CORRESPONDENCE

Losses in PWM converters using IGBTs: On the effect of bus-clamping on the distortion of the AC-side currents

Indexing terms: PWM inverters, IGBTs, Switching losses

In [1] the conduction and switching losses of power semiconductors have been calculated analytically for the continuous and discontinuous modulation of a 3-phase voltage DC link PWM converter system. However only a relatively coarse estimate was given there for the switching losses occurring for discontinuous modulation. Therefore, in [2] a discussion was published (serving as a completion of the mentioned estimate) giving a detailed analysis for the reduction $k_{f,k}^{-1}$, k = 4, 5, 6, 7, of the switching losses for discontinuous modulation. There, the pulse frequency has been assumed to stay equal as for continuous modulation. Also a possible increase $k_{f,k}$ of the effective pulse frequency for equal switching losses was considered.

Now, in the author's reply, general questions were raised (questions which go beyond the scope of the original contribution [1]) concerning the following issues:

• for an increase in the RMS value of the phase current harmonics one has to pay for the reduction in the switching losses (resulting from the case of maintaining the pulse frequency for discontinuous modulation), and/or

• whether for equal switching losses (i.e. for appropriate increase of the pulse frequency) for discontinuous modulation there is a reduction in the harmonic current RMS value below the value given for continuous modulation.

Therefore, in the following (as an extension of [2]) we want to compare the RMS values of the phase current harmonics (and/or the harmonic losses) resulting for harmonic-optimal continuous modulation and for the different discontinuous modulation methods. Also, we want to determine the modulation method being optimal for a given modulation index M and given power factor (load current phase angle φ). For the sake of brevity we omit mathematical derivations and consider only graphical representations of the results.

As already mentioned, we use as a basis for the comparison of the modulation methods the RMS value $\Delta I_{N,rms}$ of the distortion and/or harmonic content

$$\Delta i_N = i_N - i_N^* \qquad (1)$$

of a phase current i_N of the converter system resulting in each case. There, i_N^* denotes the reference value related to i_N and being of sinusoidal shape in general. There, the square of the RMS value of the current distortion

$$\Delta I_{N,rms}^2 = \frac{1}{T_N}\int_0^{T_N} \Delta i_N^2 dt \qquad (2)$$

can be interpreted as normalised harmonic power loss.

According to [4], for *continuous* modulation the possibility for a minimisation of the harmonic loss is given by modification of the shape of the phase modulation function (being sinusoidal in the simplest case) by addition of a 3rd harmonic. Harmonic-optimal continuous modulation $\Delta I_{N,rms}^2 \rightarrow$ min is obtained for $\hat{U}_{U,(3)} = 1/4\hat{U}_U^*$. There, $\hat{U}_U^* = \hat{U}_{U,(1)}$ denotes the required fundamental of the phase voltages and $\hat{U}_{U,(3)}$ the amplitude of the 3rd harmonic (being equal for all phases). However, for this control method only a limited control region is given (cf. Fig.10 in [5]). Therefore, in the following the control method $\hat{U}_{U,(3)} = 1/6\hat{U}_U^*$ (mentioned also in [1] in connection with the calculation of the conduction and switching losses), which guarantees full controllability, is considered as being characteristic for the optimal continuous modulation concerning the harmonic losses. This is admissible because (as a more detailed analysis shows, Fig.11 in [5]) a change of the amplitude of the 3rd harmonic in the vicinity of the optimum $\hat{U}_{U,(3)} = 1/4\hat{U}_U^*$ has only a minor influence on the resulting harmonic losses. To denote the (sub)optimal continuous modulation method in the following the index 2 will be used.

Remark: As shown in [5], modulation method 2 is equivalent (concerning the control region and the resulting harmonic losses) largely to a continuous modulation method which is based on space vector calculus and which is called in general space-vector-modulation (cf. p. 1200 in [6]), having wide industrial application.

As opposed to continuous modulation, for *discontinuous* modulation [4–7] (cf. Fig.1 in [2]) no possibility for minimising the harmonic loss by modification of the shape of the phase modulation functions is given. The reason is that clamping of one phase is obtained by setting the value of one modulation function m_i in the different time intervals to $m_i = \pm 1$. There, the shapes of the two other phase modulation functions are completely determined by the requirement to generate sinusoidal line-to-line voltages (cf. Fig.1 in [2]). Therefore, discontinuous modulation functions are basically characterised by a non-harmonic-optimal shape of the modulation functions. Therefore, they show higher harmonic losses than given for (sub)optimal continuous modulation 2 or space vector modulation with equal pulse frequency (cf. Fig.1, $k_{f,k} = 1$, k = 2, 4, 5, 6, 7). This is also shown by the considerations made in [3].

