VOLTAGE PEAKS OF LOW VOLTAGE INDUCTION MOTORS DUE TO PWM INVERTER SUPPLY

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Abstract In industrial variable speed drives, the supply of low voltage induction motors by IGBT-PWM inverters through screened cables may cause dangerous over-voltage surges at the motor terminals. These voltage peaks of about twice the dc link voltage, with a short rise time of about 200 nsec, increase the armature insulation stress and may damage the motor insulation. The present study provides a theoretical approach to this matter and is completed by tests performed on two 3 and 7.5 kW drives, with different cable lengths. Its target is to define the properties of these voltage peaks, their dependency on the installation parameters, and to present two measures to reduce the voltage gradient du/dt or the peak voltages at the motor terminals in order to raise motor lifetime of such a.c motors.

Keywords inverter supply, cable, peak voltage, voltage gradient.

INTRODUCTION

An increasing part of low voltage standard induction motors are operated with Pulse Width Modulation (PWM) voltage source inverters using IGBT transistors. This solution is applied to a wide range of power: 0.1 kW up to about 200 kW. The PWM inverter mode of control generates a large frequency spectrum. Without using any extra filtering device, and in order to protect the environment from the electromagnetic disturbances caused by this mode of control, the motor can be fed through a screened cable. Nevertheless, this solution leads to undesired overvoltages at the motor terminals and sollicitates heavily the motor insulation much more than in a direct connection to the power supply network.

Usual standards applied to the industrial induction motors recommend to keep the limit value of du/dt < 500 V/µsecond for the motor in order not to reduce its lifetime. This value is suitable for a standard motor fed directly by the network power supply, but when the motor is fed by an inverter without any extra filtering device, the voltage gradient du/dt may reach up to 4000 V/µsecond or even more depending on the installation (especially with short motor cables) . Therefore, for each case, it is very important to make sure that the insulation of the motor used will stand such a supply mode.

STUDIED SYSTEM

Fig. 1 shows the studied system. It consists of an induction motor fed by a frequency converter through a screened cable.

Drive 1 :Motor: 3 kW, 380-420VΔ, 1430 t/min, 50 Hz
Drive 2: Motor:7.5 kW, 380-420VΔ,1440 t/min, 50 Hz
Cable $(3\times1.5\text{mm}^2)$, l = 52 m
Cables $(4\times13\text{mm}^2)$, l = 10 m, 4m, 2m, 1m

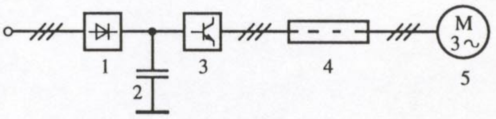

Figure 1: Studied system.
1 : diodes rectifier
2 : capacitor
3 : PWM inverter
4 : cable
5 : induction motor

The power elements used in the frequency converter are IGBT transistors, providing a short switching time of about 200 nseconds. The PWM carrier frequency f_c can be set from 1 to 12 kHz.

SYSTEM MODELLING

Cable. The results obtained from various simulations of the cable considered as composed of several cells, showed that the π modelling of the cable - as a single cell - leads to a sufficient approach (fig. 2). This model simplifies also the formulas in the theoretical approach.

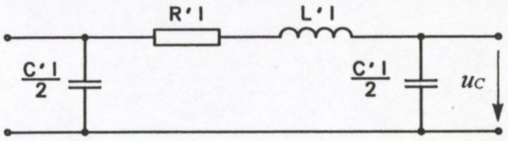

Figure 2: π-circuit diagram of the cable.

Motor and converter. The motor is represented by Park's two axes model. Figures 3 and 4 show respectively the principle scheme of the inverter, and the corresponding PWM (Pulse Width Modulation) control mode. The intersection between two voltages (fig. 4) defines the instants of commutation of both IGBT transistors belonging to an inverter phase. The first voltage u_{hk} has a carrier frequency up to 12 kHz, the second one u_{cmk}, a reference frequency corresponding to the motor operating frequency.

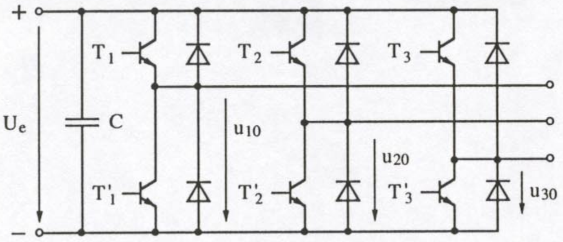

Figure 3 : Principle scheme of the inverter.

