A practical approach to the influence of long lead cables on inverter supplied induction motors

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Abstract

It is known that the steep voltage changes caused by IGBT frequency inverters may cause insulation problems in induction motors. Filters are introduced in order to limit the rate of change of the voltage du/dt. In order to study the practical implications of the choices made, a number of tests have been carried out. An inverter was connected to the motor with several types/lengths of cables. Also several types of inverters were used. In order to study the influence of motor filters, several filters were used at the inverter or at motor side. To check the influence of the motor, tests were also performed without motor connection to the lead cables.

1 Measurements

1.1 Introduction

In order to study the phenomena of overvoltages at motor and inverter terminals due to the rate of change of the voltage du/dt, four types of experiments are carried out :

A : motor not connected, no filter
B : motor at cable terminals, no filter
C : motor at cable terminals, filter at inverter terminals
D : motor at cable terminals, filter at motor terminals

The influence of different inverters, cables and filters is based on these set-ups, where the lengths of the cable as parameter.

1.2 Measurements : various cable length

The first group of experiments are performed on a set-up with one type of inverter and one type of motor. Only the length and type of cable and the inverter parameters are changed (table 1).

Table 1 : Motor terminal voltage – unshielded cable

	2 [m]	5 [m]	10 [m]	50 [m]	100 [m]
A	704	760	920	1080	1080
B	672	736	940	1000	1000
C	776	784	784	808	808
D	760	752	792	1280	1280

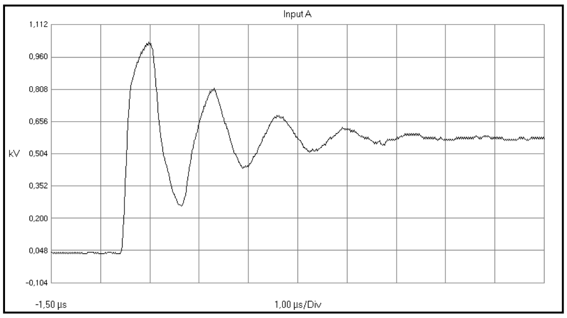
The experiments show that for ratings less than 15kW, the precence of the motor does not matter at all [1]. Only in case of a filter installed at inverter output terminals a substantial improvement is found. In a second experiment the cable is changed. Under these condition there is a substantial difference in motor terminal voltages, especially when the cable is long (table 2).

Table 2 : Motor terminal voltage – shielded cable

	2 [m]	5 [m]	10 [m]	50 [m]	100 [m]
A	576	696	800	1020	920
B	656	696	832	1040(*)	980
C	776	776	784	800	824
D	776	768	776	1260	1240

The damping of the shield causes lower values of the voltage at motor terminals (figure 1). The number of oscillations is function of the reflection coefficient and the period is function of the cable length. Whether or not the shield is grounded, does not influence the voltage values. The new generation cables (type ferrite-cables) are not yet tested. In both experiments, the fundamental supply and carrier frequencies are changed. These changes have no effect on the results.

Figure 1 : Measurement on a 50 meter shielded cable



1.3 Measurements : various cable type

The next group of experiments are performed on different type of the cable, more specific single-core and multi-core cable with varios cross-sections. The cross-section affects the magnitude of the du/dt substanially. The value of the resistance descreases with increasing cross-sections, yielding a lower damping factor (table 3). A similar effect is noticed by using single-core and multi-core cables. However, the difference is quite substantial. Oversized cross-sections can be used for reducing the voltage drop especially at low speeds increase the overvoltage problem. On the other hand the use of single-core or multi-core cable does not cause a substantial difference (Table 4).

Table3 : Motor voltage multi-core shielded cable

100 [m]	4*1.5 [mm²]	4*2.5 [mm²]	4*4 [mm²]
A	920	1060	1080
B	980	1000	1020
C	816	880	900

Table4: Motor voltage–single-core vs.multi-core cable

10 [m]	Multi-core 3*1.5 [mm²]	Singe-core 3*1.5 [mm²]
A	920	864
B	940	1000
C	784	784

1.4 Change of inverters

Several types of inverters were used, three of them scalar control and one using field orientation. The tables show that the type of IGBT-control doesn't influence the value of the overvoltage. The measurements are performed for a length of 100m single-core cable. The value of the du/dt at inverter terminals was approximately equal for all used types.

