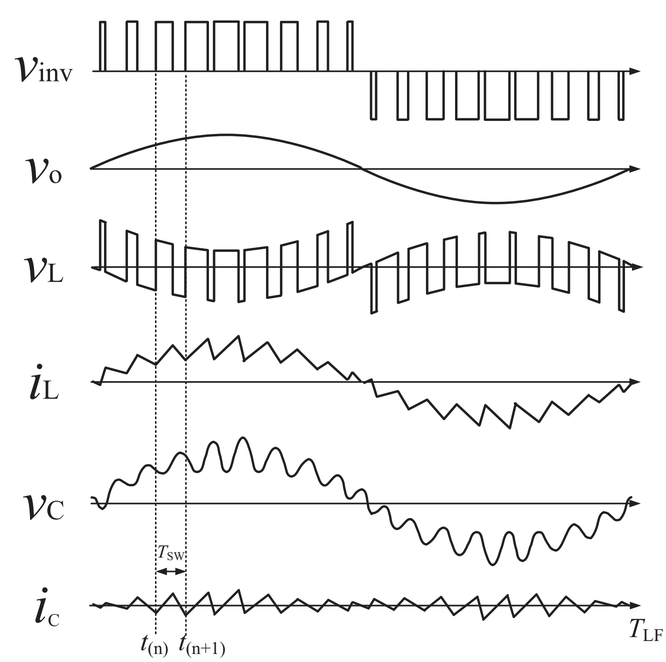

Fig. 3. Definition of one switching period.