EXPERIMENTAL INVESTIGATION OF CONVERTER-TO-MOTOR CABLING INFLUENCE ON TRANSIENT OVERVOLTAGES AND COMMON MODE CURRENTS

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Abstract **–Differential overvoltages on motor terminals and common mode currents are likely to happen in PWM induction motor drive systems. Filters, of different types and topologies, are generally used to reduce these undesirable high-frequency phenomena. However, due to their cost, volume and power losses, among other factors, they can't be considered the ultimate solution regarding the problem. In this context, the aim of this paper is to investigate the possibility of reducing the transient overvoltages and earth-return currents by means of different geometric disposition of the cables connecting the frequency converter with the motor. Preliminary results show a variation up to nine percent of the transient peak voltage at motor terminals for different cable arrangements. Further research is ongoing, whose results will be shown in the future.**

Keywords **– Cable parameters, common mode currents, long cables, PWM drive systems, skin effect, transient overvoltages.**

I. INTRODUCTION

High-frequency phenomena in PWM induction drive systems have been extensively studied in the last fifteen years [1-7]. Differential overvoltages, generated by the reflection of the PWM pulses at cable endings, can harm the motor insulation, and, in critical cases, reduce the motor life to few weeks [8]. The earth-return currents, produced by the inverter common-mode voltage, can lead to EMI problems in industrial facilities, misoperation of ground-fault protection systems and motor-bearing failures [4]. Figures 1 and 2 ilustrate the transient overvoltage and the common-mode current phenomena, respectively.

Typically, the solution for these undesirable high-frequency phenomena is based on filters. The most simple and cheapest one, which is largely employed, is a reactor installed at the output of the inverter. It smooths the voltage pulse edge, decreasing its dv/dt and increasing the cable critical length, thus reducing the voltage stress of the motor windings. Another advantage of this filter is that the common-mode dv/dt is also decreased. However, it presents some drawbacks, such as [2, 9, 10]: i) it can introduce a series voltage drop even at fundamental frequency, decreasing the motor torque; ii) it may reduce the dynamic performance of the drive; iii) new oscillations, at other frequency, can appear; iv) limitation of the switching frequency of the inverter, v) bulky at larger drive horsepower.

Another solution is the "impedance-matching" filter, which makes the reflection coefficient at motor terminals near to one. As a result, reflected pulses are not generated and there are no voltage oscillations, saving the motor from the high transient peak voltages. The main disadvantages of this alternative are the often unavailability of the motor terminals and the fact that this filter exerts no influence on the common-mode voltage. In order to reduce common-mode excitation, an impedance-matching filter specific for this mode must be used [11].

A R-L-C filter at the inverter output is also frequently used, aiming the reduction of both differential and common-mode dv/dt. As in the case of the inverter ouput reactor, a limitation of the switching frequency can occur. The connection of the neutral point of the inverter output R-L-C filter to the middle point of the converter DC link results in a much greater reduction of the common-mode voltage, but requires that the total DC link capacitance be divided in two; this connection also leads to an increase in the filter power losses [12]. Increasing its reactive components, a sinusoidal filter can be obtained, which virtually eliminates the high-frequency phenomena discussed here. Unfortunately, such solution happens to be very voluminous and expensive [13].

In short, according to the information mentioned in the last paragraphs, volume, cost, power losses and some problems concerning the drive operation are the main disadvantages associated with filters. Therefore, different alternatives for the transient overvoltage and common-mode current control have been proposed in the literature, such as: the use of soft-switching converters [14], the connection of a capacitor between the gate and the collector of the switch [15], the variation and control of the inverter switching frequency [16], the use of multi-level converters [17], among others. All of them present some drawback, limitation or were conceived to a very specific application, as a sub-sea motor drive, for instance. In [18], the application of cables with different electrical permittivities was considered, aiming the reduction of the overvoltages. However, only a very simplified single-phase theoretical study was presented, and the common mode issue was not mentioned.

