Hidden reflection phenomena on inverter-fed induction motors

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Abstract

When supplying an induction motor by a PWM-inverter through long cables, reflections occur. For some inverters other reflection phenomena than the usual overvoltages appear at the motor side, namely steps smaller than 0.5 p.u. of the busvoltage, also called stair stepping. The stair stepping reflection phenomenon occurs at the commutation from IGBT to diode. Stair stepping depends on the magnitude of the current, the cable impedance and on the dead time of the IGBT gate-signal. The reflection phenomenon increases the turn on time of the diode.

1. Introduction

When supplying an induction motor by a PWM-inverter, reflection phenomena occur if the feeding is done through long motor cables. Several papers discuss and simulate the overvoltage appearing at the motor side [1-2]. The consequences of the overvoltage are a widespread topic [3]. Filter design focuses on impedance matching and lowering the voltage rise time [4-7].

This paper deals with other reflection phenomena observed with different PWM-inverters supplying an induction motor through long motor cables, i.e. stair stepping. Stair stepping is well known in high speed digital design. In this paper it is shown that the origin of the phenomenon is different. It is more severe for small currents, with values in the order of 5 to 10 A. As proven, it also depends on the characteristic impedance of the cable. These phenomena occur only when the current commutates from the IGBT to the diode of the inverter bridge. A detailed time observation is required to notice it.

The first consequence of the reflection is no overvoltage, but a delay of a full turn on of the diode, due to the multiple reflections. The second consequence is that the IGBTs are switching at moments normally diodes should be conducting. It is proven that the dead time of the IGBTs is in part the discriminative factor between inverters showing the phenomena and those that do not.

This paper is divided in two main parts. In the first part, the appearance of the reflection phenomenon is discussed. In the second part, a physical and mathematical interpretation is given. Additional measurements are discussed to support the theory.

2. The reflection phenomenon

Measuring at the motor terminals, normally reflections above 1 per unit busvoltage occur at turn on. At turn off an equal but negative transient appears (fig. 1).

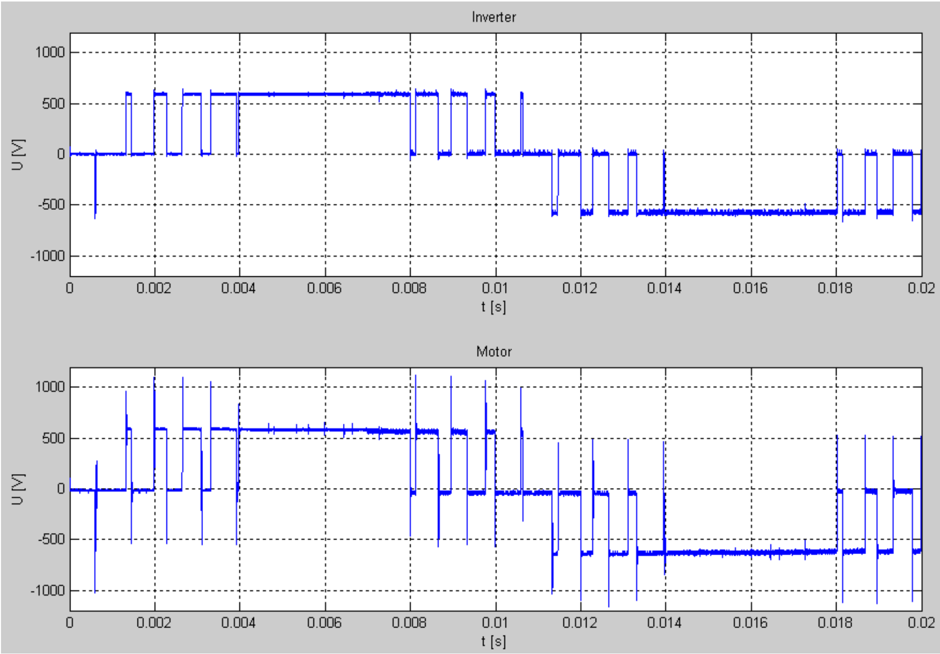

Fig. 1: Voltage at inverter side (top) and motor side (bottom)

