A practical approach to the influence of ground connection on inverter supplied electrical machines

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Abstract - **It is known that the steep voltage changes caused by IGBT frequency inverters can cause overvoltage problems at motor terminals and in the motor winding [1,2,3]. Moreover, due to the distributed phase capacitances of the cable, these voltage changes cause a voltage variation in the ground wire [4], which can only be partially eliminated by introducing filters that limit the rate of change of the voltage [5]. This paper investigates, through a number of test measurements, the influence of cable type and cable length on the induced ground wire voltage for most practically applied combinations of ground connections.**

1. Introduction

This paragraph provides a brief description of the constitution of ground wire voltages.

In an ideal Insulated Supply System (ISS), the line potentials of the cable connection between inverter and motor are floating with respect to the earthpotential. Practically, those line potentials must be referenced to the potential of the protectional earth (PE) by the parasitic capacitance between phaseleads and earthlead (Fig.1). The earthlead takes a steady state position, in comparison to the 3 phaseleads, determined by the inverter-switching-state and the distribution of voltage over the three parasitic capacitances of the cable (Fig.1). Switching of the inverter (for example: phase V is switched from $+V_{DC}$ to 0V), yields to a change of the voltage between phaseleads U, V and W, and causing a change of the voltage distribution over the parasitic capacitances. The charging and discharging of these capacitances leads to a new steady state position of the protectional earthlead.

When all three parasitic capacitances are equal as in Fig.1, the charge current of one capacitance is compensated by the discharge current of the others. Thus, no current flows through the protectional earthlead and there is no voltage occuring over the PE. Practically however, the capacitances always show some mutual differences, the voltages are not distributed symmetrically over the parasitic capacitances and the charging and discharging currents of the different capacitances at switching time, do not compensate each other entirely. Consequently, a transient current is flowing through the PE, causing a voltage drop. The magnitude of this current is determined by both the slope of the voltage changes and the mutual differences between the parasitary crosscapacitances. The rate of the voltage change, dU/dt depends on the rise time of the inverter IGBT's (typ. 100ns), the possibly applied filter and the cable parameters.

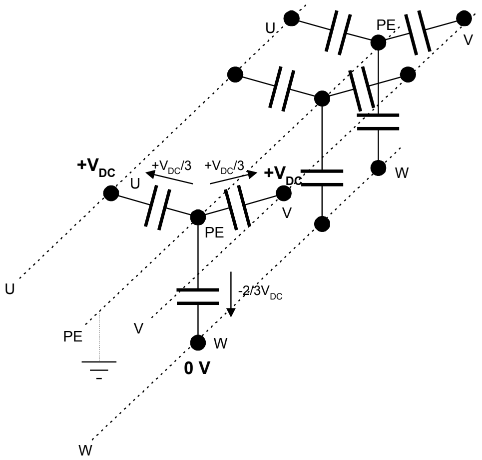

Fig.1. Voltage distribution for Steady State position of protectional earthlead in reference to phaseleads at a certain inverter switching state (+V_{DC} at phase U and V, 0 V at phase W; with V_{DC} the DC-bus voltage of the inverter)

Both cablelength and cableparameters affect the ground wire voltages:

1) The change of steady state position of the earthlead, at switching time of the inverter, is seen first at inverterside and arrives delayed (a traveltime t_t (1) of the cable) at the motorside. Consequently there's an influenced cablezone where currents are drawn through the earth lead causing voltage over that zone. For short cablelengths, this zone consists of the entire cablelength and increases with increasing cablelength, yielding an increasing voltage over the PE. For longer cables, when the risetime of the PWM pulses descends beneath the traveltime of the cable ($t_r \leq t_t$), the length of the influenced zone comes to a maximum as well as the voltage measured over the PE. Thus the traveltime t_t, and in origin the cablelength and cable parameters, will be determining for the voltage occuring over the groundwire:

$$t_t = \frac{l_c}{v} \quad \text{and} \quad v = \frac{1}{\sqrt{L_c C_c}} \qquad (1)$$

with

l_c: cablelength [km]
v: transmission speed of the cable [km/s]
L_c: phase lead series inductancy [H/km]
C_c: parasitic crosscapacitance phase to PE [F/km]

