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Blanking-time effects in the context of modular multilevel converters

Abstract. *Blanking-time (or blocking-time) effects in power-electronic converters have been known since long. They introduce disturbances which are not easily handled by control means. Their compensation is not straightforward, because they depend on the sign (direction) and to a much lesser degree on the magnitude of the current flowing through the switching devices. Depending on the topology of the converter and the relation between blanking time and pulse period, the influence on the output quantities is relevant. This paper analyses blanking-time effects based on measurements performed on a modular multilevel converter – where these effects also influence the harmonic content of the DC voltage considerably. A straightforward FPGA-based compensation mechanism is implemented and its mitigation effect documented.*

Streszczenie. *Efekty pauz (lub czasu blokowania) w przekształtnikach energoelektronicznych są znane od dawna. Wprowadzają one zaburzenia trudne do opanowania metodami sterowania. Nie są one bezpośrednio kompensowane ponieważ zależą one głównie od kierunku a w mniejszym stopniu od wartości prądu przełączników. Wpływ pauz na wielkości wyjściowe przekształtnika zależy od jego topologii oraz stosunku czasu pauzy do czasu trwania impulsów łączeniowych. Artykuł ten analizuje skutki pauz na pomiary przeprowadzone na modularnych przekształtnikach wielopoziomowych, w których wpływają one znacząco na zawartość harmonicznych i na napięcie wyjściowe. W artykule został zastosowany bezpośredni, oparty na FPGA, mechanizm kompensacji i udokumentowane zostaly jego skutki.* ***Efekty pauzy w modularnych przekształtnikach wielopoziomowych***

Keywords*:* blanking time, blocking time, modular multilevel converter (MMC)
Słowa kluczowe: Czas pauzy, czas blokowania, modularne przekształtniki wielopoziomowe (MMC)

I. Introduction

In highly-dynamic model-based control the quality of the control strongly depends on the congruence of the model and the real system. With regard to blanking-time issues it is often necessary or desirable to include the inverter characteristics into the model or to compensate the error in the control chain. This paper concentrates on the dynamic error $\Delta u_{F,dyn}$ between the actual inverter output voltage and its set-point value [1 □ 4]. A major part of this dynamic error, $\Delta u_{dyn,bl}$, is caused by the blanking time deliberately introduced by the inverter control to prevent short-circuits within each arm of the inverter. It depends on the sign and the magnitude of the current [5].

The voltage deviation introduced by the blanking time has some characteristics which make its compensation (by control suppressing the resulting disturbance or by model-based pre-control eliminating the effect more directly) difficult:

- Blanking time strongly depends on the sign of the current in the actual switching instant
- Measurement uncertainties make the prediction of the sign of the current around its zero-crossing in the relevant power-electronic devices challenging
- The slope of the current depends on the state of the converter and on the attached load and its point of operation

This paper analyses the effects of blanking time, backed on measurements made at a modular multilevel converter as demonstrative example. A straightforward blanking-time compensation mechanism is implemented and its effects on the operation of the MMC are analysed.

II. Blanking-Time Voltage Error

Fig. 1 shows the typical structure of one pair of arms of a voltage-source converter. The high-side switching element S_1 (in this case an IGBT) actively connects the positive DC potential to the output of the converter, the low-side element S_2 the negative DC potential. Depending on the direction of the output current, the high-side switching element and the low-side diode or the low-side switching element and the high-side diode carry the output current and such control the output voltage of the arm.

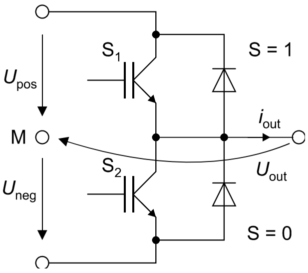

Fig. 1. Typical power-electronic structure of a voltage-source converter pair of arms with high-side (S_1) and low-side (S_2) switches

The effect of the blanking time generated by the control electronic to prevent short-circuits in each converter arm depends on the current direction. Fig. 2 illustrates the relevant signals and the resulting consequences for the positive and the negative current direction.