In Fig. 1 the dependency of the harmonic losses on the modulation index $M = 2\hat{U}_U^*/U_{ZK}$ for continuous and discontinuous modulation is shown. The representation is based on the following relations:

$$\Delta I_{N,rms,2}^2 = \frac{1}{6}\Delta i_n^2 M^2\left\{1 - \frac{8M}{\sqrt{3}\pi} + \frac{3M^2}{4}[1 - k_{31}(1 - 2k_{31}]\right\}$$

$$\Delta I_{N,rms,4}^2 = \frac{1}{6}\Delta i_n^2 M^2 \frac{1}{k_{f,4}^2} \times \left[4 - \frac{M}{\sqrt{3}\pi}(62 - 15\sqrt{3}) + \frac{9M^2}{8}\left(2 + \frac{\sqrt{3}}{\pi}\right)\right]$$

$$\Delta I_{N,rms,5}^2 = \frac{1}{6}\Delta i_n^2 M^2 \frac{1}{k_{f,5}^2} \times \left[4 - \frac{M}{\sqrt{3}\pi}(8 + 15\sqrt{3}) + \frac{9M^2}{8}\left(2 + \frac{\sqrt{3}}{2\pi}\right)\right]$$

$$\Delta I_{N,rms,6}^2 = \frac{1}{6}\Delta i_n^2 M^2 \frac{1}{k_{f,6}^2}\left[4 - \frac{35M}{\sqrt{3}\pi} + \frac{9M^2}{8}\left(2 + \frac{3\sqrt{3}}{4\pi}\right)\right]$$

$$\Delta I_{N,rms,7}^2 = \frac{1}{6}\Delta i_n^2 M^2 \frac{1}{k_{f,7}^2}\left[4 - \frac{35M}{\sqrt{3}\pi} + \frac{9M^2}{8}\left(2 + \frac{3\sqrt{3}}{4\pi}\right)\right] \qquad (3)$$

and $k_{31} = \hat{U}_{U,(3)}/\hat{U}_{U,(1)}$, which result from extensive analytical calculations [4]. Fig. 1 is based on $k_{f,k} = 1$; this means that the frequency increase possible for discontinuous modulation is not considered *a priori*. The harmonic losses of the modulation methods [4–7] are higher than for (sub)optimal continuous modulation 2 for all values of M. Only at the control limits $M \rightarrow 2/\sqrt{3}$ and $M \rightarrow 0$ do all modulation methods show approximately equal harmonic losses $\Delta I^2_{N,rms}$. This can be explained clearly for $M \rightarrow 2/\sqrt{3}$ by the largely equal time behaviour of the modulation functions of (sub)optimal continuous and discontinuous modulation (cf. Fig. 8 in [7]). $M = 0$ is obtained ideally for both modulation methods by free-wheeling of the converter. The phase current shape in this case is determined exclusively by the (in general) sinusoidal source voltage of the load (inverter operation) or by the mains voltage (rectifier operation); therefore, the phase currents have purely sinusoidal shapes and $\Delta I^2_{N,rms} = 0$ follows.

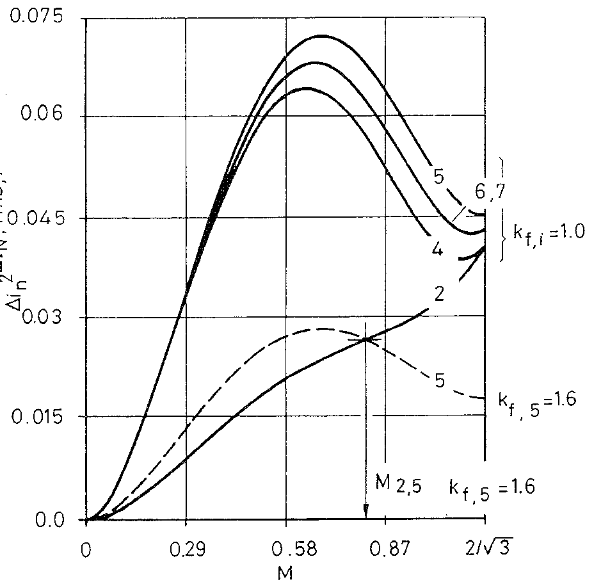

Fig. 1 *Comparison of normalised harmonic losses for continuous modulation 2 and discontinuous modulation 4, 5, 6, 7*
Based on $k_{f,k} = 1$ ($\Delta i_n^2 = (U_{ZK}T_p/8L)^2$) [8].
As shown for the example of modulation method 5, under consideration of the frequency increase $k_{f,k}$, k = 4, 5, 6, 7 (being possible for discontinuous modulation as opposed to continous modulation) in the upper control region lower harmonic losses are obtained (harmonic losses shown by a broken curve for $k_{f,5} = 1.6$); for $M > M_{2,5}$ control method 5 has to be preferred concerning the harmonic losses as compared to the control method 2.