Table 5 : Motor terminal voltage – Inverter types

100 [m]	I	II	III	IV
A	920	1080	n.a.	1080
B	980	1040	1040	1020
C	816	832	856	840

1.5 Influence of filters

Nowadays a lot of filters exist in order to reduce the rate of change of the voltage du/dt. The best known types are parallel resistor at motor terminals, first order motor terminator, second order shunt filter terminator, LC-filter or sine-filter, LC-filter with insulated capacitor and load reactor. The tests were only examined on load reactors (Table 6). The inductance of the load-reactor influences the overvoltage. A larger inductance decreases the value of the overvoltage. On the other hand power losses are generated in the coils.

Table 6 : Motor terminal voltage – load-reactors

100 [m]	I	II	III	IV	V	VI
C	816	840	860	820	792	848

Using simulations (Section 3) to predict the overvoltage, differences between several types of filters are shown (Table 7).

Table 7:Voltage and slope at motor terminals for several types of filters at inverter terminals (slope at inverter : 5000V/µs)

30 [m]	Slope [V/µs]	Overvoltage [V]
No filter	4842	982
Load reactor	**328**	**649**
Parallel resistor	2693	616
First-Order RC	1474	661
Second-Order RLC	1474	653

The simulation shows that the overvoltage decreases in a similar way for all kinds of filters. However, when we take account of the slope at motor terminals (important for insulation breakdown in motor coils [6]) the load-reactor gives the best solution. Clearly, only the load-reactor is a valuable way of reducing the voltage changes without increasing the losses to a major extent.

2 Theory

2.1 Introduction

When a voltage front of a PWM pulse travels from the inverter to the motor, a transmission line effect is found. This voltage front sees an impedance mismatch at the motor terminals producing a reflection. The reflection returns towards the inverter, where it is again reflected towards the motor. The load reflection coefficients Γ_L be expressed as,

$$\Gamma_L = \frac{R_L - Z_0}{R_L + Z_0} \quad (1)$$

where R_L is the load resistance and Z_0 is the characteristic impedance of the cable, given by

$$Z_0 = \sqrt{\frac{L_C}{C_C}} \quad (2)$$

where L_C and C_C are cable parameters.
The source voltage reflection coefficient Γ_S is also defined as:

$$\Gamma_S = \frac{R_S - Z_0}{R_S + Z_0} \quad (3)$$

where R_S is the source resistance. At the inverter we get the same shape as the incoming wave but with the corresponding points multiplied by Γ_S (almost –100%). The motor characteristic impedance is 10 to 100 times larger than the characteristic impedance of the cable. This results in large reflections causing the voltage doubling at the motor terminals. Normal voltage reflection coefficients are given in table 8.

Table 8 : Voltage reflection coefficient at motor terminals vs. motor power [2]

Motor kW	R_L	Z_0	Γ_L
18.5	1500	80	0.90
37.5	750	70	0.83
75	375	50	0.76
150	188	40	0.65
300	94	30	0.52

2.2 Effect of the slope

The time the voltage pulse requires to travel from the inverter to the motor (t_t in µs) can be expressed as :

$$t_t = \frac{l_C}{\upsilon} \tag{4}$$

where l_C is the cable length and υ is the pulse velocity given by :

$$\upsilon = \frac{1}{\sqrt{L_C \cdot C_C}} \tag{5}$$

where L_C and C_C are cable parameters. When the travel time (t_t) gets larger (longer cables) than the rise time (t_r) of the voltage pulse, a doubling of the voltage at the motor terminals occurs. Notice that t_r of an inverter output voltage is typically 0.1 µs for IGBT's .[3,4]

