On-Line Capacitance Estimation of DC-Link Electrolytic Capacitor by Input Current Injection for ac/dc PWM Converters

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Abstract: In this paper, a novel on-line capacitance estimation of dc link capacitor using input current injection is proposed for the ac/dc PWM converters. At no load, a controlled input current at a lower frequency than the line frequency is injected into the input side, which causes the dc voltage ripples at the output side. With the ac voltage and current ripple components on the dc side extracted by the digital filters, the capacitance can be calculated simply through a voltage-current relationship. This method can be implemented only by software without any additional hardware. It is shown that the estimation error is less than 1.5% from the experimental result.

Keywords: PWM converters, dc link, electrolytic capacitor, current injection, digital filters.

I. Introduction

In recent, the three-phase ac/dc/ac PWM converter is increasingly used for industrial applications such as mill drives, elevators, wind power generation system, UPS, and so on. The ac/dc/ac PWM converters usually have a dc link with large electrolytic capacitors as an energy buffer. The lifetime of the electrolytic capacitor is usually shorter than that of the other components of the power converter. The capacitance of the electrolytic capacitor is decreased according to aging [1]. It is known that its life is ended when the capacitance is reduced by more than 25% from the initial value [2]. Thus, it is necessary to decide the appropriate exchanging time of the capacitor for safe operation.

In spite of the importance of the large electrolytic capacitor in the power converters, the research results of them are very few. Ref. [1] proposed a fault diagnosis of the capacitor by estimating the ESR (equivalent series resistance) at specific temperature. However, it requires an additional hardware such as temperature sensors. Some references dealt with a life prediction of the capacitor [3] – [5], which algorithms are very complicated and they are difficult to estimate the lifetime precisely since the capacitor characteristics are sensitive to the operating frequency and temperature. Furthermore, these methods require the capacitor to be operated continuously without the pause.

The dc capacitor used for the most power converters is installed inside the system, so that it should be detached from the system to measure the capacitance by the instrument. It is very troublesome to measure the dc capacitance in the power converter of the wind power generation system which is located at the high tower or off-shore.

To overcome these difficulties, this paper proposes a novel one-line capacitance estimation method in the PWM converter systems. To diagnose the degree of deterioration, the capacitance of the capacitor is estimated periodically by using input current injection. At initial state before load application, a certain level of ac input current at a lower frequency than the power line frequency is injected into the ac/dc PWM converter. Then all the output current of the converter flows through the dc capacitor since the load is disconnected at initial state. The injected input current causes the dc ripple voltages on the output side. Since the dc link voltage is usually measured for the voltage regulation, the ripple voltage component can be extracted easily from the measured voltage by band-pass filters. On the other hand,
the dc-side current is not usually measured unlike ac-side currents used for current control and over-current protection. Instead, here, it can be estimated from the ac input current and the gating time of the switching devices. With the rms value of these ripple current and voltage, \( \tilde{I}_{\text{rms}} \) and \( \tilde{V}_{\text{rms}} \), respectively, the capacitance is calculated by

\[
C = \frac{\tilde{I}_{\text{rms}}}{\omega_{\text{in}} \tilde{V}_{\text{rms}}}
\]

where \( \omega_{\text{in}} \) is an angular velocity of the ac component. Compared with the capacitance value measured by the RLC meter, it is confirmed that the estimation error is less than 1.5%. The experimental result verifies the effectiveness of the proposed algorithm.

II. Estimation of Capacitance of DC Link Capacitor

1. Current injection

First, consider the operation of the ac/dc/ac PWM converter at no load, which means the inverter side is disconnected with the dc link. If the dc output voltage is well controlled at the reference value, the q-axis current reference is zero and the dc voltage is kept constant except the switching frequency-related ripple component. Here, if ac current at a low frequency, for example, of 30Hz is injected into the PWM converter, the pulsed current of which fundamental frequency is 30Hz flows through the dc capacitor. This ac current incurs the ripple voltage component at 30Hz.

