Selection Criteria of Capacitors for Flying Capacitor Converters

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Multilevel converters have a number of capacitors as sources of multilevel voltages. The volume of the capacitors should be minimized to realize a high-power-density converter. In this paper, the selection criteria of the capacitors in a flying capacitor converter are investigated. In this type of converter, the required capacitance, consequently, volume of the capacitors are decreased when the PWM carrier frequency is higher. However, there is a limitation on the reduction in the volume due to the temperature increase caused by the power losses in the capacitors when the volume becomes small during high-PWM-frequency operation. On the basis of an investigation including the temperature increase, it is clarified that a capacitor with a high capacitance density is not necessarily the best for the flying capacitor depending on the operating conditions.

Keywords: capacitor, flying capacitor converter, multilevel converter, equivalent series resistance (ESR), power density

1. Introduction
In the case of multilevel converters, the volume of the capacitors that is required to maintain different voltages is a major concern for realizing converters with high power density. Among the various multilevel topologies, the flying capacitor converters shown in Fig. 1 are expected to be a promising solution to realize high power density in small power converters (1). On the other hand, the temperature rise of capacitors caused by power loss attributed to the equivalent series resistance (ESR) of the capacitors must be considered for appropriate selection (2). To realize an extremely high power density converter, the required capacitance and the allowable temperature rise.

In this study, selection criteria of the capacitors for the flying capacitor converters to minimize the size are investigated based on the characteristics of the capacitors such as capacitance density and ESR. From the results, the capacitors that are best suited for the flying capacitor converters are clarified on the basis of the operating conditions.

2. Requirements of Capacitors for Flying Capacitor Converters
2.1 Required Capacitance In the case of flying capacitor converters, the required capacitance of the capacitors is inversely proportional to the PWM carrier frequency \( f_{PWM} \) because the capacitors are charged and discharged in each PWM switching period (1). The required capacitance \( C_{FC} \) is expressed for a given voltage of the converter and capacitor as follows (2):

\[
C_{FC} = C_0 \cdot M_C \propto \frac{I_m}{f_{PWM} \cdot \Delta V_C} \tag{1}
\]

Here, \( C_0 \) is the capacitance per unit volume (capacitance density), \( M_C \) is the volume of the capacitor, \( I_m \) is the maximum instantaneous value of the load current, and \( \Delta V_C \) is the allowable voltage ripple of the capacitor. From (1), a capacitor with higher \( C_0 \) should be applied to minimize the size of the capacitor.

2.2 Allowable Temperature Rise The temperature rise of a capacitor must also be considered for selecting an appropriate capacitor. The temperature rise \( \Delta T_{FC} \) of a capacitor is obtained as follows.

\[
\Delta T_{FC} = R_t \cdot R_{ESR} \cdot I_{rms} \propto R_t \cdot R_{ESR} \cdot I_m^2 \tag{2}
\]

Here, \( R_{ESR} \) is the ESR of the capacitor, and \( I_{rms} \) is the RMS value of the capacitor current considering the duty ratio depending on the number of levels, modulation factor, and power factor of a load (2). \( R_t \) is the thermal resistance, which is inversely proportional to the surface area of the capacitor. Thus, we can obtain the following relationship between \( \Delta T_{FC} \) and \( M_C \).

\[
M_C \propto \frac{1}{R_t} \propto \frac{R_{ESR} \cdot I_m^2}{\Delta T_{FC}} \tag{3}
\]

In (3), it is approximated that the surface area of the capacitor is proportional to \( M_C \). The validity of this approximation has been confirmed statistically for a typical dimension of commercially available capacitors. The generated power loss must be decreased to maintain the temperature rise below the allowable level, despite a decrease in the volume. Thus, a capacitor with a low ESR should be selected to minimize the volume of the capacitor.

3. Suitable Type of Capacitor for Volume Reduction
From (1) and (3), it is found that a capacitor with high capacitance \( C_0 \) per unit volume and low ESR should be selected to realize a converter with high power density. Table 1 lists the typical characteristics of the actual commercially available capacitors (3,4). From this table, it can be inferred that...
class-II (high dielectric type) ceramic capacitors are suitable for use in flying capacitor converters owing to the fact that they exhibit the highest relative dielectric constant \( \varepsilon_r \), which is proportional to \( C_0 \). However, their \( \tan \delta \) which is the normalized value of the ESR, is two orders of magnitude greater than that of class-I (temperature compensation type) ceramic capacitors. On the other hand, although \( \tan \delta \) of plastic film capacitors is comparable to that of class-I ceramic capacitors, the former capacitors exhibit a much lower relative dielectric constant \( \varepsilon_r \) than both the abovementioned types of ceramic capacitors. Further, the capacitance of aluminum electrolytic capacitors is high, despite a low \( \varepsilon_r \), owing to their wafer-thin film construction \(^3\). However, their high ESR becomes a critical issue particularly in a high-frequency operation.