After the time t_t the pulse is reflected at the motor terminals. The amplitude of this voltage is:

$$V(t_t) = \frac{t_t \cdot V_{DC} \cdot \Gamma_L}{t_r} \quad \text{for } t_t < t_r \tag{6}$$

$$V(t_t) = V_{DC} \cdot \Gamma_L \quad \text{for } t_t \geq t_r \tag{7}$$

with V_{DC} the DC-bus voltage of the inverter. When t_t<tr/2 then the pulse is still increasing at the motor terminals while the begin of the pulse is reflected to the inverter and back to the motor. This incoming reflected wave has the opposite sign of the original pulse and reduces the overvoltage. The overvoltage is expressed as:

$$V_{\max} = V_{DC} \cdot (1 + \Gamma_L) \cdot \left[1 + \sum_{k=1}^{k=n} (-1)^k \cdot \Gamma_L{}^k \cdot \left(1 - 2k \frac{t_t}{t_r} \right) \right]$$

$$\text{for} \quad \frac{1}{2n+2} \leq \frac{t_t}{t_r} \leq \frac{1}{2n} \tag{8}$$

The relative overvoltage for long cables is

$$\frac{V_{\max}}{V_{DC}} = (1 + \Gamma_L) \cdot \left[1 + \sum_{k=1}^{k=n} (-1)^k \cdot \Gamma_L \cdot \left(1 - 2k \frac{t_t}{t_r} \right) \right] \tag{9}$$

With this equation the overvoltages are calculated that can be expected with a certain inverter, cable and motor combination. Figure 2 shows the computed relative overvoltage versus the travel time/rise time (with Γ_L=0.9, 0.8 and 0.7).
Notice that the critical cable length (minimum cable length after which voltage doubling occurs) becomes shorter with faster inverter output pulse rise time.

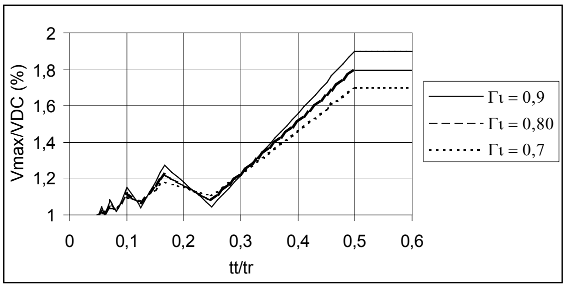


Figure 2 : Motor terminal voltage versus t_t/t_r

2.3 Effects on motor insulation

The overvoltage with fast slope and ringing occurs at both ends of one pulse. Depending on the PWM algorithm of the inverter, this transients may occur 20-100 times per period (50 Hz – 20 ms). As much as 85% of the peak of this transient voltage is found across the first turn of the first coil of the motor windings [1] (Figure 3).

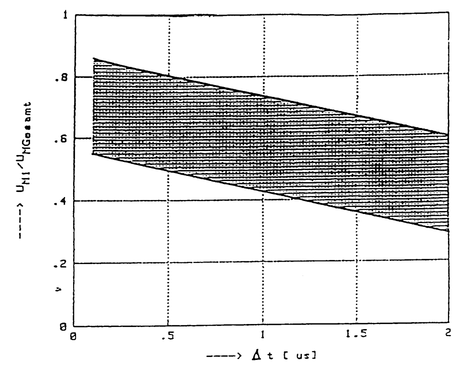


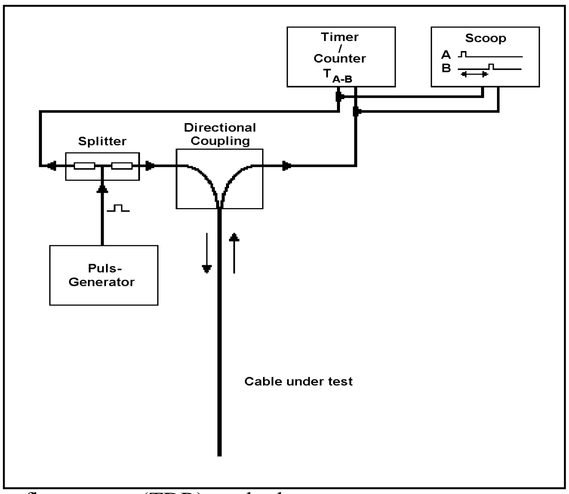
Figure 3: Voltage across the first turn vs. Rise time of the voltage pulse [7]

It is unlikely that the interturn insulation of the motor fails at the first surge. However, damaging effects are accumulated over a period of time. It is very likely that dielectric partial discharges occur in the ending region of the machine winding. These discharges accelerate the normal ageing process. In the worst case the partial discharge forms a fixed channel and eventually causes major insulation failure[1,5].