2) Reflection of the PWM pulses at motor terminals causes oscillating line overvoltages at motorside [2], which do not occur at inverterside. The overvoltages cause a higher charging and discharging current of the crosscapacitances of the cable, thus drawing a higher current through the PE and consequently, a higher voltage over the groundwire is found. With increasing cablelength, the overvoltage, and accordingly the groundwirevoltage, rises to its maximum value, reached at the critical cablelength [2]. Consequently, cablelength again will determine the ground wire voltage.

The period of the oscillations T_{osc} (2) in the line overvoltage waveform is function of the traveltime t_t of the cable and determines the period of the ground wire voltage.

$$T_{osc} = 4t_t \tag{2}$$

The number of oscillations in the line overvoltage waveform is function of the reflection coefficients at motor and inverter terminals, and of the attenuation constant α (3) of the cable.

$$\alpha = \sqrt{rg} \tag{3}$$

where r: series resistance per meter
g: cross conductancy per meter

The number of oscillations however, only affects the rms values of the ground wire voltages, the peak values are indifferent since the peak is always reached at the first oscillation.

2. Measurements

A. Introduction

1) Performed Experiments In order to study the ground voltages across motor and inverter terminals due to the rate of change of the voltage du/dt over the parasitic crosscapacity between phase and ground leads, three types of experiments have been carried out:

A: ground connection only at motor terminals
B: ground connection only at inverter terminals
C: ground connection at motor and inverter terminals

The investigation of the influence of different filters and cables, is based on these set ups, where the length and the type of the cable are parameters, as well as the carier frequency of the inverter.

2) Test Set up An inverter supplied induction motor IM 1, U/f controlled and fed through a long cable X-Y (Fig.2.), is loaded by a second induction motor IM 2. IM 2 operates in generator mode, and the field orientation of inverter 2 provides an adjustable loadtorque for IM 1. The entire configuration is supplied by a transformer without grounding of the secondary neutral point and thus, providing an ISS.

In particular, the subject of the performed experiments, is the cable connection X-Y (Fig.2), for:

- different groundings: in X, in Y, or X and Y
- different cable types: single or multi core, shielded or non-shielded
- different cable lengths: 2 to 100 m
- different filtersituations: no filter, dU/dt-filter (Load-Reactor) or sine filter (LC-filter)
- different settings for inverter 1: carrier frequency and fundamental motor supply frequency

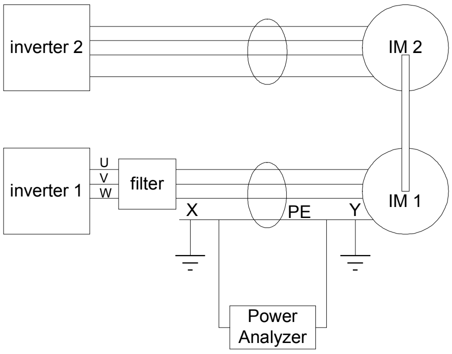

Fig.2. Test Set Up

The variables which were measured, consist of (Fig.2.):

- RMS voltages over PE, between ground connection X and Y
- Peak voltages over PE, between ground connection X and Y
- RMS currents through ground connection Y
- Peak currents through ground connection Y

B. Interpretation

1) Influence of Ground Connection and Grounding Resistance In a first experiment, only the type of ground connection was changed. Substantial differences in ground wire voltages were found, depending on the grounding configuration (Table 1; Fig.3).

