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DC LINK CURRENT IN SINGLE PHASE H-BRIDGE INVERTERS

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ABSTRACT

The dc-link current in pulsed power inverters has in addition to the dc-value a substantially ac-component. This current heads up the dc-link capacitors and must be considered for the inverter dimensioning. Because these capacitors have a major impact on the volume, weight and costs of inverters the current must be exactly determinates. In this paper the rms-current in the dc-link capacitor is calculated depending on the phase output current amplitude, phase shift angle and inverter modulation factor. The calculations are verified by practical measurements.

INTRODUCTION

In the dc-link circuit of pulsed voltage source inverters in addition to the dc-current a substantial ac-current component is produced. The ac-current heads up the dc-link capacitors and contributes substantially to the volume, weight and costs of inverters. For this reason the necessary amount of capacitors has to be determined to prevent over design if possible [1]. In this paper the dc-link current in pulsed voltage source inverters is analysed. The power stage of a single phase inverter consists of an inverter bridge, an input circuit with dc-link capacitors and a filter circuit on the ac-output side [2].

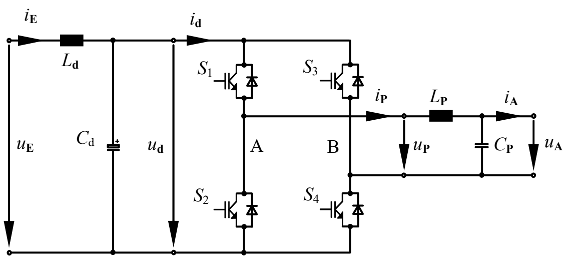

Fig. 1. Power stage of an H-bridge inverter

These H-bridge inverter can be controlled with two (Fig.2) or three voltage levels (Fig. 3), described by the voltage difference u_P of the bridge-legs voltage in the figures.

Below in the figures the fundamental portion of the voltage u_{P1} for both control schemes is presented. Besides the voltage a sine output current i_{P1} with a phase shift angle is shown.

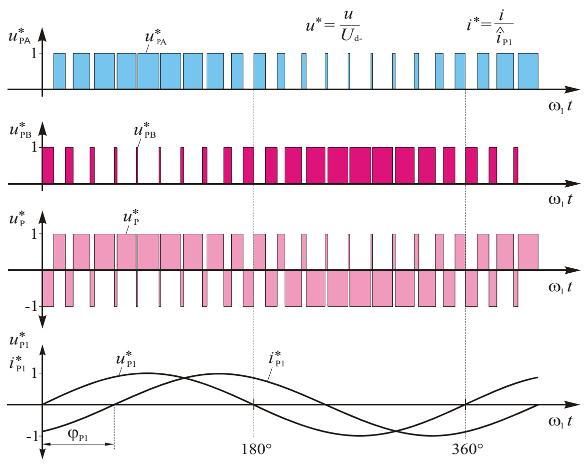

Fig. 2. Control scheme with two voltage levels

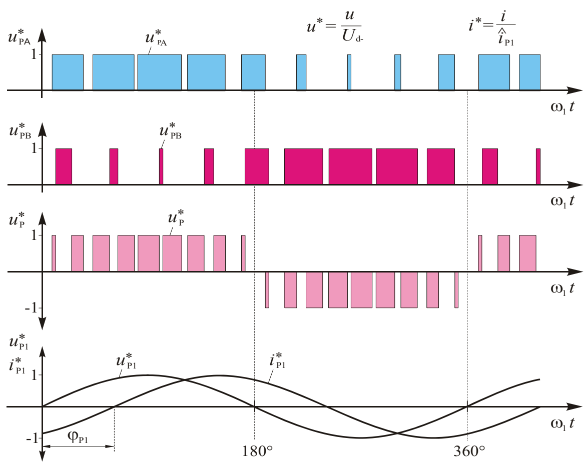

Fig. 3. Control scheme with three voltage levels

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DC-LINK CURRENT CALCULATION

Now the current in the dc-link circuit for a two voltage levels control H-bridge inverter will be calculated. Beside a sinusoidal duty cycle shape that means a sine wave modulated voltage u_P, a sine wave current i_{P1} at the output of the inverter bridge is assumed. Moreover, the dc-link voltage u_d is presumed as constant. With these conditions the dc-link current of the inverter can be split in a dc-component, an ac-component with double fundamental frequency and a higher-frequency component [3]. The input current and its split into the components for ohmic load in Fig. 4 and for inductive load in Fig. 5 are shown [4, 5].

