Simulation of stair stepping on inverter-fed induction motors

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Abstract: When supplying an induction motor by a PWM-inverter through long cables, reflections occur. Besides the well-known overvoltages at the motor side, stair stepping can occur at both inverter and motor side. These reflections cause EMI in the range of several 100 kHz up to several MHz. The stair stepping reflection phenomenon occurs at the commutation from IGBT to diode. The stair stepping phenomenon 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. In this paper, stair stepping is explained and further investigated through simulation.

I. INTRODUCTION

When supplying an induction motor by a PWM-inverter in order to control its speed, reflection phenomena occur if the supply is done via long cables. Several papers discuss and simulate the overvoltage appearing at the motor terminals [1-2] and the consequences [3]. Besides overvoltages, reflection phenomena also cause stair stepping. Measurements and an explanation of the phenomenon have been given [4]. The present paper shows simulations of stair stepping, to support the given explanation and to further investigate it.

The reflections cause spectral components of several 100 kHz to several MHz. The frequency depends on the cable length and wave velocity. Fig. 1 shows the PWM-line voltage with and without overvoltages. Fig. 2 gives a closer look on one overvoltage pulse. The oscillation frequency is 330 kHz. Fig. 3 shows the spectral contents of both waveforms. At the upper figure, harmonics at 300 to 400 kHz can be seen. These harmonics correspond to the frequency of overvoltages and stair stepping.

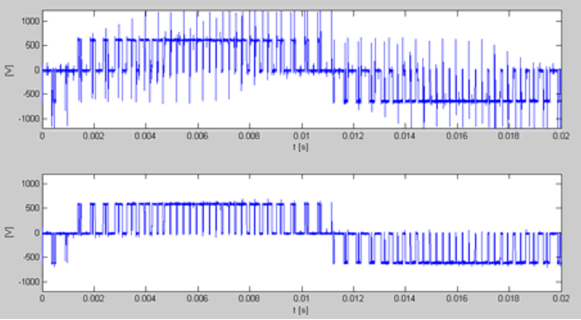

Fig. 1 Line voltage: long cable (top), short cable (bottom).

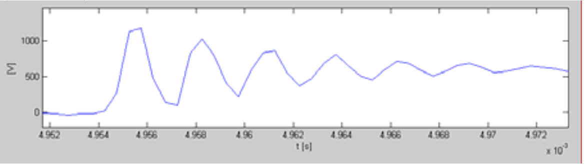

Fig. 2. Zoom of one overvoltage pulse on fig. 1.

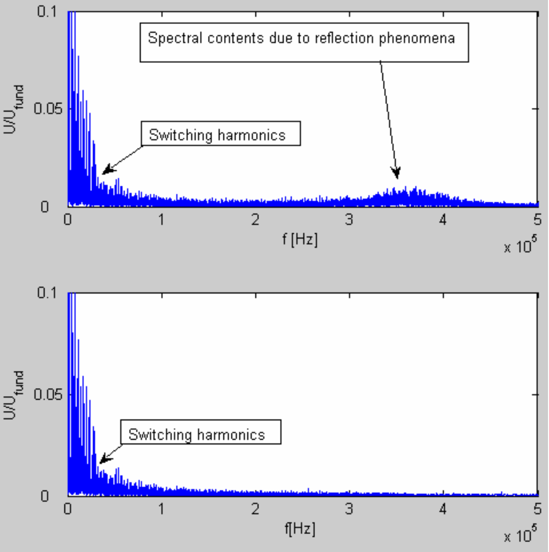

Fig. 3. Spectral contents of the waveforms on fig. 1.

As will be proven, stair stepping is caused by a current instead of a voltage step. To simulate this, a low and a high frequency model of the induction motor are needed. The simulation is done by using pSpice.

II. STAIR STEPPING

The test setup consists of a PWM-inverter, a shielded cable of 100 m and a motor of 735 W. The motor cable behaves as a transmission line with characteristic impedance Z_c. Fig. 4 shows the line voltage, measured at the motor terminals. At the rising edge, the amplitude of the first step is 120 V. As this is already a voltage doubling, 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 terminals confirms this (fig. 5). The step voltage starts at the inverter and reflects at the motor. After multiple reflections, the voltage finally reaches the DC-bus voltage of 540V, without overvoltage.

At the falling edge, a normal overvoltage reflection or ringing appears.