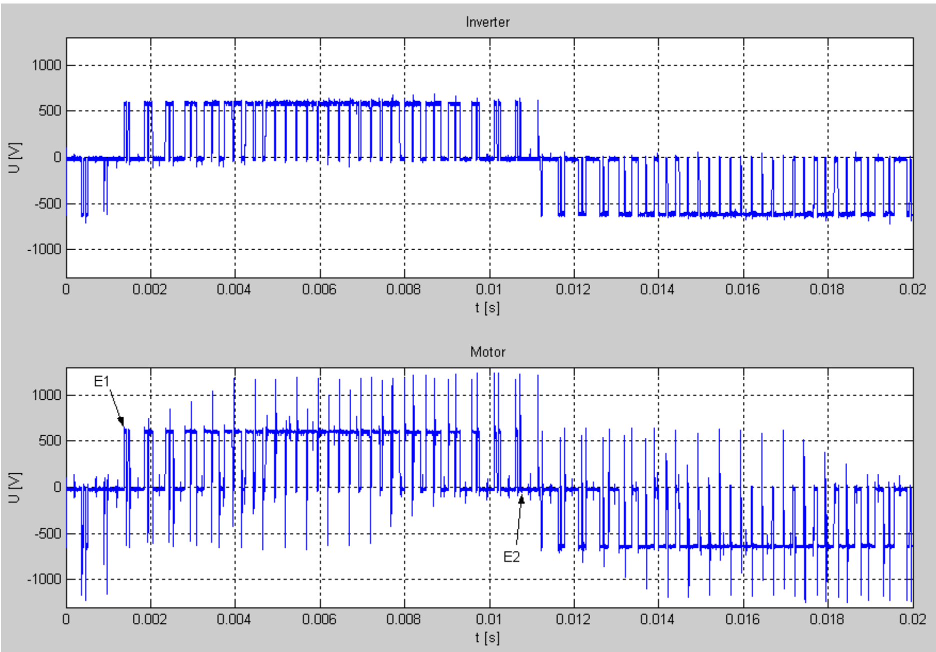

Fig. 2: Voltage at inverter side (top) and motor side (bottom) at small load

Fig. 2 shows the same measurement with another inverter connected to the same load, using the same cable. These measurements lead to two important observations. First, not all rising and falling edges result in an overvoltage, as marked by the points E1 and E2 on figure 2. Second, the reflections at the rising edge do not occur at the beginning of the positive voltage alternation, neither at the falling edge at the end of the positive alternation.

Other measurements have been done on the same motor at different load, changing the magnitude and phase angle of the current. Analysing these measurements (fig. 3), shows that at higher motor load, i.e. at higher power factor, more overvoltages occur at the motor side. This leads to the assumption that the type of reflection, namely a reflection over 1 p.u. or under 1 p.u., depends on the phase angle of the fundamental of the current.