TABLE 1
MEASURED GROUND WIRE PEAK VOLTAGE FOR DIFFERENT GROUNDING LOCATIONS (SHIELDED CABLE 4x2.5mm^2)

50 m cable	Voltage [V]
Ground connection only at motor terminals	109.27
Ground connection only at inverter terminals	69.21
Ground connection at motor and inverter term.	71.44

Since the test configuration is performed as an Insulated Supply System, the only reference of line voltages to ground potential is through the parasitic capacitance between phase and earth leads of the supply cable (Fig.1). For long cables, the steep voltage changes of the PWM pulses cause an oscillating overvoltage at motor terminals [2], initiating oscillating voltages over the parasitic capacitances towards the earthlead, as described in paragraph 1.

Consequently, when grounded at motorside, the entire system, referenced to ground potential through the parasitic capacitance at motorside, is oscillating, refered to the earth.

At inverter side, overvoltages do not occur. Consequently when grounded at inverterside, the oscillation of the entire system in reference to the earth, when transiting from one swichting state to another, is eliminated. Accordingly, the induced ground wire voltages are reduced substantially (Fig.3).

When grounded at motor and inverter, small circulating earth currents occur, causing a slight increase of the induced ground wire voltages in comparison to a configuration with grounding at inverter side only.

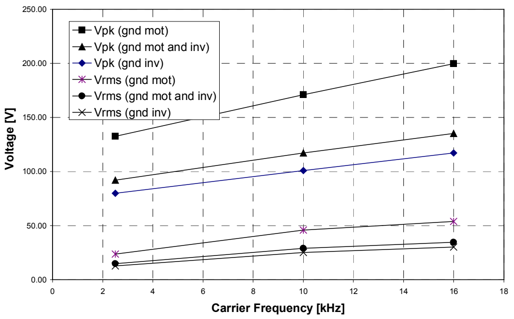

Fig.3. Voltage over 100 m Protectional Eartlead, dU/dt filter, shielded cable (4x2.5mm^2)

A second analyzed parameter is the grounding resistance. In a configuration with grounding at inverter and motor terminals, a difference in potential between the different grounding points is found for different grounding resistances. For other earth configurations, the grounding resistance will be a lot less determining.

The possible voltage between the two grounding points increases with increasing resistance between the two points. For the test set up described in paragraph 2.A.2), the grounding resistance measured between point X and Y (Fig.2), equals 23 Ω.

An experiment was performed, with the PE lead at the inverter terminal connected to the PE at the motor terminal over a variable resistance, without any ground connection.

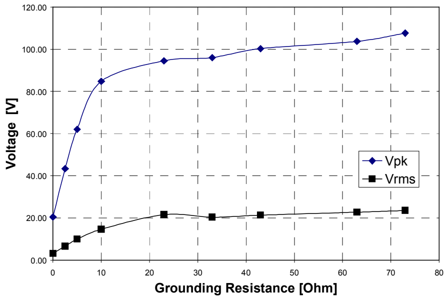

Fig.4. Ground wire voltage for 50 m shielded cable (3x2.5mm^2), no filter, carrier frequency 10 kHz, grounded at inverter and motor

By varying the resistance value, the influence of the grounding resistance on the induced ground wire voltage, could be verified (Fig.4).

2) Influence of Inverter Settings Relevant adjustable inverter parameters are the carrier frequency and the motor frequency.

With increasing carrier frequency, the number of voltage changes per time unit will increase linearly. Consequently, the RMS voltage over the ground wire will increase linearly as well. When varying the carrier frequency from 2.5 kHz to 16 kHz, the measured RMS voltage rises for over 50% (Fig.5).

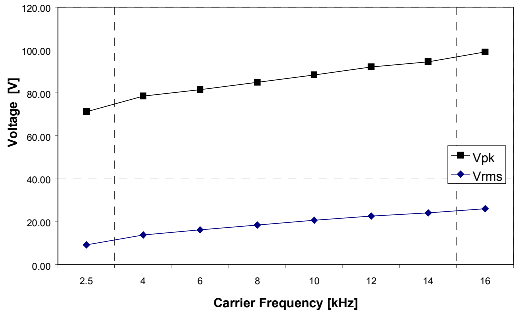

Fig.5. Voltage over 50 m Protectional Earthlead, no filter, shielded cable (3x2.5mm^2), grounded at motor and inverter

Varying the motor frequency between 20 Hz and 50 Hz, does not really affect the induced ground wire voltages (Fig.6). The ground wire voltages are induced by the steep voltage changes and are only related to the carrier frequency.