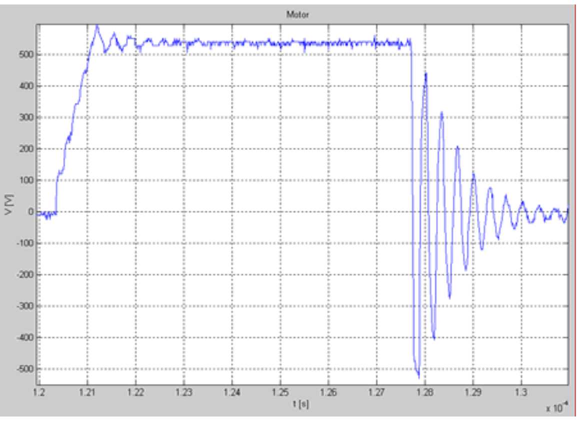

Fig. 4. Zoom of one PWM-pulse at the motor terminals, showing stair stepping at the rising edge and ringing at the falling edge.

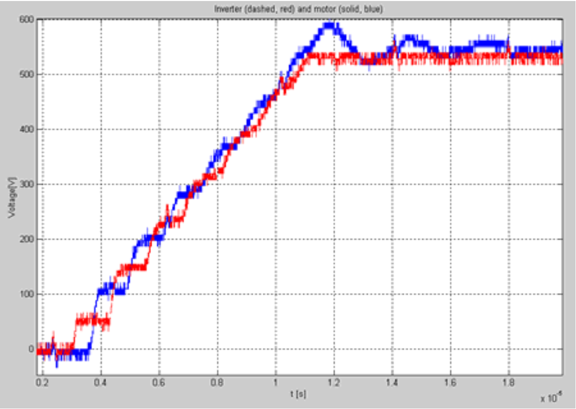

Fig. 5. Line voltage at inverter- (dashed) and at motor-side (solid)

III. Explanation

An explanation of the phenomenon has been given with additional measurements [4]. The cause of the stair stepping is shortly summarized here.

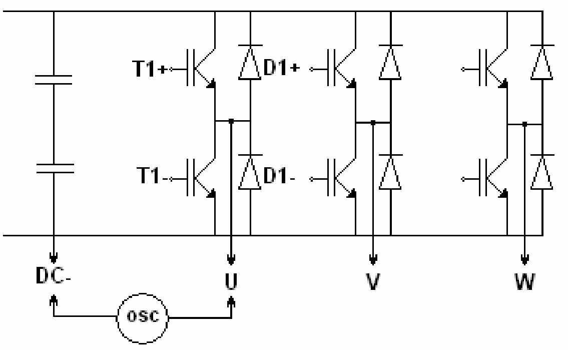

Fig. 6. Measurement between phase U and the DC negative pole.

Consider the inverter in fig. 6. Fig. 7 shows both measured current and the voltage at the inverter output when IGBT T1- turns off. The current 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 so, as it can't reverse. The diode D1- can't conduct as the cathode voltage is larger than the anode voltage. The IGBT T1+ can't conduct, as the dead time is not over yet (fig. 8). Summarized, when T1- turns off, the current falls 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+ do not conduct. At each reflection the current remains zero at the inverter terminals and equals the initial value at motor side.

The current wave also starts a voltage wave $Z_c.\Delta I$. The reflection factor for voltages at the inverter is +1 as no component conducts, while the reflection factor at the motor is near +1. In the ideal case of a lossless line, the voltage increases with $Z_c.\Delta I$ at each reflection at motor and at inverter side, resulting in the stair stepping phenomenon at both inverter and motor side. The reflection lasts until a sufficient voltage (DC-bus voltage + 0.7 V) is reached or until the dead time of the IGBT has passed. When the diode finally turns on, the current becomes negative again. Despite the inductive nature of the motor, the current changes very fast at the inverter output, due to the presence of long cables.

Fig. 9 shows a similar phenomenon at commutation from T1+ to D1-. The current falls back to zero, but as the current is larger, less voltage steps and less reflections are needed to turn the diode on.

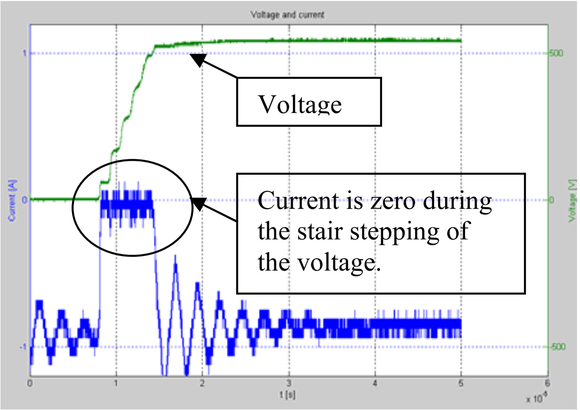

Fig. 7. Stair stepping when the current is small. Commutation from T1- to D1+.