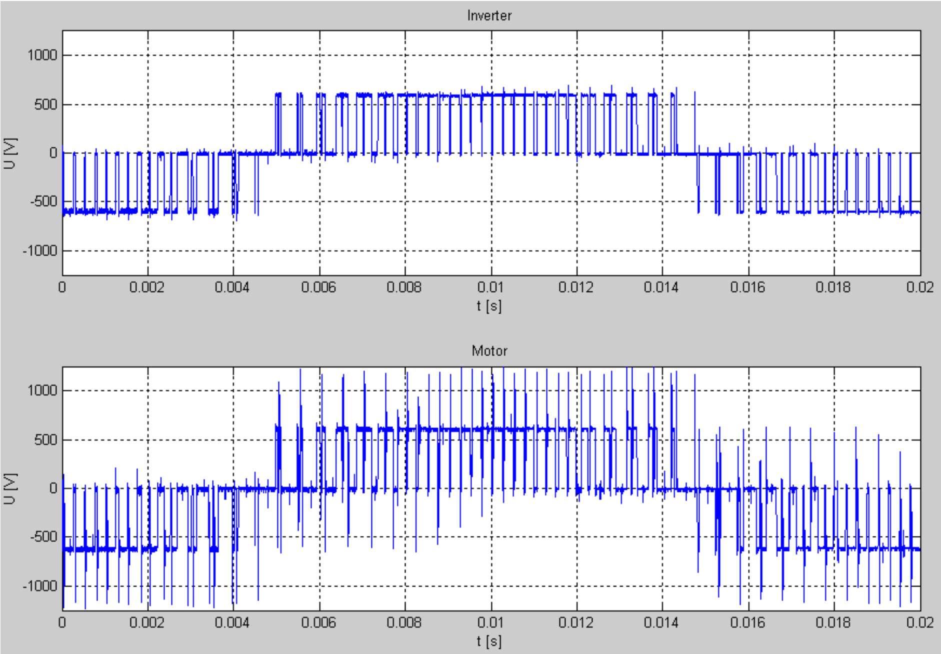

Fig. 3: Voltage at inverter side (top) and motor side (bottom) at full load

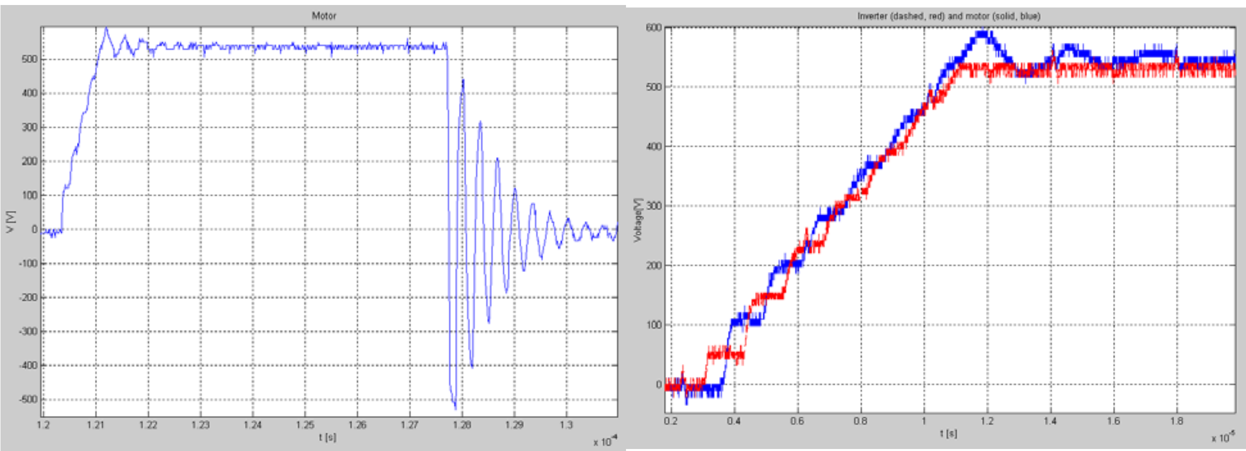

Fig. 4. Zoom of pulse E1 (left) and voltage at inverter-side (dashed) and at motor-side (solid) (right)

On fig. 4 an enlargement of the pulse indicated as E1 on fig. 2 is shown. At the rising edge, the amplitude of the first step is 120V or less than 0.25 p.u. As this is already a doubled voltage, due to the high motor impedance for pulses, the output voltage of the inverter should be half of the motor voltage. A measurement at the inverter side confirms this (fig. 4, right). The step voltage starts at the inverter and reflects at the motor. After multiple reflections, the voltage finally reaches a 1 p.u. voltage, without overvoltage.

At the falling edge, a normal overvoltage reflection appears.

3. Explanation

3.1. Physical interpretation

The measurement on fig. 2 in comparison to fig. 3 led to the assumption that the type of reflection depends on the sign of the fundamental of the current. Analysing the current confirms this. At present, the voltages are measured at the inverter side, between one phase of the inverter output and the negative pole of the DC-bus (fig. 5). Fig. 6 shows the possible voltage – current combinations. These pictures are taken to see when diodes and when IGBTs should be conducting. If the inverter output generates a 1 p.u. output voltage, reflections over 1 p.u. occur at the motor side. If the output generates a step smaller than 1 p.u., steps smaller than 1 p.u. as in fig. 4 appear at the motor side.