The middle part of the figures shows the current pulses at the input of the inverter. The positive and negative sinusoidal current build the envelope curve for the inverter input pulses. The instantaneous value of the current in the pulse periods depends on the amplitude $\hat{\imath}_{P1}$, the phase shift angle φ_{P1} and the actual duty cycle of the modulation factor m.

In the following formulas the waveform of the current and the related duty cycles in the switch-on state - that means the connection to positive, and in switch-off state the connection to negative terminal of dc-link capacitors are shown.

Switch-on state current and duty cycle:

$$i_{de}(t) = \hat{i}_{P1} \cdot sin(\omega_1 t - \varphi_{P1}) \tag{1}$$

$$\frac{t_e(t)}{T_P(t)} = \frac{1}{2} \cdot \left[1 + m \cdot sin(\omega_1 t)\right] \tag{2}$$

Switch-off state current and duty cycle:

$$i_{da}(t) = -\hat{i}_{P1} \cdot sin(\omega_1 t - \varphi_{P1}) \tag{3}$$

$$\frac{t_a(t)}{T_P(t)} = \frac{1}{2} \cdot \left[1 - m \cdot sin(\omega_1 t)\right] \tag{4}$$

for $0 \le m \le 1$ and $-180° \le \varphi_{P1} \le 180°$

The average-value of the current pulse in each individual period results in a waveform consisting of a dc-current which is superimposed by an alternating current with double fundamental frequency $[I_{d-} + i_{d2}(t)]$.

This current can be determined by multiplication of the current - with the duty cycle formulas. The sum of the two partial results gives the expected current waveform.

$$I_{d-} + i_{d2}(t) = i_{de}(t) \cdot \frac{t_e(t)}{T_P(t)} + i_{da}(t) \cdot \frac{t_a(t)}{T_P(t)} \tag{5}$$

$$I_{d-} + i_{d2}(t) = m \cdot \hat{i}_{P1} \cdot sin(\omega_1 t - \varphi_{P1}) \cdot sin(\omega_1 t) \tag{6}$$

The split of this current show: The dc-component is depended on the phase shift angle φ_{P1} and the modulation factor m. However, the rms-current of the double fundamental frequency portion has the same value at all phase shift angles φ_{P1} and varies only with the modulation factor m. Having controlled the inverter with three voltage levels these two components show the same results [1, 4, 5].

Dc-current I_{d-} and double fundamental frequency current $I_{d2}(t)$:

$$I_{d-} = \frac{m \cdot \hat{i}_{P1}}{2} \cdot cos(\varphi_{P1}) \tag{7}$$

$$I_{d2} = \frac{m \cdot \hat{i}_{P1}}{2 \cdot \sqrt{2}} \tag{8}$$

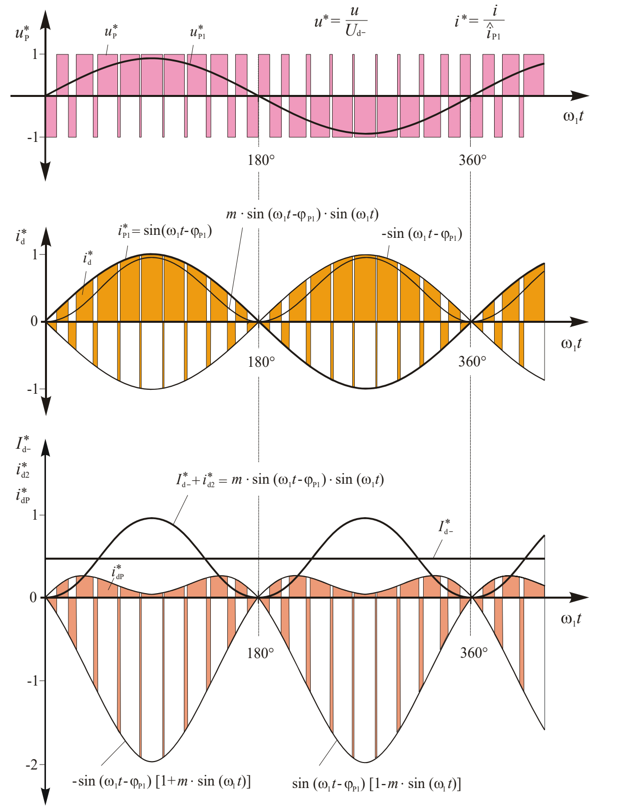

Fig. 4. Input current in a two level controlled Inverter (φP1 = 0°)

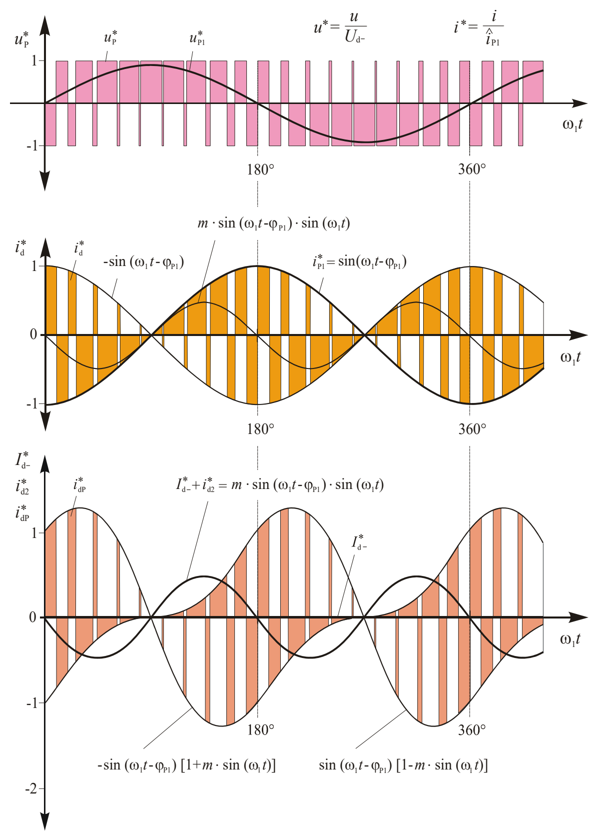

Fig. 5. Input current in a two level controlled Inverter (φ_{P1}=90°)

With the low-frequency current waveform of equation 6 the envelopes of the higher-frequency current portion are now determined. This can be done by subtracting the low-frequency current portion from the output current and the inverting output current. The higher-frequency current portion is shown below in Fig. 4 and Fig 5.

Higher frequency current portion in switch-on $i_{dO\ e}(t)$ and switch-off state $i_{dO\ a}(t)$:

$$i_{dOe}(t) = \hat{i}_{P1} \cdot sin(\omega_1 t - \varphi_{P1}) \cdot [1 - m \cdot sin(\omega_1 t)] \tag{9}$$

$$i_{dOa}(t) = -\hat{i}_{P1} \cdot sin(\omega_1 t - \varphi_{P1}) \cdot [1 + m \cdot sin(\omega_1 t)] \tag{10}$$

With the duty cycles in the switch-on and switch-off state the rms-value of the high frequent current can be determinate by integration. Then the geometric sum of the two partial values gives the result.