Since the capacitance of the capacitor is calculated in steady state of sinusoid as

\[
C = \frac{\tilde{I}_{\text{rms}}}{\omega_{\text{in}} \tilde{V}_{\text{rms}}}
\]

Fig. 1 Block diagram of estimating dc capacitance for three-phase PWM converters
The lower the frequency of the injected current at the same magnitude, the larger the dc ripple voltage. Thus the low frequency current component is desirable to obtain a significant component of the ripple voltage since the allowable ripple current level of the capacitor is not so high[6].

Fig. 1 shows an overall block diagram for estimating the dc capacitance of the PWM converter which involves the dc output voltage and ac input current control. The ac current is transformed into the d- and q-axis currents in a synchronous reference frame. The d-axis current is controlled to be zero at unity power factor of the source side and the q-axis current is regulated to control the dc voltage. At no load, the q-axis current becomes zero.

When a certain level of ac current reference at 30[Hz] is added to the q-axis current reference, ac ripple current at 30[Hz] flows through the dc capacitor, which causes ac ripple voltage at the same frequency. With these ripple current and voltage, the capacitance can be found by (1).

2. DC link ripple current

To calculate the capacitance in (1), it is needed to measure the capacitor current. While the ac input current is measured for current control and over-current protection, the dc link current is scarcely done. Instead, the dc link current can be reconstructed from the ac input currents and switching function as [7], [8]

\[ i_{dc} = S_a i_{as} + S_b i_{bs} + S_c i_{cs} \]  \hspace{1cm} (2)

Since the instantaneous current of the capacitor in (2) is of the pulsed-waveform, it is not easy to obtain the rms value. After eliminating the high frequency component by the low-pass filter, only the ripple component at the frequency of the injected current can be obtained by using the band-pass filter. However, this process is complicated.

Fig. 2 Instantaneous and averaged dc-link currents according to gating pulses and phase currents
Instead, using the gating time and the phase currents, the mean value of the dc link current each sampling period can be found as

\[
\bar{i}_{dc} = \frac{T_{ga}i_{a} + T_{gb}i_{b} + T_{gc}i_{c}}{T_{samp}}
\]

where \(T_{ga}, T_{gb}, \text{ and } T_{gc}\) are gating times of each phase and \(T_{samp}\) is the sampling period.

Fig. 2 shows the relationship between the phase current and the dc link current according to the switching state. The waveform of \(\bar{i}_{dc}\) shows a natural filtering effect. If the dead time of the switching devices is compensated well, its effect in (3) can be neglected[9].

3. Digital filtering

To extract the ac ripple component required from the measured dc voltage and the estimated dc link current in (3), a second-order band-pass filter is used[10], [11]. The transfer function of it is as

\[
H_{BPF}(s) = \frac{K_{BPF} \left( \omega_{BPF} / Q_{BPF} \right) s}{s^2 + (\omega_{BPF} / Q_{BPF}) s + \omega_{BPF}^2}
\]

where \(K_{BPF}\) is a gain, \(Q_{BPF}\) is a quality factor, \(f_{BPF}\) is a cut-off frequency, and \(\omega_{BPF} = 2\pi f_{BPF}\). The filter output is not so sensitive to the quality factor since there is no other components near 30[Hz]. Fig. 3 shows frequency response of the band-pass filter in case that \(K_{BPF} = 1, Q_{BPF} = 4, \text{ and } f_{BPF} = 30[Hz]\).

On the other hand, the dc ripple voltage component should be rejected since the average value of the dc link voltage should be fed back for the dc voltage control. For this, so, a second-order band-stop filter is used, of which transfer function is given by

\[
H_{BSF}(s) = \frac{K_{BSF} (s^2 + \omega_{BSF}^2)}{s^2 + (\omega_{BSF} / Q_{BSF}) s + \omega_{BSF}^2}
\]

where \(K_{BSF}\) is a gain, \(Q_{BSF}\) is a quality factor, \(f_{BSF}\) is a cut-off frequency, and \(\omega_{BSF} = 2\pi f_{BSF}\). Fig. 4 shows the frequency response of the band-stop filter in case that \(K_{BSF} = 1, Q_{BSF} = 2, \text{ and } f_{BSF} = 30[Hz]\).
The voltage filtered by the band-pass filter still contains the high frequency components due to the switching action of the devices. To eliminate these components, a second-order low-pass filter is used, of which transfer function is given by

$$H_{LPF}(s) = \frac{K_{LPF} \omega_{LPF}^2}{s^2 + (\omega_{LPF}/Q_{LPF})s + \omega_{LPF}^2}$$  \hspace{1cm} (6)

where $K_{LPF} = 1$, $Q_{LPF} = 2$, $f_{LPF} = 200[Hz]$, and $\omega_{LPF} = 2\pi f_{LPF}$ are chosen for experiment.