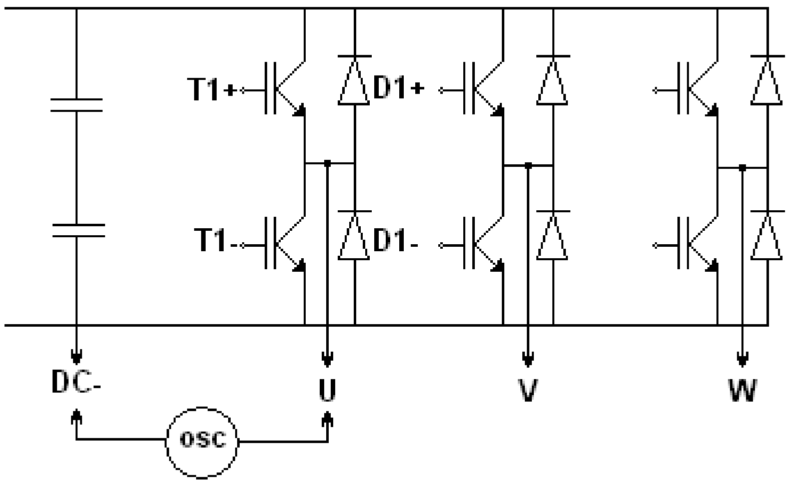

Fig. 5. Measurement between phase U and DC negative pole

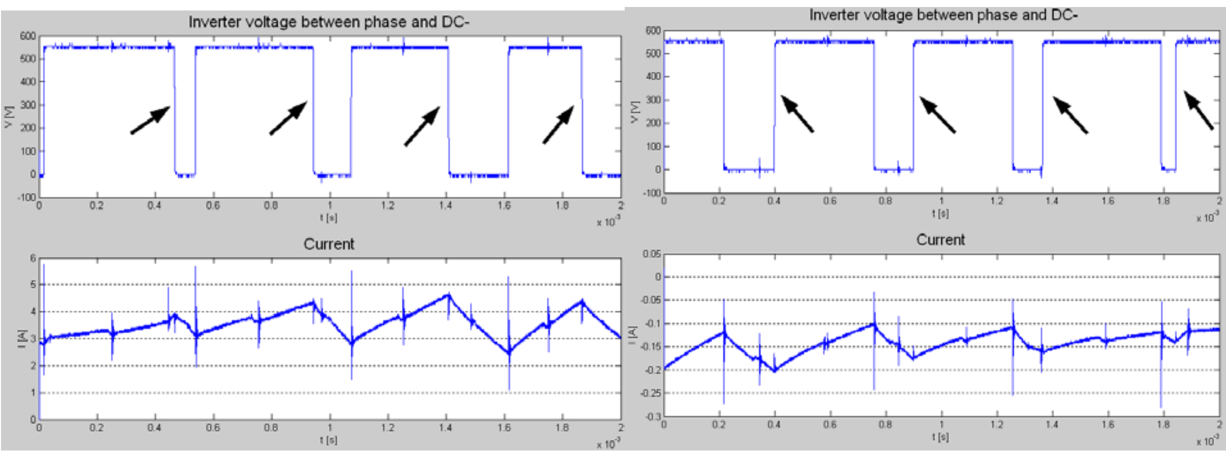

Fig. 6. Voltage/current combinations: the arrows show the edges with steps smaller than 1 p.u., the other edges are 1 p.u. steps

At the motor side, the overvoltage reflection appears when the absolute instantaneous value of the current increases. The stair stepping appears when the absolute instantaneous value of the current decreases. Therefore, the type of reflection depends on whether the IGBT or the diode should be conducting. Stair stepping occurs on the commutation from T1+ to D1- and from T1- to D1+, as indicated by arrows on fig. 6.