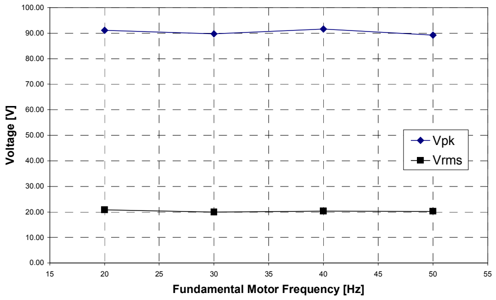

Fig.6. Voltage over 50 m Protectional Earthlead, no filter, shielded cable (3x2.5mm^2), carrier frequency 2.5kHz, grounded at motor and inverter

3) Influence of Motor Load Conditions Varying the motor power, and consequently the load current conducted by the cable, does not affect the induced ground wire voltages (Fig.7). This analysis confirms the assumption, that the cause of ground wire voltages is under no circumstances from an inductive origin.

Since the power doesn't have an influence on the experiments, the rest of the measurements were performed at 80% of the nominal motor power, but the results can be considered as valid for all other load conditions.

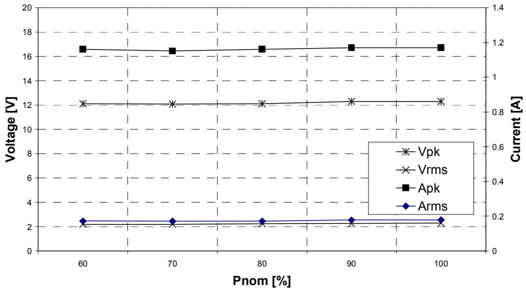

Fig.7. Voltages over and Current through Protectional Earthlead, dU/dt filter, carrier frequency 2.5 kHz, shielded cable ($3x2.5mm^2$), in function of a percentage of the nominal motor power P_{nom}

4) Influence of Applied Filter The filter at the output of the inverter, determines the slope of the voltage changes of the PWM switching pulses and accordingly the charging and discharging currents of the parasitary crosscapacitances are influenced. Consequently, the same influence is seen in the ground wire voltage.

In Fig.8 and Fig.9, the measured Peak and RMS voltages are given for test set ups without filter, with dU/dt filter (Load Reactor) and with sine filter (LC filter) in function of the cablelength, of which the influence is discussed later.

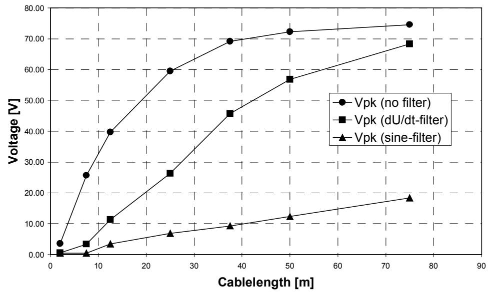

Fig.8. Peak Voltages over Protectional Earthlead, shielded cable ($3x2.5mm^2$), carrier frequency 2.5kHz, grounded at motor and inverter

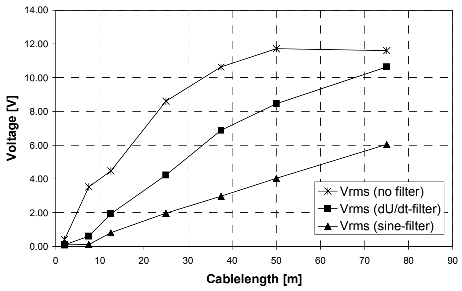

Fig.9. RMS Voltages on Protectional Earthlead, shielded cable ($3x2.5mm^2$), carrier frequency 2.5kHz, grounded at motor and inverter

In Fig.8 and Fig.9 it is clear that the sinusfilter proves to be very effective for all of the tested cablelengths (2m-100m) with measured values of the ground wire voltage up to only 15%(*) of those measured for the same test set up without any filter.