Figure 2 shows the theoretical selection criteria of the capacitors based on the lower limitations given by expressions (1) and (3). The straight line and curve show the lower limits of the capacitor volume determined by the voltage ripple and temperature rise, respectively. The capacitors must be selected in the shaded selectable area. On the left-hand and right-hand sides of the intersection between the line and the curve, the selectable area is determined by the ripple voltage and the temperature rise, respectively. When the PWM frequency is set to high, the slope of the straight line becomes gentler, and the intersection approaches the origin. In this case, the selectable area is determined by the curve in most of the operating area of the current, indicating that the limitation of the temperature rise becomes a dominant factor for the selection in the case of the high PWM frequency.

Therefore, the class-II ceramic capacitor is suitable when the voltage ripple of the capacitor determines design limitations such as a condition of low PWM frequency. In contrast, the class-I ceramic capacitor is suitable when the PWM switching frequency is high. In this case, the voltage ripple can be maintained under an allowable level with a low capacitance.

**4. Measurement of Temperature Rise of Capacitors**

In our experiment, we use a three-level flying capacitor converter to measure the temperature rises of the various capacitors, in order to verify the capacitor selection criteria discussed above. Table 2 lists six ceramic capacitors with different parameters used in this experiment. The input voltage, maximum value of the output current, and modulation factor of the converter are 100 V, 2.0 A, and 1.0, respectively. The PWM frequency is adjusted to obtain the same ripple voltage of the capacitors under all the experimental conditions, as shown in Fig. 3. In this regard, the ambient temperature is 30.0°C.

Figure 3 shows the experimental result obtained for the temperature rises of the capacitors. From this figure, it is observed that the temperature rise of the class-II capacitors (D–F) increases significantly. In particular, the temperature rises of capacitors E and F are greater than 20°C. On the basis of this observation, both capacitors E and F should not be selected because, typically, the temperature rise of a capacitor should not exceed 20°C from the ambient temperature. Therefore, the volume of a capacitor can be no less than 46.1 mm\(^3\) of that of capacitor E at least. In contrast, the temperature rises of the class-I capacitors (A–C) are low, even for a high PWM frequency, owing to a low ESR. In the case of capacitor C, whose volume is approximately identical to that of capacitor F, the temperature rise is less than 20°C, indicating that the volume can be reduced to less than 20.0 mm\(^3\) by increasing the PWM switching frequency. Thus, in the case when the capacitance and volume decrease with an increase in the PWM frequency, class-I capacitors can be used to minimize the capacitor volume.

**5. Conclusions**

This study investigates the selection criteria of the capacitors for the flying capacitor converters to realize high power density. From the results of this study, it has been clarified that class-I ceramic capacitors with a lower capacitance density than class-II capacitors are suitable in the case of a high switching frequency operation, where the limitation of the temperature rise of a capacitor is a dominant factor over voltage ripple. The results will also be useful in the selection of capacitors for some types of converters such as charge pump circuits whose charge and discharge operations are similar to those of a flying capacitor.

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**References**

1. T.A. Meynard and H. Foch: “Multi-level conversion High voltage choppers and voltage — source inverters”, Proc. IEEE PESC’92, pp.397–403 (1992)
2. H. Obata, M. Kamaga, T. Ito, and Y. Sato: “An Investigation of Capacitors for Flying Capacitor Converters”, IEEJ Trans. IA, Vol.131, No.12, pp.1393–1400 (2011) (in Japanese)
3. Murata Manufacturing Co., Ltd.: Fundamentals and Applications of Ceramic Capacitors (Seramikku Kondensa no Kiso to Ouyou), Ohmsha (2003) (in Japanese)
4. S.L. Swartz: “Topics in Electronic Ceramics”, IEEJ Trans. Electrical Insulation, Vol.25, No.5, pp.935–987 (1990)