Solutions for these overvoltages with high du/dt are:
- inverter duty motors
- minimise the length of the cable
- use filters, reactors

3 Simulations

First the cable was assumed to be loss-free so the cable parameters where measured using the time domain



reflectometry (TDR) method.

Figure 4 : Experimental setup for TDR-measurements

The results of the measurements of a shielded cable of 50 meter can be seen in figure 5. The time delay between incoming pulse and reflected pulse is 600 ns so the travel-time (t_t) of the cable is 300 ns. The characteristic impedance (Z_0) of this type of cable is 65 Ohms.

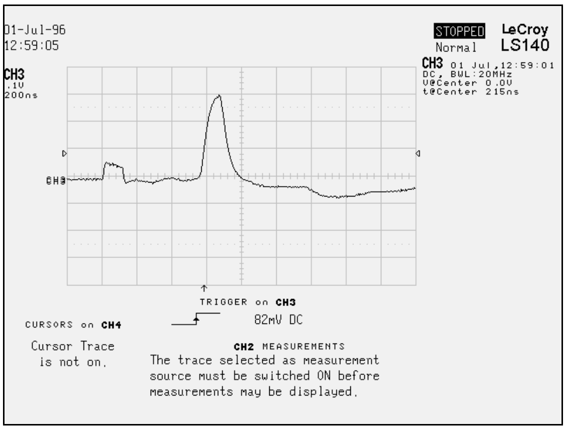


Figure 5 : Results of 50 meter shielded cable

The motor is simulated as a resistor that causing the same voltage reflection coefficient (Γ_L) as in the measurements. The simulations are done with only one incoming voltage pulse because the transmission effect is the same for each pulse of the PWM wave. Simulation results with a 10 m cable without filter and with a 100 m cable without filter are shown in figure 6 and 7.

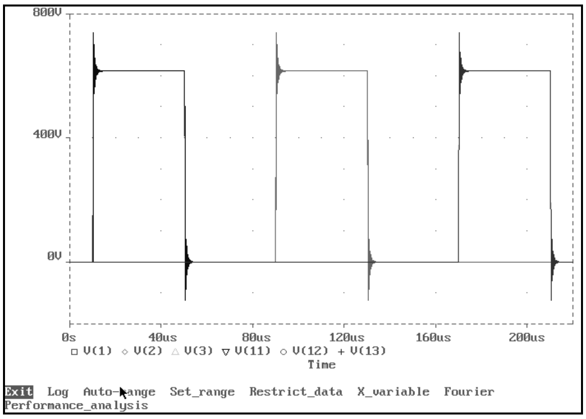


Figure 6 : Simulation with 10 m cable without filter

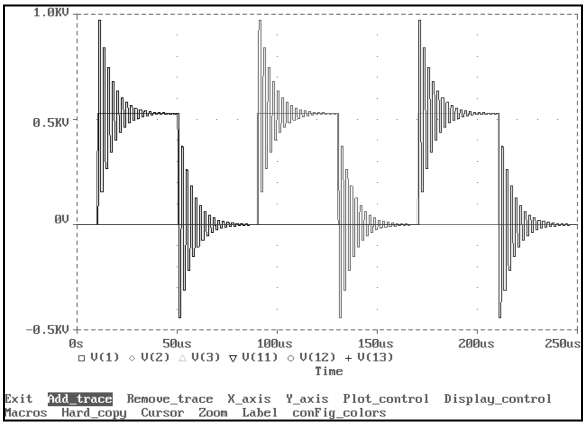


Figure 7 : Simulation with 100 m cable without filter

In the figures 8 and 9 the results are shown of the simulations with 10 resp.100 m shielded cable with a filter connected at the inverter terminals.