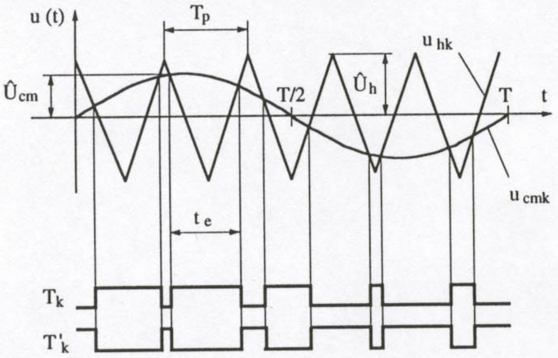

Figure 4 : PWM control mode of one phase of the inverter.

THEORETICAL STUDY

Resonant Frequencies

The cable or cable-motor impedances are given by:

$$\underline{Z_{eq}} = R_{eq} + jX_{eq} \qquad (1)$$

The resonant frequencies are determined by:

$$\mathrm{Im}(\underline{Z_{eq}}) = X_{eq} = 0 \qquad (2)$$

The calculation of these frequencies requires the precise determination of the cable and motor parameters. The cable parameters (R', L', C') are determined by an impedance measurement at different frequencies. The determination of C' takes into consideration all the capacitors between phase-phase, and between phase-earth.

For the whole installation cable-motor, three resonant frequencies are determined: two of them f_1 and f_2 relative to the cable, and f_3 due to the presence of the motor. One obtains for the drive 1 with a cable length l = 52 m:

f_1= 594 kHz ; f_2= 840 kHz ; f_3= 12.25 kHz ;
with $f_2 = \sqrt{2} \cdot f_1$

Because of the corresponding real-parts, only the frequency f_1 may be excited in this case. The frequencies f_1 and f_2 are practically in inverse ratio to the cable length.

Determination of the Peak Voltages at the Motor Terminals

Analytical method: the voltage waveform of a PWM control is not a pure sinewave function of a single frequency, rather it consists of various step functions (fig. 5).

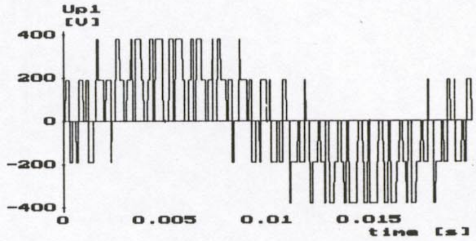

Figure 5: PWM waveform - line-to-neutral applied voltage (f_c=1 kHz, reference frequency=50 Hz).

When these rapid step-functions changes are applied to the cable or to the induction motor through a cable, the results in impulse voltages at the cable or at the motor terminals are given respectively by the following analytical expressions (3) and (9) :

cable :

$$u_C(t) = U[1 - \exp(-t/\tau)\cdot\cos(\omega t)] \qquad (3)$$

with

U: Applied voltage

$\tau = 2L/R$ Time constant (4)

$f = \omega/(2\pi) = (\sqrt{(1/LC) - R^2/(4L^2)})/(2\pi)$ (5)

$L = L' \cdot l$ (6)

$C = C' \cdot l/2$ (7)

$R = R' \cdot l$ (8)

l : length of the cable

cable-motor :

By using Laplace transformation, one obtains :

$$u_C(t) \cong U_{C0} + A[1 - \exp(-t/\tau_1)] + B[1 - \exp(-t/\tau)\cdot\cos(\omega t)] \qquad (9)$$

τ_1: time constant depending on the motor characteristics.

A , B are constants depending on the applied impulse voltage U, and on the cable and motor parameters.

U_{C0}: initial value of the voltage

Numerical method: a set of differential equations relative to the cable and the motor has been established. A numerical program using Runge-Kutta integration method has been used. Because in some cases of the time constant relative to the cable

TABLE 1 - U_{peak} and du/dt measured at the cable output, for different cable lengths (U_e=540 V, f_c=1 kHz, reference frequency=50 Hz)

		1 m		2 m		4 m		10 m		52 m
Voltage	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]
380 V	784	4977	815	4794	845	4970	920	4088	906	1087

TABLE 2 - U_{peak} and du/dt measured at the motor terminals, for different motor cable lengths, induction motor at no-load (f_c=1 kHz, reference frequency=50 Hz)

		1 m		2 m		4 m		10 m		52 m
Drive	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]	U_{peak} [V]	du/dt[V/µs]
3 KW	768	4042	798	3800	804	3573			900	1080
7.5 kW							903	4300		

(≅ 0.5 µsecond), a stepsize equal to 0.02 µsecond was necessary. An automatic procedure calculates in the program the instants of commutation of different transistors, and determines consequently the voltages applied to the cable. These ones depend on the point of operation of the inverter (carrier frequency f_c and reference frequency f).