An advantage of discontinuous modulation as compared to continuous modulation is given only by considering the frequency increase $k_{f,k}$, k = 4, 5, 6, 7 (being different for different control methods) as calculated in [2]. As shown in Fig. 1 for an example of modulation method 5 for $k_{f,5} = 1.6$ (according to Fig.3 in [2] related to a phase angle $\varphi = 0.722$) this results in any case in the region of high modulation indices in a reduction of the harmonic losses as compared to continuous modulation. For $k_{f,5} = 2$ (and/or $\varphi = 0$) the harmonic losses are below the values resulting for continuous modulation within the entire control region. However, there again a significant reduction of the harmonic losses is given only for the upper control region.

Remark: In this connection it is important to note that based on Fig. 1 it is not admissible to conclude that due to the lower harmonic losses (in comparison to [5–7] for $k_{f,k} = 1$) method 4 would represent an optimal discontinuous modulation method. This can be explained by the fact that the actual harmonic losses are essentially influenced by the possible frequency increase $k_{f,k}$ and that $k_{f,k}$ can assume very variable values for different modulation methods, dependent on the respective phase angle φ (cf. Fig.3 in [2]).

By extending the considerations made here, the question is obvious as to which modulation method would lead to a minimum value of the harmonic losses for given phase angle φ of the converter output current i_N and for given modulation index M where equal switching losses are assumed. For a calculation of the modulation method being optimal we have to calculate there for each method k and for each pair of quantities M, φ the admissible frequency increase $k_{f,k}$ from Eqns. 6–9 as already given in [2]. The result has to be inserted into Eqn. 3. By comparison of the harmonic losses of the different modulation methods there follows then immediately the optimal modulation method for each case and also the (minimum) harmonic RMS value obtainable thereby. Finally, the application regions of the different modulation methods are thereby determined if all values $M \in [0, 2/\sqrt{3}]$ and $\varphi \in [-\pi, +\pi]$ are considered. The result of the relevant analysis is shown in Figs. 2 and 3.

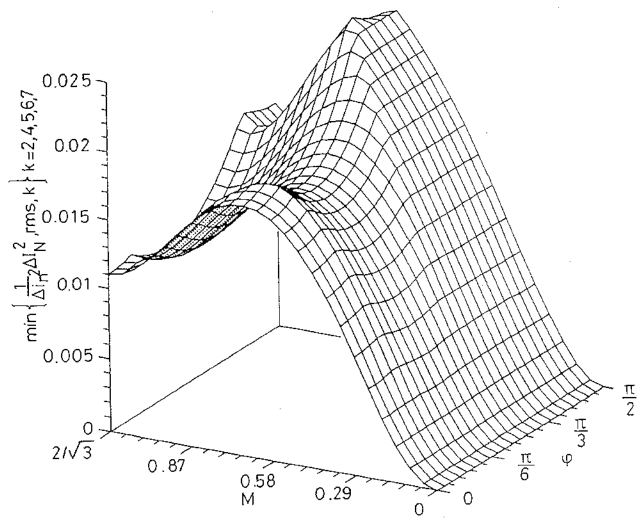

Fig. 2 *Dependency of the obtainable minimum harmonic losses* $min\{1/(\Delta i_n^2)\Delta I^2_{N,rms,k}\}_{k=2,4,5,6,7}$, *for optimal combination of continuous modulation 2 and discontinuous modulations 4, 5, 6 or 7*
For discontinuous modulation increases $k_{f,k}$ of the pulse frequency are assumed in such a way that equal average switching losses result (related to continuous modulation). Based on the representation limited to values of the phase angle of the output current $\varphi \in [0,\pi/2]$ one can easily obatin the results for arbitrary phase angles by considering symmetry relationships and by considering Fig.3 in [2]