$$I_{dO}^2 = \frac{1}{\pi} \cdot \int_0^{180°} \left[i_{dOe}^2(t) \cdot \frac{t_e(t)}{T_P(t)} + i_{dOa}^2(t) \cdot \frac{t_a(t)}{T_P(t)} \right] d\omega_1 t \tag{11}$$

$$I_{dO} = \hat{i}_{P1} \cdot \sqrt{\frac{1}{8} \cdot \left[4 - m^2 \cdot \left(1 + 2 \cdot cos(\varphi_{P1})^2 \right) \right]} \tag{12}$$

The rms-result shows the higher frequency dc-link rms-current is depended on the fundamental phase shift angle φ_{P1} and the modulation factor m. The maximum rms-value of this current is $I_{do\ max} \approx 0.71\ \hat{i}_{P1}$.

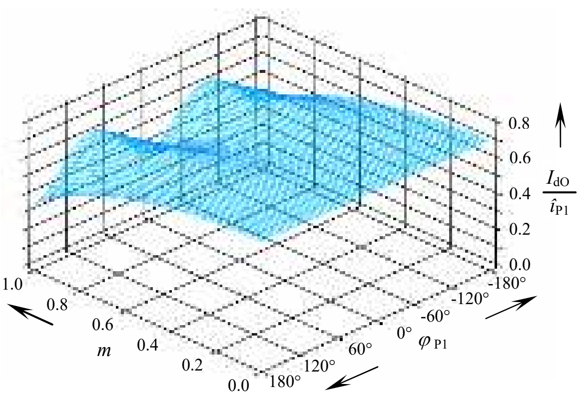

Fig. 6. Higher frequency dc-link rms-current for control with two voltage levels

For control of the inverter with three voltage levels, the currents in the dc-link circuit are also calculated [1, 4, 5]. The rms-result is shown in the following formula.

$$I_{dO} = \hat{i}_{P1} \cdot \sqrt{\frac{m}{24 \cdot \pi} \cdot [24 - 6 \cdot \pi \cdot m + (8 - 3 \cdot \pi \cdot m) \cdot cos(2\varphi_{P1})]} \tag{13}$$

The equation 13 shows: For inverter control with three voltage levels the higher frequency rms-current in the dc-link circuit also depends on the phase angle φ_{P1} and the modulation factor m. But the maximum value is much lower $I_{do\ max} \approx 0.35\ \hat{i}_{P1}$.

Now the higher frequency dc-link rms-current for control with two (Fig. 6) and three voltage levels (Fig. 7) can be compared with each other. Over a wide range the rms-current value for control with three voltage levels is clearly smaller. The maximum value is half as large in case of control with three voltage levels.

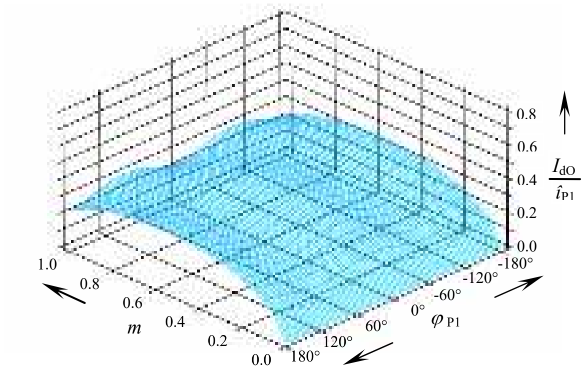

Fig. 7. Higher frequency dc-link rms-current for control with three voltage levels

DC-LINK CURRENT MEASUREMENTS

Now the calculated current in the dc-link circuit will be compared with practical measurements of an IGBT inverter. The inverter (Fig.1) has a dc-link voltage of $U_{d-} = 108$V and a nominal output power of $P_{AN} = 1200$W. The inverter can be controlled with two - or with three voltage levels.