TEST RESULTS

Cable Table 1 shows the line-to-line peak voltage U_{peak} and the voltage gradient du/dt measured at the cable output, at no-load for different cable lengths.

Cable-motor : Table 2 shows the line-to-line peak voltage U_{peak} and the voltage gradient du/dt measured at the cable output, induction motor at no-load for different motor cable lengths, and different drives.
One notices that:
-For installations with short motor cables the ratio du/dt is about 4000 V/µsecond >> 500 V/µsecond (*recommended value*).
-The increase of the cable length leads to a decrease of the voltage gradient du/dt ,and an increase of U_{peak} , which remains within acceptable values.
-Because of the motor impedance, the loading of the cable by the motor has a small influence on the results.

Comparison Between Test and Theoretical Results

Tables 3 and 4 compare different methods. One notes good agreement between computed and measured values (Drive 1 - cable l =52 m).

INFLUENCE OF VARIOUS PARAMETERS

Load of the motor and operating frequency of the motor: Different measurements and computations show that the load of the motor and its operating frequency have practically no influence on the amplitude of the peak voltages.

TABLE 3: Cable at no-load (l=52 m)

	Peak Voltage [V]	Frequency [kHz]
Analytical	962	594
Numerical	961	595
Measurement	906	588

TABLE 4: Cable (l=52 m) +induction motor 3 kW at no-load

	Û [V]	du/dt [V/µs]
Analytical	961	1139
Numerical	961	1117
Measurement	900	1080

PWM carrier frequency f_c: Changing the PWM carrier frequency f_c (voltage harmonics) may alter the behaviour of the system: possible excitation of one resonant frequency (f_1, f_2 or f_3) of the system. For the studied systems, the frequencies f_1, f_2 and f_3 were well damped because of the relative high values of the corresponding dampings (real parts of the impedances). Nevertheless, this aspect has to be verified for each installation.

Figure 6 shows the line-to-line voltage of the motor terminals (f_c = 5 kHz, l=10 m, drive 2: 7.5 kW) . These peak voltages applied continuously to the motor - during short periods of time - will sollicitate the insulation more especially as the PWM carrier frequency f_c is high.
In extreme cases where: t_e/T_p duty cycle is very low (PWM carrier frequency f_c high) and the time constant of the circuit is also high, the voltage may commutate

Figure 6: line-to-line voltage at the motor terminals: computed values by the numerical program (f_c = 5 kHz, reference frequency=50 Hz, l=10m, 7.5 kW drive).

before getting stable leading to more important peak values Û .
Higher is f_c, more is the insulation of the motor sollicitated.

Cable characteristics The different cable characteristics (R', L', C', l) modify the values of both resonant frequencies (f_1, f_2).

MEASURES TO RAISE MOTOR LIFETIME

To raise motor lifetime of a.c motors supplied by IGBT-PWM inverters, different improvements of the inverter and of the motor are proposed in the technical literature:
- reinforcement of the motor insulation system, Binder (2)
-optimum pulse patterns, and use of passive filter circuit, Zurowski and Krüger (5).

In this study, two measures to reduce the voltage gradient or the peak voltages at the motor terminals have been tested.

Insertion of Coils Between Inverter Output and Motor

Table 5 compares the voltage gradient , the line-to-line peak voltage and the rise time measured in the following cases:
Case a - Drive 1 - cable l =1 m without additional coils
Case b- Drive 1 - cable l =1 m with 3 × 0.2 mH
Case c- Drive 1 - cable l =1 m with 3 × 1.5 mH

One notes that the insertion of coils between inverter output and motor increases the rise time and so limits the voltage gradient du/dt at the motor terminals (cases b and c). But a limited voltage gradient due to a limited value of the additional coil leads to a higher value of the peak voltage (case b).

Figures 7 and 8 show respectively the line-to-line voltage measured at the motor terminals (f_c=1 kHz, reference frequency=50 Hz, l =1m, U_e=540 V) in cases a and c.