Stair stepping is fully described in papers discussing high speed digital design [8-9]. Consider a voltage source driving a transmission line, with a characteristic impedance Z_c. The stair stepping occurs when the impedance Z_c is very small in comparison to the load impedance and small in comparison to the source impedance. In case of a motor and inverter combination, the output impedance of the inverter seems to be higher than the characteristic impedance of the cable when the diode is conducting. The output impedance seems to be lower when the IGBT is conducting.

Measuring the current gives a totally different view on the origin of the steps. Fig. 7 shows both the current and voltage. The current on the left figure is smaller than the current on the right. The current has a large influence on the step size. The larger the current, the bigger the initial step will be. For currents above 7.5A, the step is on top of 540 (DC-bus voltage + 0.7V) and the diode turns on immediately. For smaller currents, the voltage must reflect several times, before the diode turns on and clamps to the DC-voltage. The smaller the current the longer the turn on takes.

Another important fact is that the current becomes zero, as the IGBT T1- is turning off. The current decreases and should flow through the diode D1+. However this diode can not turn on, because the anode voltage is less than the cathode voltage. The current becomes zero and remains zero, as it can't reverse sign. The diode D1- can't conduct because the cathode voltage is larger than the anode voltage. The IGBT T1+ can't conduct, because the dead time is not over yet. To prove the latter, the gate voltage of T1+ is shown on fig. 8.

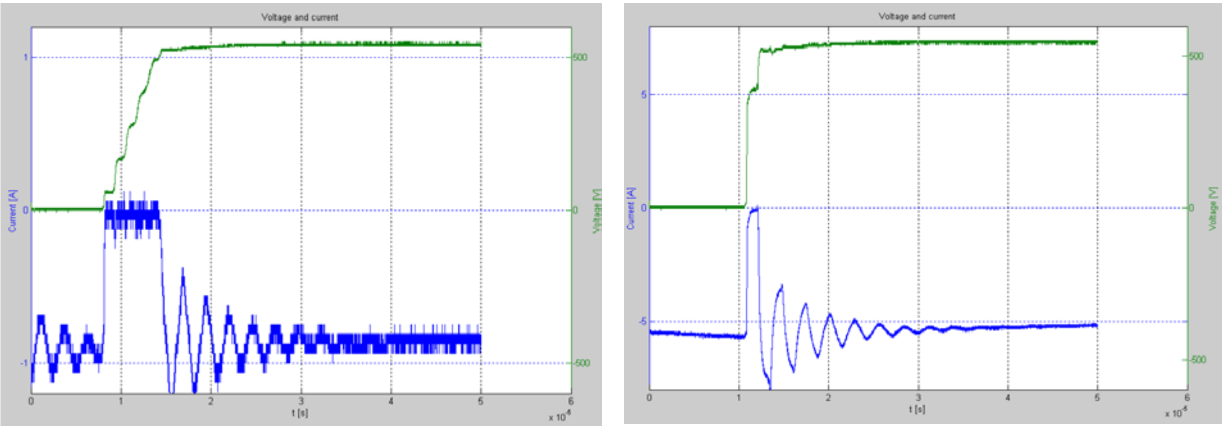

Fig. 7. Stair stepping when the current is small (left) and larger (right)