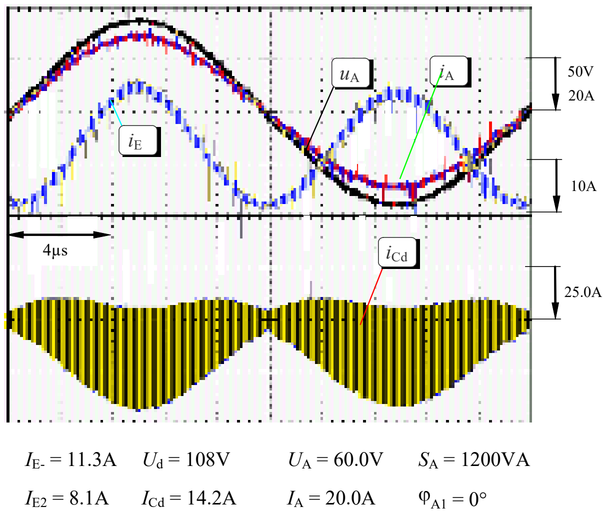

Fig. 8. Practical measurements in case of control with two voltage levels [6]

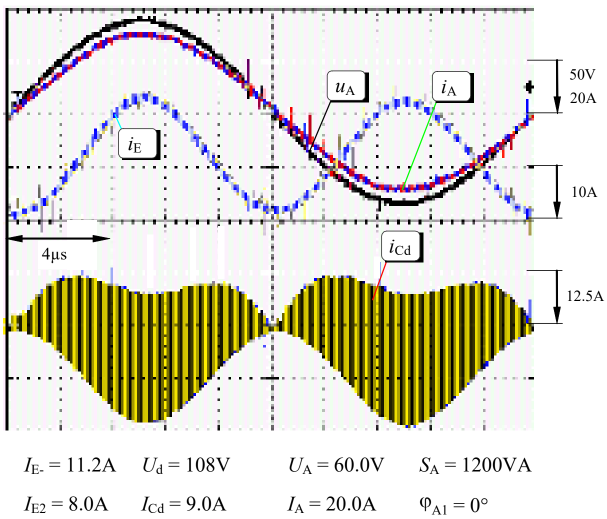

Fig. 9. Practical measurements in case of control with three voltage levels [6]

The sine output values u_A and i_A as well as the input current i_E of the inverter for control with two voltage levels in Fig. 14 and with three voltage levels in Fig. 15 are presented. In each case the inverter operates with nominal ohmic load. The dc-link voltage of 108V is approximately constant in all cases (not presented). The current in the dc-link capacitors i_{Cd} is shown below in the diagrams. The scales of the electrical values are presented on right figure-side, whereby the tip of each arrow marks the zero-line.

The results show that the inverter input current i_E consists of a dc-component I_{E-} with a double fundamental frequency portion i_{E2}. Because of the high inverter switching frequency the envelope curve of the capacitor current i_{Cd} is visible. The waveform repeats after a half fundamental period. The small asymmetry in the current curve can be seen. The reason is a small double fundamental current in the dc-link capacitors and a small phase shift angle at the output filter circuit. In principle the waveforms correspond very well with the mathematical derivations.

CONCLUSION

In this publication the dc-link current has to be calculated for single-phase H-bridge inverters. Thereby a constant input dc-voltage as well as a sine current and voltage waveform at the inverter output is assumed. The result shows the bridge input current can be split in a dc -, a double fundamental frequency - and a higher-frequency component. The dc-component completely flows into the input of the inverter. The double fundamental frequency current is split into the dc-link capacitor - and the inverter input depends on the dc-link inverter design. The higher-frequency current flows almost completely through the dc-link capacitors.

The influence of inverter output harmonics, which result from the filter circuit and from the switching transitions in the inverter bridge, is analyzed too [6]. It is shown that with small output power significant capacitor load is caused by these harmonics. But with higher output power the calculated capacitor current of the sine output current dominates in most applications.

Finally the calculations are compared with practical measurements of an IGBT inverter. There is an obvious correspondence between the calculated and measured values.

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