TABLE 5: Insertion of coils between inverter output and motor

	Peak Voltage [V]	du/dt [V/µs]	rise time [µs]
Case a	768	4042	0.19
Case b	798	3627	0.22
Case c	680	289	2.35

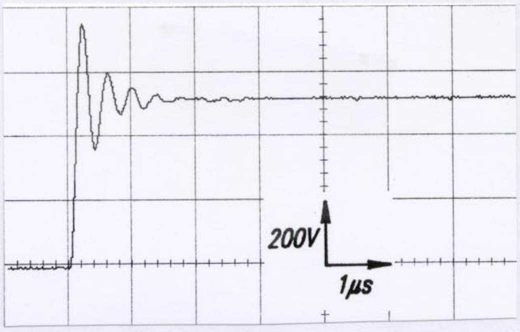

Figure 7 Case a: line-to-line voltage at the motor terminals: measured value (cable l=1 m without additional coils, induction motor 3kW at no-load)

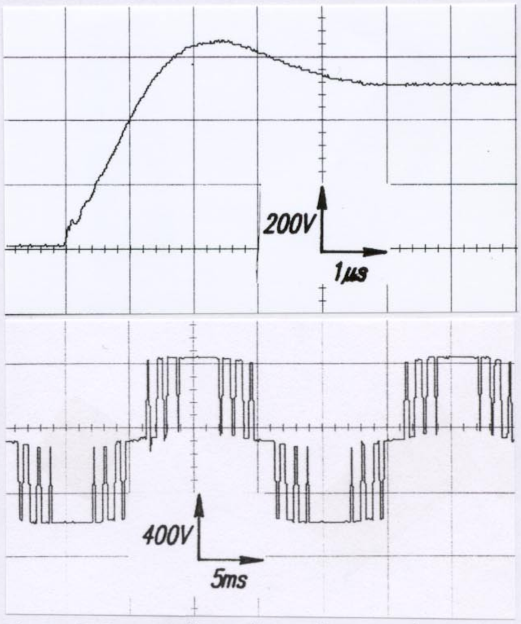

Figure 8 Case c: line-to-line voltage at the motor terminals: measured value (cable l=1 m with 3 × 1.5 mH, induction motor 3kW at no-load)

Insertion of Zener Diodes at the motor terminals

In some applications with low voltage induction motors supplied by PWM inverters, the insertion of Zener diodes at the motor terminals (diodes in series but opposite direction), may constitute a measure in order to suppress undesired peak voltages .

Figures 9 and 10 show respectively the line-to-line voltage measured at the cable output (f_C=1 kHz, reference frequency=50 Hz, l =4m, U_e=540 V) in the following cases:
Case d - cable l =4 m without Zener diodes
Case e - cable l =4 m with Zener diodes

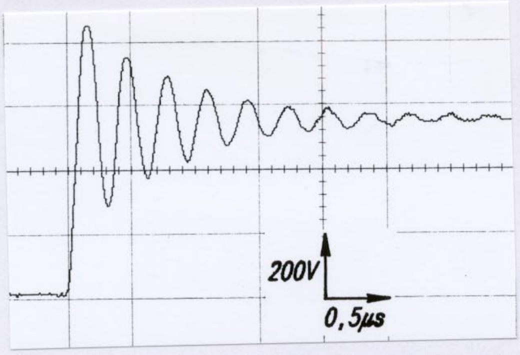

Figure 9 Case d: line-to-line voltage at the cable output: measured value (cable l=4 m without Zener diodes)

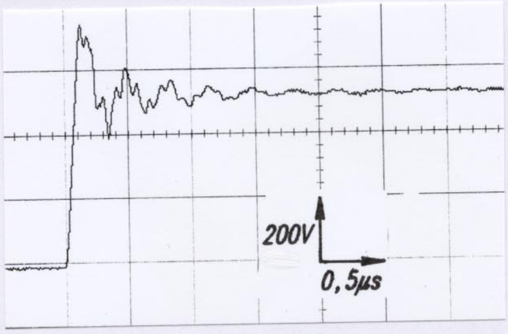

Figure 10 Case e: line-to-line voltage at the cable output: measured value (cable l =4 m with Zener diodes)

Table 6 compares the line-to-line peak voltage measured in cases d and e. One notes a limitation of the voltage measured at the cable output (case e). This limitation (700 V in this case) is fixed by the choice of the combination of diodes inserted at the cable output.

TABLE 6: Insertion of Zener diodes at the cable output

	Case d	Case e
Peak Voltage [V]	845	760

CONCLUSION

The present theoretical approach meets the results of the tests performed on the studied 3 kW and 7.5 kW drives with different cable lengths. The precise determination of the cable parameters is necessary in order to predetermine the voltage gradient at the motor terminals for a planned installation. In order to suppress the peak voltages or to reduce the voltage gradient at the motor terminals, two measures which may be used separately or together, have been tested.

One should be aware of the limits of the motor insulation, since the overvoltages appearing when fed by an inverter may be too high. This phenomenon may not be the same for small and large installations since the R, L and C values are not in the same ratio. Therefore, this aspect should be studied for each case and the necessary criteria should be taken into account for the engineering and the design of motors fed by inverters.

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