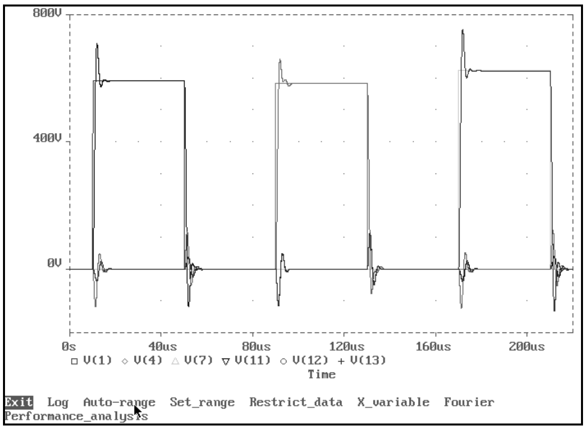


Figure 8 : Simulation with 10 m cable with filter on the inverter terminals

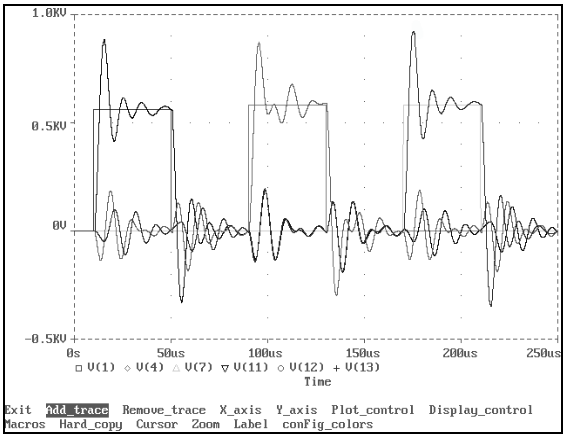


Figure 9 : Simulation with 100 m cable with filter at the inverter terminals

Now we can compare the simulated results with the measured results. Table 9 and 10 compare the overvoltages without and with filter, while table 11 and 12 gives the slope values. In both cases, the motor terminal voltage from the simulated and the measured results are similar. An exception is found for cable lengths from 10 m and less. In these cases there is a noticeable difference of the overvoltage. The reason of this difference can be explained by the figure 2 and (8). For short cables, the overvoltage is determineted by this expression and a small difference in cable length or rise time can give a large difference in overvoltage.

Table 9 : Motor terminal voltage – shielded cable without filter

	2 m	5 m	10 m	50m	100m
Measured	576	696	800	1020	920
Simulated	642	655	730	1058	970

Table 10 : Motor terminal voltage – shielded cable with filter at the inverter terminals

	2 m	5 m	10 m	50m	100m
Measured	776	776	800	800	824
Simulated	608	634	710	890	884

Table 11 : Motor terminal slope [V/µs] – shielded cable without filter

	2 m	5 m	10 m	50m	100m
Measured	6200	5600	5000	4500	3913
Simulated	6371	5675	5568	5042	4648

Table 12 : Motor terminal slope [V/µs] – shielded cable with filter at the inverter terminals

	2 m	5 m	10 m	50m	100m
Measured	1160	720	560	208	159
Simulated	950	750	585	348	226

In figure 10 a comparison between a simulated and a measured pulse is given.

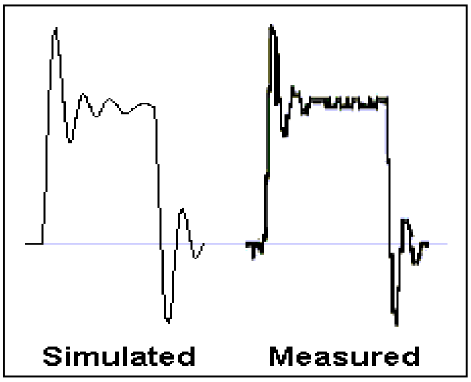


Figure 10: Comparison between simulated and measured pulse (100 meter shielded cable with filter at the inverter terminals)

Conclusions

From the data gathered, a number of conclusions may be drawn regarding their influence on the overvoltages at the terminals of a PWM-supplied induction motor.

The problems concerning overvoltage are due to reflection. Therefore the characteristic impedance and the reflection coefficients are important. The experimental results show an influence on the cable length, the cable type (shielded, not shielded, composite) and conductor cross-section. Reflection coefficients are defined experimentally. The motor ratings have an influence (larger ratings). Clearly that the filter inductor has an important influence due to its major impact on the slope du/dt. Other factors as the carrier frequency, the fundamental power supply frequency or parameter settings on the inverter do not have an impact concerning overvoltages. The grounding of the cable shielding does not affect the problem of overvoltage.

Acknowledgment

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