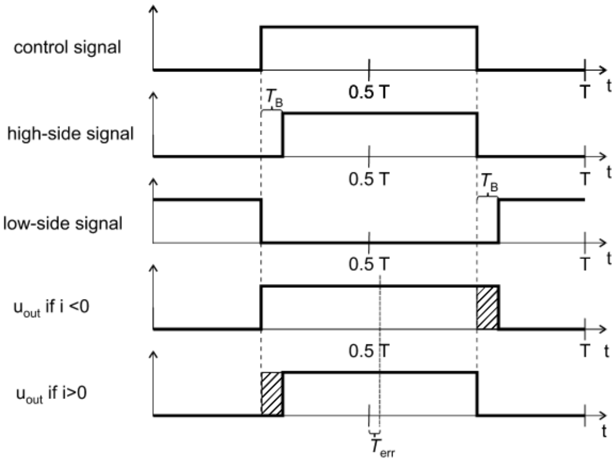

Fig. 2. Output voltage waveform generated by a converter arm as function of the direction of the output current

The resulting error is marked by the hatched areas in the graph of the output voltage and can be calculated by:

(1) $$\Delta u_{\mathrm{dyn,bl}} = -\mathrm{sgn}(i) \cdot u_{\mathrm{li}} \cdot TB \cdot f_{\mathrm{s}}$$

Additionally the blanking time causes a pulse delay given by:

(2) $$T_{\mathrm{err}} = T_{\mathrm{B}}/2.$$

III. Blanking-Time Compensation Issues

The straightforward option for blanking-time compensation is to measure the current, derive the sign and modify the pulse pattern accordingly, cf. Fig. 3 and Fig. 4.

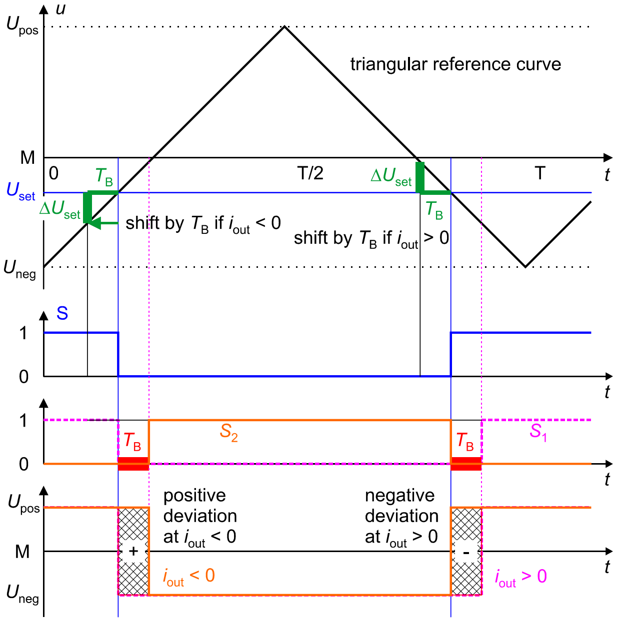

Fig. 3. Blanking-time compensation by modification of set-point value

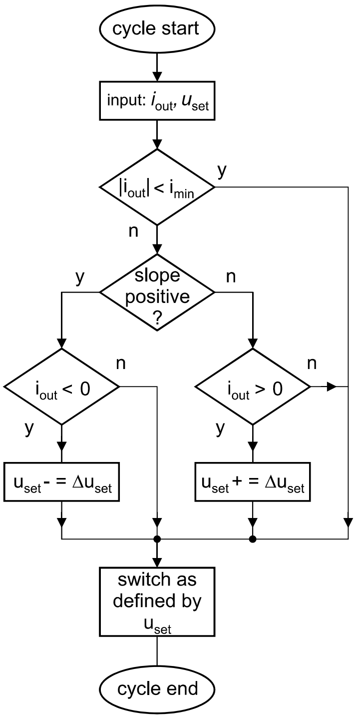

Fig. 4. Flow chart describing the implemented blanking-time compensation

Fig. 3 illustrates the basic idea of blanking-time compensation: If the output current is negative, there is no reaction to the actuating signal on the high-side switch. Turning on the low-side switch acts on the output voltage. Consequently, the affected switching instants have to be shifted for the duration of the blanking time towards earlier switching instants. This can be done in an uncomplicated way by a suitably modified voltage set-point value. If the output current is positive, the rising edge of the output voltage is to be delayed for the blanking time. Again earlier switching instants are required – and again a suitable modification of the voltage set-point value solves the task.

The compensation itself is based on a cycle depicted in Fig. 4. At the beginning, the actual current and the voltage set-point value are read. Within a region of uncertainty described by the current threshold value i_{min}, compensation is not reliable as discussed below in more detail. If compensation is allowed, the type of slope together with the direction of the output current determines if the voltage set-point value is to be modified or not. At the end of each cycle, the new set-point value to be compared with the reference curve evolves.

This method is employed in the subsection on measurements to compare with operation without blanking-time compensation.