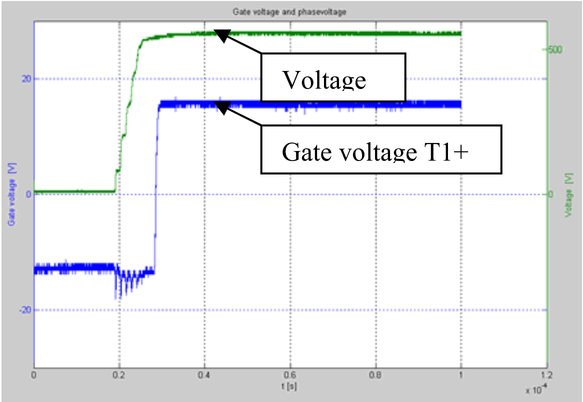

Fig. 8. The diode turns on after several reflections. At that time, the gate of the top IGBT is still off, due to the dead time.

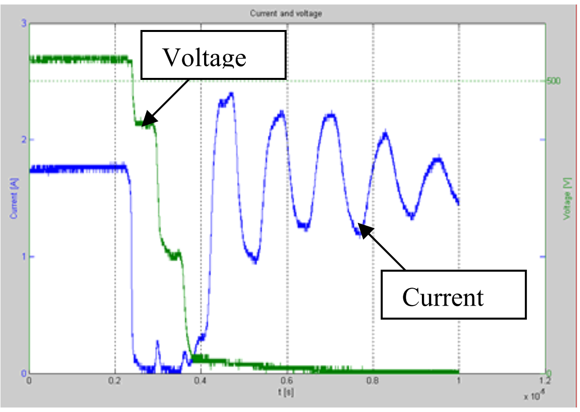

Fig. 9. Stair stepping when the current is larger. Commutation from T1+ to D1-.

IV. SIMULATION MODEL

The pSpice-model contains three parts: inverter, motor cable and motor. As it is only intended to support the previous mentioned physical explanation, some simplifications are made. The model contains a PWM-source with dead-time generator. The dead-time, necessary to avoid two complementary switches to be in the on-state at the same time, is tuneable. The IGBTs are modelled as voltage controlled switches with non-zero impedance. A three phase model for the cable and the motor has been developed, increasing the simulation time significantly. For the motor, a d-q-model is under development. At this moment a simplified model, representing one state is sufficient to simulate the transient effect. The simulated state is called L1, L2+L3. L1 acts as signal conductor and L2 and L3 as return conductor. This means that one top IGBT, and two bottom IGBTs are conducting (fig. 10). At the transient, the top IGBT T1+ turns off and after the dead time the bottom IGBT T1- turns on.

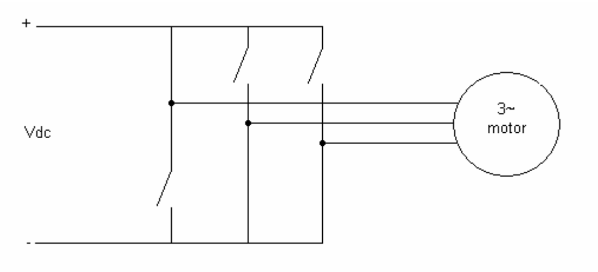

Fig. 10. One of the six possible active switch positions, representing L1, L2+L3

Because the origin of stair stepping is a current step, a combination of a high-frequency model and a low-frequency model is necessary. Besides the high-frequency components, the motor-model will contain the low-frequency steady-state model to simulate the steady-state current.

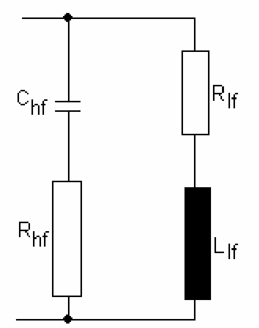

Fig. 11. Differential mode motor model

The motor model (fig. 11) is a differential or line to line mode motor model [5], with values taken for a 735 W induction motor. At low frequencies, the motor behaves as an inductive/resistive series impedance ($R_{lf}+j\omega L_{lf}$). At high frequencies, the motor behaves as a capacitive/resistive series impedance ($R_{hf}+1/j\omega C_{hf}$).

The 100 m cable is simulated by the pSpice lossy transmission line model. The cable impedance is analysed as described in [6-7]. The impedance measurement is done with a vector impedance meter in a frequency range from 400 kHz to 100 MHz.

V. SIMULATION RESULTS

Fig. 12 shows the simulation results of the shielded cable. The cable impedance is 45 Ω for the L1, L2+L3 configuration. At turning off the IGBT, the current falls down to zero. The current step is -1.5A resulting in a voltage step of -68V. After multiple reflections, the diode turns on.