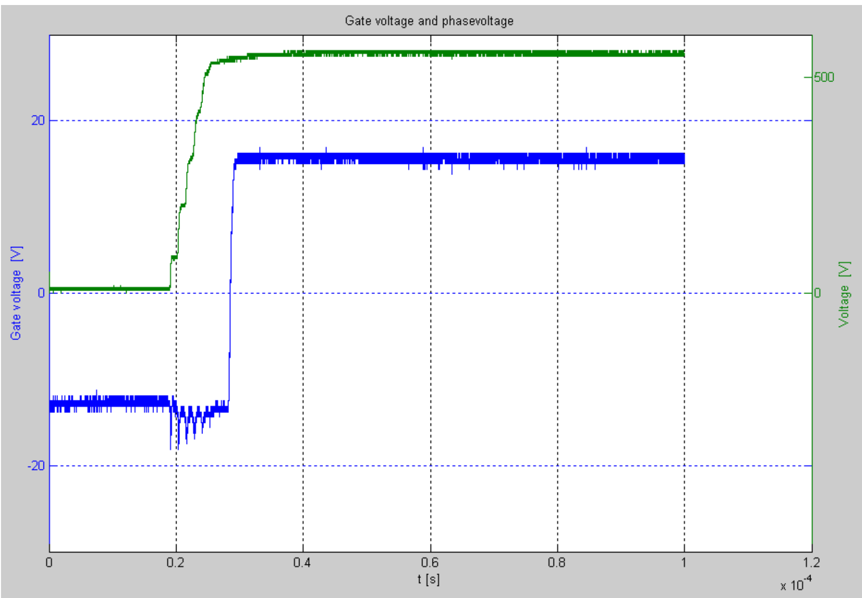

Fig. 8. The diode turns on after several reflections. At that time, the gate of the top IGBT is still off, due to the dead time

When the diode finally turns on, the current becomes negative again (fig. 7). Normally, the current is supposed no to change much, due to the inductive load. Furthermore, the motor normally generates a back-emf that turns the diode immediately on. The measurements show this is not true when using long cables. When putting 65 mH immediately after the inverter, at the beginning of 100 m cable, the back-emf turns the diode immediately on. Besides, the inverter output is in that case not connected to a transmission line. When putting 65 mH at the end of 100 m cable, just before the motor, no difference at inverter side is noticed and the stair stepping remains. Output coils and filters are one possible reason why stair stepping doesn't occur at all inverters. When using a resistive load, the same steps are noticed.

3.2. Mathematical interpretation

As the phenomenon takes just some microseconds, the current is supposed to be constant just before turning off T1-. When T1- turns off, the current falls back to zero, i.e. a current step of ΔI, added to the initial current $-\Delta I$. This current wave propagates to the motor, reflects, returns to the inverter and reflects again as long as T1+ or D1+ are not conducting. The current wave starts also a voltage wave $Z_c.\Delta I$.

The reflection factors and transmission lines are assumed to be ideal, as this is sufficient for the explanation. For simulation, a lossy line and precise reflection factors must be taken, but this is beyond the purpose of this paper. The reflection factor for currents at the inverter side K_{invI} is -1, at the motor side K_{motI} = -1. The reflection factor for voltages K_{invU} is +1 and K_{motU} is +1.