As already mentioned above, this is straightforward for larger currents but becomes challenging around the zero-crossing of the current:

- The sign of the current has to be measured exactly
- This needs measuring devices with their uncertainties. Especially current measurement offsets can cause deviations between the measured sign and the actual sign of the current around current zero
- Transfer function of the measuring equipment, delays and stochastical effects cause further uncertainties
- If the sign is predicted in the wrong way, compensation doubles the error

Consequently, a region around “current zero” has to be defined in which blanking-time compensation is not to be carried out at all. This region is defined by the interval of current measurements, the current measurement precision and the expected maximal slope of the current. It can be quite large, especially if the maximal slope is steep and the interval between current measurements is long.

Model-based compensation may improve compensation, but requires exact model parameters and higher computational effort. It is not treated in this paper, but under research.

IV. Modular Multilevel Converter (MMC)

The MMC [7–8] present a newly introduced converter topology, cf. Fig. 5.

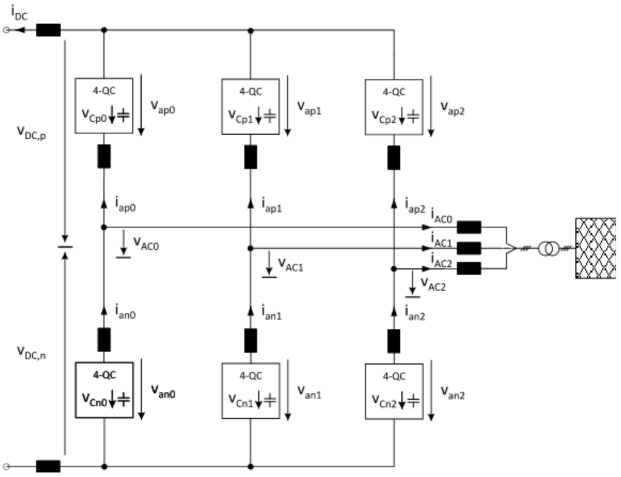

Fig. 5. Structure of a MMC connected to an AC grid

The topology allows to simply stack a big number of converter modules in each of the arms without attention to low-inductive construction and can thus directly be connected to high voltage. Also, the quality of the voltage waveform is excellent because the voltage step size is small in relation to the output voltage if many modules per arm are connected in series and switch with suitable time shifts. In this paper 4-quadrant-converter modules are assumed in each of the arms of the converter.

The arm inductors are mandatory and lead in effect to a current-source converter behaviour, where the arm currents are controlled by suitable control of the six 4-quadrant-converter output voltages v_{ap0} to v_{an2}. Consequently, the voltages on the ACside and on the DCside contain distortions generated by the switching of the converter modules. Natively no DC capacitor is required, these harmonics remain on the DC side as well as on the AC side.

The major disadvantage of this converter structure is the single-phase energy conversion. It necessitates relatively large capacitances for the converter modules, because these have to cope with the mandatory pulsation of power within each arm.

A further aspect of the topology is the ability to have circular currents within the converter topology which do not influence the voltages and currents on the terminals of the converter, but are needed to control the fluctuation of the module capacitances in a favourable way [8].

With regard to blanking-time issues it is important to note that each arm current individually crosses zero and that all modules stacked within an arm run into blanking-time compensation troubles at the same time instant. All modules switching around current zero are affected by blanking-time compensation issues.

Part of the blanking-time effect is stochastic, so symmetry is imperfect and all integral multiples of 300 Hz are to be expected, too – but with decreasing amplitude.

V. Analysis of Measurements

The basic operation of the MMC selected for this analysis is no-load operation at nominal AC-grid conditions (purely positive-sequence voltages). Circulating currents (negative-sequence, 100 Hz) with an amplitude of 70 A are commanded ? to provide a representative load-independent working point, which can be reproduced with any kind of MMC.

The straightforward blanking-time compensation uses high-speed FPGA-based current measurement including a suitably selected suppression-of-compensation interval around current zero.

The relevant parameters of the used MMC are:

- One 4-quadrant-converter module per arm
- Switching frequency per converter leg 5 kHz, pulse frequency per converter 10 kHz
- Commercial converters as basis, fixed blanking time of 4 µs
- Arm inductance 2.2 mH
- Phase-to-phase rms voltage (AC) 230 V / 50 Hz
- DC-side R-Cfilter: 1.38 □ in series to 120 µF

The DC-side filter would normally not be needed. In this special layout with only one single module per arm it is used to damp the pulse-frequent voltage harmonic of 10 kHz on the DC-side voltage, which would be excessive without filter.

The following subsections present and discuss the results:

A. No blanking-time compensation

The arm current is shown in Fig. 6.