The dU/dt-filter turns out to be a lot less effective than the sine filter, but still achieves good results for short cablelengths, up to 50% of the ground wire voltages, measured for the same test set up without any filter (Fig.8 and Fig.9). For longer cablelengths, the attained reduction with a dU/dt-filter in comparison to a set up without filter, strongly decreases. Above a certain length, the influence of the dU/dt-filter will even become negative.

For very small cablelengths, the gain in absolute values with a filter, is restricted (Fig.8 and Fig.9).

5) Influence of Cablelength As described in the introduction, the cablelength is one of the most determining parameters, inherent to the system. The line overvoltages at motorside increase with increasing cablelength (as long as $t_r>2t_t$), as well as the disturbance zone on the earthlead (as long as $t_r>t_t$), both yielding an increasing ground wire voltage.

The curve of the ground wire voltage as a function of the cablelength, is strongly determined by the slope of the voltage changes, which mainly depends on the applied filter (Fig.8, Fig.9). The measured ground wire voltage, reaches a maximum when $t_r=t_t$ (e.g. 85m for set up without filter) and stays on this value for higher cablelengths.

For the test set ups applying a dU/dt-filter or sine filter, the maximum induced ground wire voltage is not reached within the tested cablelengths (2-100m) since t_r is too high.

For a configuration with dU/dt-filter, the maximum value of the ground wire voltage, will be higher in comparison to a configuration without filter, since higher values are already reached for most cable types at cablelengths, larger than 85 meter.

On the basis of the performed experiments, no conclusion can be made, about the maximum value of the ground wire voltage in a configuration with sine filter.

6) Influence of Cabletype The tested cable types consist of

- a shielded cable, $3x2.5mm^2$
- a shielded cable, $4x2.5mm^2$, shield and protectional earth core grounded together
- a non-shielded cable, $4x2.5mm^2$

The performed measurements proved substantial differences in ground wire voltage between different cables (Fig.10), even when both shielded.

Simulation established the influence of the cable parameters.

The entire charge or dischargecurrent (I_{Uch}, I_{Vch} and I_{Wch}) of the parasitary crosscapacitances is drawn through the phaseleads U, V and W (Fig.11) with their inherent series inductancies. The groundwire voltage will decrease with increasing phaselead series inductancies L_{Ph} since this L_{Ph} will limit the maximum charging current drawn through the phaseleads.

(*) All given values, are only in effect for one specific cable type. Nevertheless, they illustrate trends that are found for all tested cabletypes.

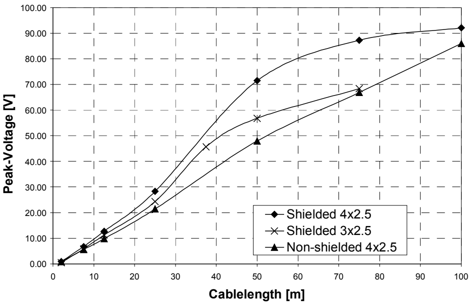

Fig.10. Peak Voltage over Protectional Earthlead for different cable types, carrier frequency 2.5 kHz, configuration with dU/dt-filter, grounded at inverter and motor