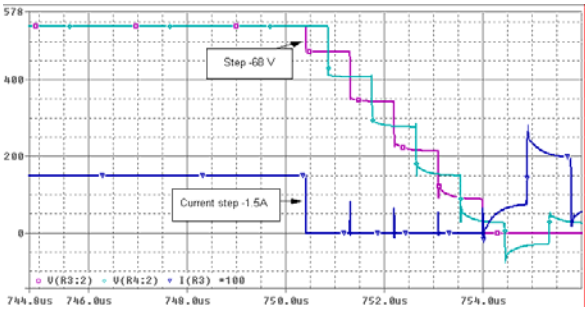

Fig. 12. Simulation (Z_c cable 45Ω, current step -1.5A, voltage step -68V, dead time 10 µs)

Fig. 13 shows the same simulation at the end of another PWM pulse. The current is larger, resulting in a larger voltage step. After a smaller number of reflections in comparison to fig. 12, the diode turns on. After the dead time, the IGBT turns on, resulting in a voltage step of 540 V at inverter side, almost twice that at motor side.

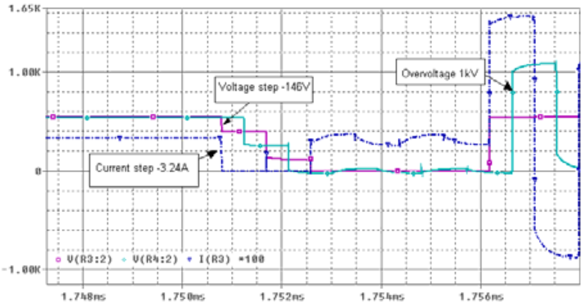

Fig. 13. Simulation (Z_c cable 45Ω, current step -3.24A, voltage step -146V, dead time 10 µs)

VI. TRANSIENT AT INTERFERENCE OF THE DEAD TIME

Stair stepping is not noticed with all inverters. One reason is the use of output coils. The back-emf turns the diode directly on. A second reason is a short dead time. As the stair stepping can take several microseconds, a dead time of 1 µs will interfere with the stair stepping. At that moment the voltage changes directly to 540 V (T1+) or 0V (T1-) at inverter side, causing an overvoltage at the motor side. Fig. 14 shows a measurement of the particular case where the current is so small that the stair stepping lasts longer than the dead time.

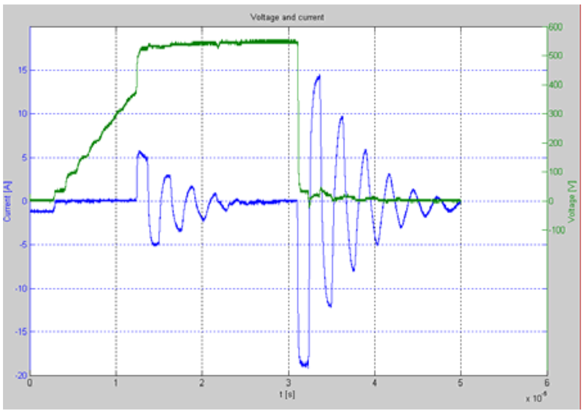

Fig. 14. IGBT T1+ turns on faster than the diode D1+, as the dead time has passed.

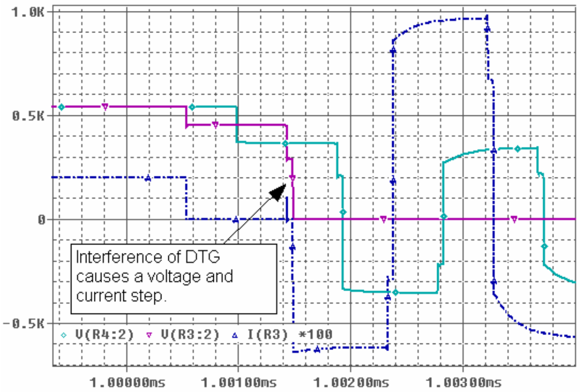

Fig. 15. Simulation, interference of the DTG causes a voltage step and current step.

In the simulation results of the interference of the dead time and the stair stepping (fig. 15), the following figures can be noticed. At turn off of IGBT T1+, the current step is -2 A, resulting in a voltage step of -90 V at the inverter side. After one full reflection, the next voltage step is -160 V, being less than -180 V, due to cable losses and a reflection coefficient at motor terminals smaller than 1. The voltage then is 290 V. The voltage wave reflects again and the current remains zero. While this wave is travelling, the dead time has passed. The bottom IGBT T1- turns on and the voltage falls back to 0 V, causing a voltage step of -290 V. This causes a current step of $\Delta U/Z_c$ = -6.4 A. The simulation confirms this.

VII. CONCLUSIONS AND FURTHER RESEARCH

For explaining the cause of stair stepping, the simple model in this paper is sufficient. The model can be improved by using a d-q-model for the motor and a more realistic model of the IGBTs. Further simulation is needed to show the influence of the stair stepping phenomenon on the inverter, the motor and filters. For instance, 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. Simulation can quantify these losses.

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 simulation proves stair stepping is caused by the current falling back to zero at the inverter side. Short dead times interfere with this reflection phenomenon. The simulation makes it possible to investigate the whole reflection process.

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