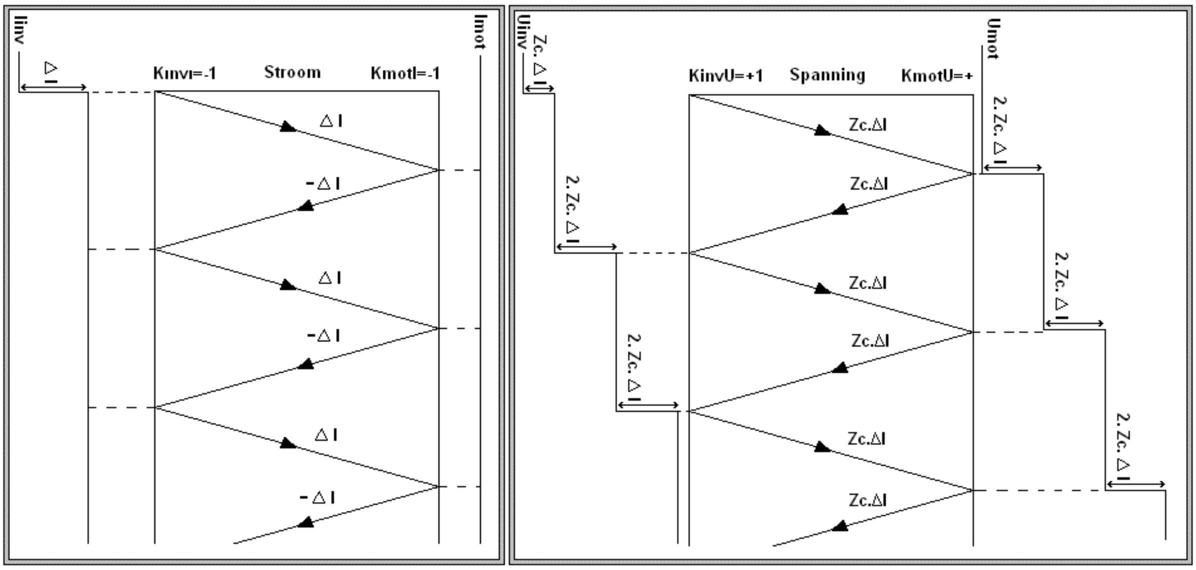

Fig. 9. Reflection diagrams

At each reflection the current remains zero at the inverter side and equals the initial value at motor side. The voltages increase with $Z_c.\Delta I$ at each reflection at motor side and at inverter side. The reflection endures until a sufficient voltage (DC-bus voltage + 0.7 V) is reached or until the dead time of the IGBT has passed.

3.3. Additional measurements

To prove this interpretation, some additional measurements are done. First, an increasing current enlarges the amplitude of the first voltage step. Comparing the left and right picture on fig. 7 proves this. On the left picture, ΔI is 0.87A, and with a cable impedance being 70 Ω, the first step is 60V. On the right picture ΔI is 5.65A, yielding a first voltage step of 390 V. It is important to notice that large steps at the inverter side causes overvoltages at the motorside. This explains the observation on fig. 2 in comparison to fig. 3.

Different line impedances yield different results. The measurements are done using two different cables (100 m length, shielded and non-shielded). The cable impedance is analysed as described in [4]. The impedance measurement is done with a vector impedance meter in a frequency range from 400 kHz to 100 MHz. The value of the shielded cable is lower than the value of the unshielded one. As there is a difference in impedances, this should have a influence on the measured voltage reflections. The impedance of the shielded cable is 45 Ω. The current- and voltage measurements confirm this.

The same steps must be found at a commutation from T1+ to D1-. This can be seen on fig. 10. The current step is -1.57 A, yielding a voltage step of -109 V.

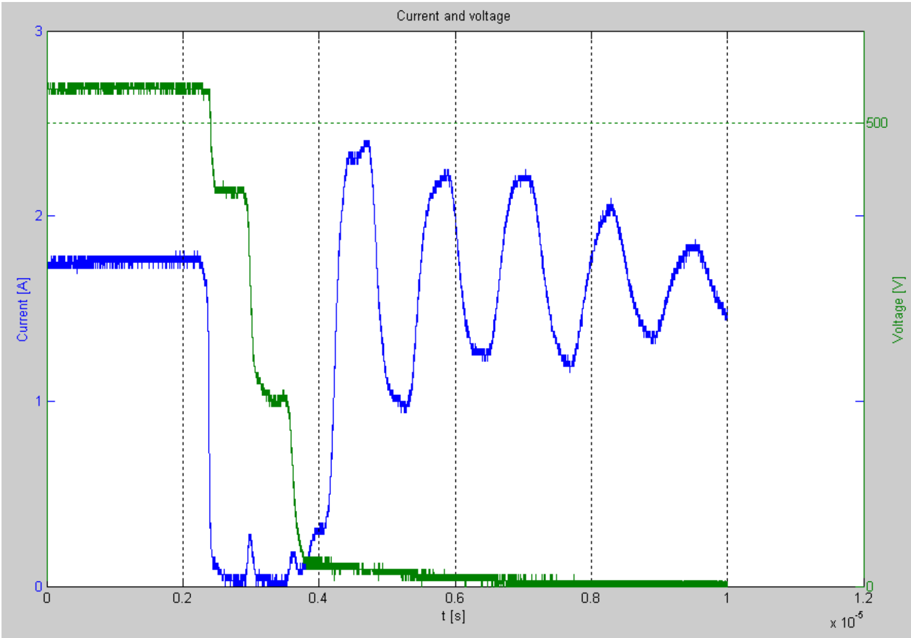

Fig. 10. Commutation from T1+ to D1-

A special case occurs when the current is so small that the reflections last longer than the dead time. As the current is zero at the moment the IGBT switches on, the IGBT conducts and clamps the voltage to the DC-bus voltage immediately after turn on (fig. 11).