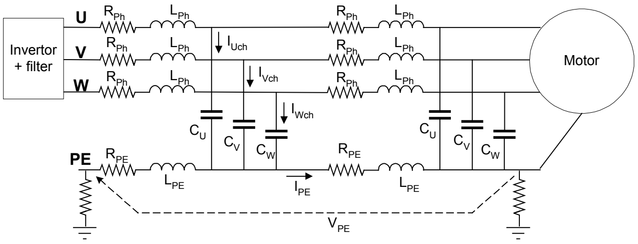

Fig.11. Model of the phase and earthlead system

On the other hand, only the difference in charging current I_{PE} of the three parasitary crosscapacitances is flowing through the seriesinductancy of the earthlead L_{PE} (paragraph 1, Fig.11). Consequently, when L_{PE} is of the same magnitude as L_{Ph}, L_{Ph} and not L_{PE} will be the most restricting parameter for the charging current. The charging current will not depend on L_{PE} and the groundwire voltage V_{PE} will rise proportionally with the seriesinductancy L_{PE} of the PE lead for small values of L_{PE}. For an increasing L_{PE} in comparison to L_{Ph} however ($L_{PE} >> L_{Ph}$), L_{PE} does become the restricting parameter for I_{PE}. An increasing L_{PE} will limit I_{PE} which engenders that V_{PE} will come to a constant maximum value for high values of L_{PE}.

In case of equal phase to earthlead crosscapacitances C, variations of C do not affect the ground wire voltages. Practically however, an increasing C often implies an increasing mutual difference between the three parasitary crosscapacitances (C_U, C_V and C_W) which does cause an increasing current through the groundwire and consequently causing an increasing V_{PE}.

The influence of series resistance of phase and earthlead is most restricted, as well as the influence of the cross conductancy between phaseleads and earthlead.

These trends, found by simulation, correspond with the measured results of Fig.10. Particularly the difference in crosscapacity is determinative (e.g. shielded cable 4x2.5mm^2: 210nF/km; shielded cable 3x2.5mm^2: 186 nF/km; non-shielded cable 4x2.5mm^2: 55nF/km).

7) Occurence of sparks The magnitudes of the measured groundwire voltages might hint a danger of sparkforming, which has to be avoided when operating in explosive atmospheres. However, only in the 'worst case' test set ups, minuscule sparks could be stired between the earthlead and the ground connection. This can be explained by the small value of the parasitic crosscapacitance of the cable, which implies, for short cablelengths, a too low stored energy to create sparks. For 100 meter cable:

$$E = \frac{CV^2}{2} = \frac{(186.10^{-9}\, {}^{F}\!/_{km}\; x\, 0{,}1\, km)\; x\; (2.700V)^2}{2} = 18{,}2.10^{-3} J \qquad (4)$$

with

C: the parasitic capacitance between phaselead and earthlead (186 nF/km for a shielded cable; 3x2.5mm^2)

V: the maximum voltage over the crosscapacitance: $V_{max} < 2.V_{DC}$ [2].

However, the ignition energy of most common explosive gasses is estimated to 10^{-4} J (group of gasses IIA in [8]).

In fact only the mutual difference in phase to earthlead capacity is determining for the possible sparkcurrent as described in paragraph 1. Moreover the voltage is expected to be about 2/3 V_{DC} instead of the worst case of $V_{max}=2V_{DC}$. Consequently, the result of (4) represents a serious overestimation (factor 10 too high) of the actual possible spark energy.

C. *Tabled measurement results*

TABLE 2
PEAK AND RMS GROUND WIRE VOLTAGES [V], FOR DIFFERENT CABLELENGTHS AND CARRIER FREQUENCIES; CONFIGURATION WITH DU/DT-FILTER, SHIELDED CABLE (4X2.5MM^2)

Cable length	2.5 kHz		10 kHz		16 kHz	
[m]	Vrms	Vpk	Vrms	Vpk	Vrms	Vpk
2	0.16	0.93	0.23	1.08	0.29	1.22
7.5	1.18	6.79	1.77	8.35	2.11	9.38
12.5	2.18	12.75	3.57	15.10	4.35	18.63
25	4.84	28.27	8.56	37.29	10.67	41.61
50	10.44	71.44	21.08	92.81	27.08	105.49
75	13.02	87.17	25.89	113.64	32.18	128.13
100	14.77	92.04	29.04	117.05	34.62	135.06

TABLE 3
PEAK AND RMS GROUND WIRE VOLTAGES [V], FOR DIFFERENT CABLELENGTHS AND APPLIED FILTERS; CARRIER FREQUENCY 2.5 KHZ; SHIELDED CABLE (4X2.5MM^2)