By considering Figs. 2 and 3 a specific modulation method has to be related to each application region of the PWM converter system. For application as a PWM rectifier system typically high modulation indices and phase angles close to 0 or $\pm\pi$ result. One therefore has to select discontinuous modulation 5 as the optimum control method regarding the harmonics. A high modulation index is also representative for operation of the system as a static VAR compensator. In this case one has to prefer modulation method 4, however, because the phase angle of the current is close to $\pm\pi/2$ there. On the other hand, for inverter operation and/or for supplying induction machines, a comparable wide phase angle region is covered. Also, due to the required change of the modulation index proportional to the motor speed (for maintaining the rated motor flux below the rated speed) a wide modulation region is covered. According to Figs. 2 and 3 and Fig.1d in [2] modulation method 7 has to be preferred for high modulation indices as compared to continuous modulation 2. The application of continuous modulation in the lower modulation region (and/or for smaller motor speed) results also from the fact that due to the limited thermal inertia of the power semiconductors the advantage of discontinuous modulation (namely the reduction of the average switching power loss, despite time-sectional increase of the local switching losses as compared to continuous modulation), can be used only down to a certain lower limit of the output frequency. For low output frequency the junction temperature of the valves is determined by the instantaneous value and not by the average value of the switching losses. Therefore, for maintaining a maximum admissible junction temperature (via appropriate dimensioning) discontinuous modulation would lead to a lower utilisation of the switching capability of the valves (cf. p. 350 in [9], or [10] or [11]). For the sake of completeness we want to point out also that other points (as, for example, the distortion of the phase currents caused by a minimum pulse time) have influence on the selection of a particular modulation method. For the sake of brevity we have to refer to [6] (cf. p. 1207) or [13] (cf. p. 147) in this respect.

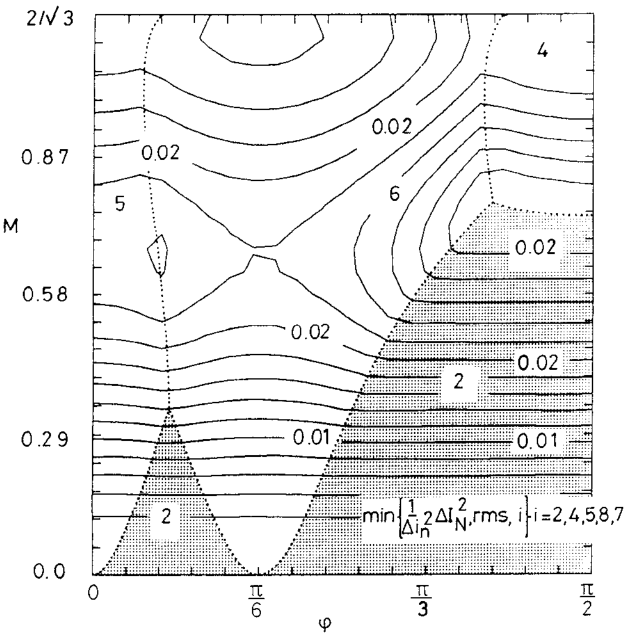

Fig.3 *Application regions of the different modulation methods for minimum harmonic losses,* $\min\{1/(\Delta i_n^2)\Delta I_{N,rms,k}^2\}$ *k=2,4,5,6,7 (continuous modulation 2 and discontinuous modulations 4, 5, 6 or 7)*
The application regions of continuous modulation are the dotted areas

With the considerations given here we have tried to clearly explain and to quantify the influence of the harmonic losses (and/or of the RMS value $\Delta I_{N,rms}$ of the distortion component Δi_N of the phase currents) for the transition from continuous to discontinuous modulation. There, the RMS value $\Delta I_{N,rms}$ is especially of interest in connection with the thermal stress of the converter-fed AC current machines. On the other hand, for the application of converter systems as PWM rectifiers (mentioned in [3]) the spectral distribution of the harmonic power is of primary importance for the dimensioning of an *LC* input filter (of 1st or 2nd order) as to be applied for avoiding of line-conducted EMI, possibly causing disturbances of other loads. Here, the possibility seems to be essential to double the switching frequency (for the preferred method 5) as compared to continuous modulation where the switching losses remain equal. Now, if (*a*) the ripple of the input current has approximately equal amplitude in both cases (as described in [1], but different RMS values) and (*b*) this ripple is thought to be concentrated in always one harmonic with switching frequency for a simple worst-case estimate (according to [14], p.29, which is even a disadvantage with respect to discontinuous modulation), then we can formulate the following: due to the different position of these harmonics in the frequency spectrum for equal corner frequency of the mains filter, for discontinuous modulation, a reduction which is higher by a factor of 2 to 4 as compared to the case of continuous modulation of the ripple of the converter input current is given. This clearly shows the advantage of discontinuous modulation and also gives the reason for an increasing industrial application of this modulation principle.

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