### 4. Calculation of the rms value

The rms value of the ac ripple voltage and current filtered by the band-pass filter is calculated by

$$\tilde{V}_{dc} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \tilde{V}_{dc}^2(k)}$$  \hspace{1cm} (7)

and

$$\tilde{I}_{dc} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \tilde{I}_{dc}^2(k)}$$  \hspace{1cm} (8)

where $N$ is the number of the sampling point for one cycle of the ac ripple component. Substituting for (7) and (8) into (1), the capacitance can be calculated.

### III. Experimental Results

To verify the effectiveness of the proposed scheme, the experiment has been carried out at laboratory. Fig. 5 shows the experimental set-up. The experiment condition is listed in Table I. The nominal capacitances used for test are compared with that of the measured ones.

Fig. 6(a) shows the voltage controller output $i_{q,e0}$ at no load and the injected q-axis current reference $i_{q,in}$, and (b) shows the modified reference $i_{q,e}$ which is obtained by adding these two references. Since the d-axis current is controlled to be zero at unity power factor, the q-axis current is kept almost zero at no load. So, $i_{q,e}$ is equal to $i_{q,in}$.

![Fig. 5 Experimental set-up](image)

<table>
<thead>
<tr>
<th>Table I System parameters</th>
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<tbody>
<tr>
<td>Input voltage</td>
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<tr>
<td>Input boost inductance</td>
</tr>
<tr>
<td>Line resistance</td>
</tr>
<tr>
<td>Converter capacity</td>
</tr>
<tr>
<td>Switching frequency</td>
</tr>
<tr>
<td>Injection current</td>
</tr>
<tr>
<td>dc-link voltage</td>
</tr>
<tr>
<td>Capacitor</td>
</tr>
<tr>
<td>$C_1 = 3300[μF]$</td>
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<tr>
<td>$C_2 = 2350[μF]$</td>
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<tr>
<td>$C_3 = 500[μF]$</td>
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</table>
Fig. 7 shows the q-axis current control performance. Control over ac component is well done, too.

Fig. 8 shows the dc link currents, where (a) is the dc current measured directly by the current probe and (b) is the waveform reconstructed from (3), and (c) is the band pass-filtered one from the waveform of (b). Fig. 9 shows the harmonic spectrum of dc link currents corresponding to Fig. 8. It is seen that the other frequency components are completely eliminated after passing the BPF.

Fig. 10 shows the dc output voltages, where (a) is the measured one and (b) is the band stop-filtered waveform for voltage feedback control, (c) is the band pass-filtered voltage from (b) for the rms value. Fig. 11 shows the harmonic spectrum of the dc ripple voltage corresponding to Fig. 10. The performance of the filters is very satisfactory.

Fig. 12 shows the variation of the capacitance value, dc link ripple voltage, and current in case that C3 is open abruptly while C2 and C3 in Table I are being operated in parallel connection. Even though the capacitance value is changed abruptly, it is observed that it is well estimated.

Table II shows the comparison of the estimated and measured data for the different capacitance of the capacitor. The estimation error is less than 1.5% in all cases.
IV. Conclusions

In this paper, a novel on-line capacitance estimation method for the three-phase ac/dc/ac PWM converter has been proposed and implemented. This scheme requires no extra hardware, which is executed in software only by injecting ac input current and signal processing with digital filters. It is observed experimentally that the capacitance estimation error is less than 1.5%. The proposed algorithm is very effective for diagnosis of the dc electrolytic capacitor’s deterioration for the ac/dc/ac PWM converter system.

References