Cable length	dU/dt-filter 2.5 kHz		sine filter 3 kHz (*)		no filter 2,5 kHz	
[m]	Vrms	Vpk	Vrms	Vpk	Vrms	Vpk
2	0.16	0.93	0.08	0.40	0.32	2.74
7.5	1.18	6.79	0.42	1.87	2.89	24.24
12.5	2.18	12.75	0.92	3.98	5.25	39.39
25	4.84	28.27	2.12	6.94	9.85	65.28
50	10.44	71.44	4.89	14.40	13.50	80.17
75	13.02	87.17	6.19	18.34	11.25	76.38
100	14.77	92.04	7.99	23.92	12.21	78.52

(*): The carrier frequency for the sine filter (3 kHz) is a fixed value and can't be set to 2.5kHz. However, the influence of this deviation is most restricted.

Table 4
Peak and RMS ground wire voltages [V], for different cablelengths and grounding connections; shielded cable (4x2.5mm^2); carrier frequency 2.5 kHz; configuration with dU/dt- filter

Cable length	Grounded at motor		Grounded at inverter		Grounded at mot. and inv.	
[m]	Vrms	Vpk	Vrms	Vpk	Vrms	Vpk
2	0.20	1.06	0.14	0.88	0.16	0.93
7.5	1.62	7.96	1.16	6.94	1.18	6.79
12.5	3.07	18.20	2.12	12.40	2.18	12.75
25	0.51	3.10	4.56	27.46	4.84	28.27
50	17.91	109.27	10.32	69.21	10.44	71.44
75	24.20	147.63	12.62	85.64	13.02	87.17
100	23.61	132.52	12.86	79.82	14.77	92.04

Table 5
Peak and RMS ground wire voltages [V], for different cablelengths and cable types; carrier frequency 2.5 kHz; configuration without filter, grounded at mot. and inv.

Cable length	Shielded 3x2.5mm^2		Shielded 4x2.5mm^2		Non-Shielded 4x2.5mm^2	
[m]	Vrms	Vpk	Vrms	Vpk	Vrms	Vpk
2	0.08	0.51	0.16	0.93	0.14	0.88
7.5	0.60	3.35	1.18	6.79	0.87	5.62
12.5	1.93	11.28	2.18	12.75	1.59	9.84
25	4.22	26.35	4.84	28.27	3.55	21.44
50	8.45	56.81	10.44	71.44	7.52	47.94
75	10.63	68.33	13.02	87.17	10.65	66.86
100			14.77	92.04	13.35	85.91

3. Conclusions

From the data gathered, a number of conclusions may be drawn regarding the influence of grounding systems on PWM supplied induction motors. However, the voltage induced over the ground wire is a function of many parameters. Consequently, no unambiguous conclusion can be stated, concerning the best configuration in order to reduce the ground wire voltage. Merely for each parameter independently, the most favourable configuration can be chosen.

In order to reduce the voltage over the protectional earthlead, it is recommended:

- to set the carrier frequency as low as possible
- to apply a sine filter for long cables (>30m); for smaller lengths (<30m), a dU/dt-filter can be sufficient; when lengths descend beneath 10 meter, the gain in absolute values with a filter is restricted
- to opt for a cable type with a small value for the parasitic cross capacity and a symmetrical composition of phasecores in comparison to the PE core, in order to reduce the mutual differences between the three parasitic crosscapacitances.
- to opt for a configuration with a low series inductancy of the PE lead
- to keep the cablelength as short as possible
- to reduce the grounding resistance as much as possible
- to ground the system at inverter, or at motor and inverter side

The influence of the motorpower and the fundamental motor frequency is most restricted, if not absent.

However, it needs to be mentioned that the energy, stored in the small parasitic capacitance of the cable, is substantially small, which brings about that only in worst case test set ups (long cables, no filter), sparks could be observed ($E \approx 10^{-3}$ J) between an open end earthlead and earth.

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