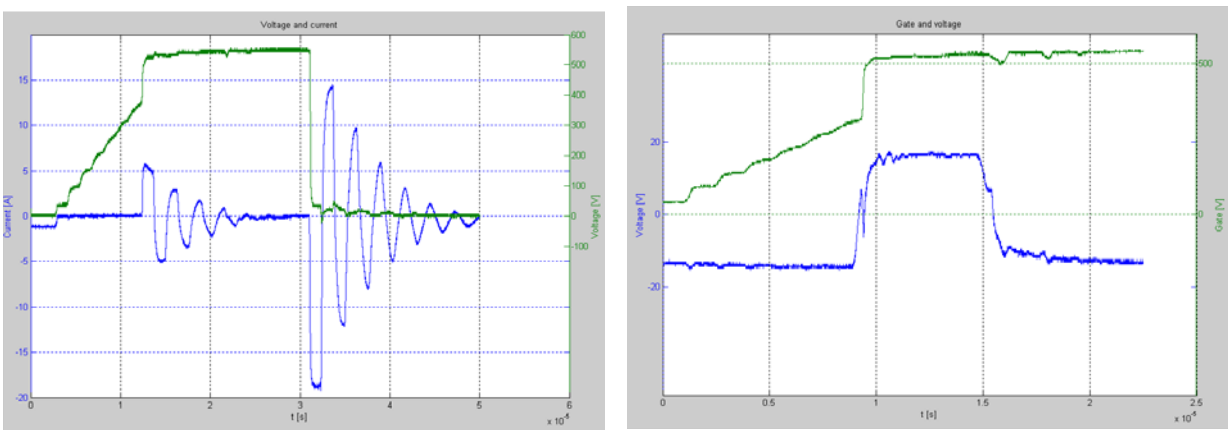

Fig. 11. The IGBT T1+ turns on faster than the diode D1+ (left) when the gate voltage on IGBT T1+ turns high (right)

4. Consequences and further investigation

Obviously, the switching time is enlarged at commutation from the IGBT to the diode. This switching time depends on Z_c, on the current and on the length of the cable. The voltage has to reflect several times before the diode turns on.

Measurements have been done on three different inverters of three different manufacturers. The hidden reflection phenomenon is found on all these inverters. On two inverters, the reflections were easy to see. On the third it was difficult to find, but measurable. The difference between these inverters is the dead time. The third inverter has a dead time as small as twice the wave travelling time. By this, a small step is seen at the inverter, immediately followed by a 1 p.u. step, due to the turning on of the IGBT. This results in an overvoltage at the motor terminals.

Shielded cables have a smaller characteristic impedance than non-shielded ones. With regard to the stair stepping, shielded cables enlarge the turn on time and there is a higher possibility the IGBT turns on, as the dead time can be reached before the diode conducts.

A short dead time lets the IGBT turn on at a moment the diode is expected to conduct. The transient current changes between the diode D1+ and the IGBT T1+ and causes additional switching losses in the IGBT.

Stair stepping causes no overvoltages at the motor terminals, if the dead time does not interfere and turns the IGBT on before the diode starts clamping the DC-bus.

The spectral contents, the radiated emission and the influence on filter design needs investigation. The difference between the inverters showing the phenomena and those which do not must, be found. The influence on the motor and inverter has to be looked at.

5. Conclusions

The reflection phenomena, discussed in this paper, are seen in different inverters. The phenomenon, called stair stepping, has another origin, than the stair stepping on high speed digital busses. It is proven that the visibility and duration of the phenomena depends on the dead time of the gate signals, the instantaneous value of the current and the cable impedance. Due to the phenomenon it is impossible for the diode to turn on. As a consequence the IGBTs can switch at moments normally the diode should conduct.

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