It can be seen that the slope of the current at positive current towards the zero crossing is much steeper than the slope of the current at negative current towards the negative peak of the current. This causes – with a symmetrical negative-sequence system - a strong 300-Hz oscillation of the DC voltage as shown in Fig. 7.

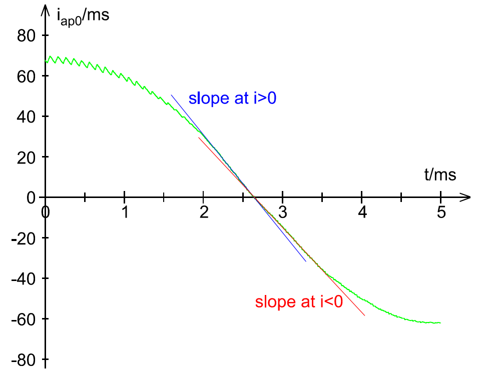

Fig. 6. Time function of arm current including slopes at $i \rightarrow +0$ and at $i \rightarrow -0$, no blanking-time compensation

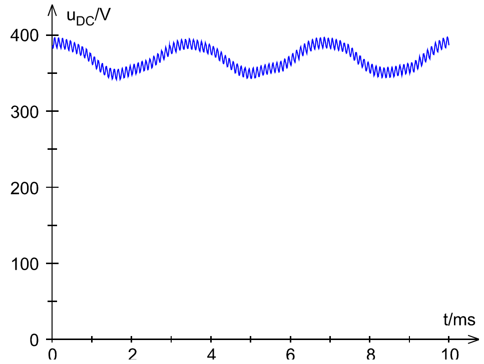

Fig. 7. Time function of DC voltage, no blanking-time compensation

The basic reason is that at positive arm current the intended voltage is larger than the effected voltage, while it is smaller at negative arm current. This effect repeats for all three arm currents with 120° phase shift, causing the oscillation of the DC voltage.

B. Straightforward blanking-time compensation

The arm current for this case is shown in Fig. 8.

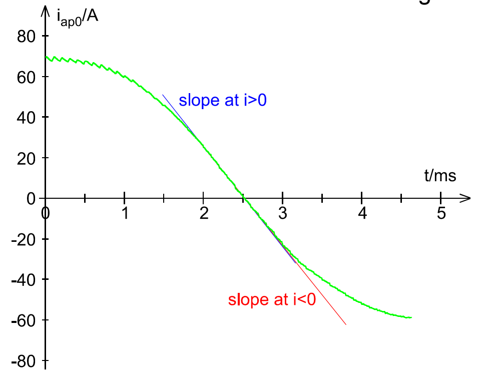

Fig. 8. Time function of arm current slopes at $i \rightarrow +0$ and at $i \rightarrow -0$, , straightforward blanking time compensation

It can be seen that the slope of the current at positive current towards the zero crossing is now nearly identicalto that at negative current. A 300-Hz oscillation of the DC voltage can still be found as shown in Fig. 9, but it is much smaller. Research work for improving the blanking-time compensation is under way to further reduce the undesirable side effects.

It should be noted that an MMC cannot be operated without closed-loop control. For circulating currents, amplification in the sense of voltage needed to drive the current is high: Only the internal impedances of converters and inductances limit these currents. Also, slight differences in capacitance and modulation factor of the 4-quadrant-converter modules would cause the module capacitor voltages to drift apart – balancing control acting on all six capacitor voltages is needed. For the analysis carried out a control is used which might influence the oscillations observed.

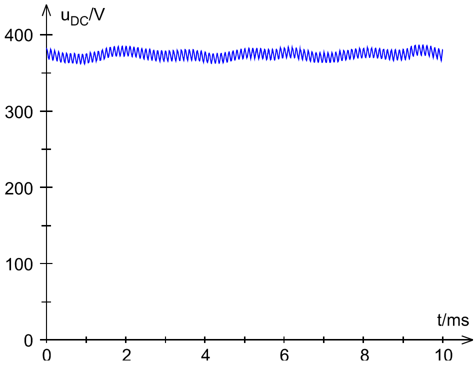

Fig. 9. Time function of DC voltage (with blanking-time compensation)

VI. Conclusion

The effect of blanking-time-induced errors on the output voltage of a MMC with four-quadrant-converter modules is discussed and demonstrated by experimental results. A selected variation of the operating conditions shows how these influence the blanking-time voltage errors.

A straightforward FPGA-based blanking-time compensation is introduced, its effects are demonstrated by measurements and comparison to the uncompensated case. Even with blanking-time compensation usually unexpected low-frequency components are found in the MMC DC-voltage. It is expected that an improved compensation of the blanking time will reduce these adverse effects considerably.

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