In this context, the present paper will investigate the possibility of reducing the transient overvoltages and earth-return currents by the use of different geometric disposition and arrangements of the cables connecting the frequency converter with the motor. Although the results from this alternative are expected to be modest in relation to the techniques above mentioned, the proposed solution can be attractive in some cases. It is stated in [19] that voltage peak reductions of just five percent can significantly increase the life expectancy of standard-insulated motors applied in long cable-PWM drive systems. Preliminary results obtained in this work show that different cable dispositions can lead to variations up to 9 % in the generated overvoltage level at

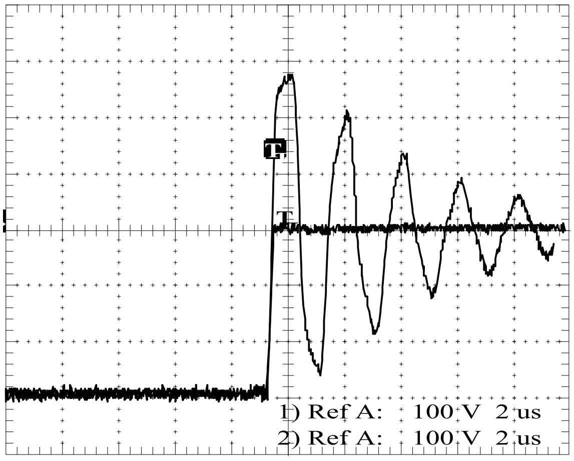

Fig. 1. Voltage pulse generated by the inverter and the resulting voltage at motor terminals.

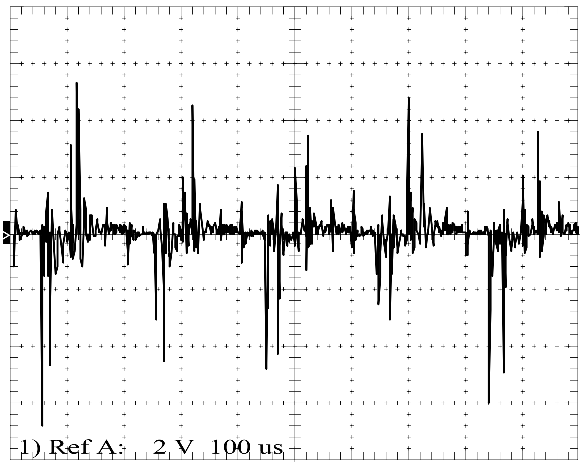

Fig. 2. Common-mode current produced by the inverter (1V ≅ 0.3 A).

motor terminals. Further research is ongoing, also comprising the common-mode quantities, whose results will be shown in the future.

II. THEORETICAL ASPECTS

The cable series impedance and capacitance matrices can be given as

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \quad (1)$$

$$C = \begin{bmatrix} C_{11} & -C_{12} & -C_{13} \\ -C_{21} & C_{22} & -C_{23} \\ -C_{31} & -C_{32} & C_{33} \end{bmatrix} \quad (2)$$

The on-diagonal elements ($Z_{ii} = R_{ii} + j\omega L_{ii}$) in (1) refers to the series self-impedance of the loop formed by the conductor "*i*" and the ground return. The off-diagonal elements ($Z_{ik} = R_{ik} + j\omega L_{ik}$) correspond to the series mutual impedance between conductors "*i*" and "*k*", and determine the longitudinally induced voltage in conductor "*k*" if a current flows in conductor "*i*", and vice-versa. The resistive terms in mutual coupling are introduced by the presence of the ground [20].

Reporting to (2), the on-diagonal elements "C_{ii}" represent the sum of the conductor capacitance to ground and to all other conductors, while the off-diagonal "C_{ik}" refers to the mutual capacitance between conductors "*i*" and "*k*", with a negative sign.

The expressions showed above represent the cable in the phase domain. However, the cable can also be represented by its modal parameters, which, in the case of a three-phase system, correspond to the positive, negative and zero-sequence parameters. In a symmetrical cable system, they can be obtained in very easy way, by means of a fixed-transformation matrix. When this does no apply, the eigen-value and eigen-vector theory must be used.

The wave speed progagation and surge impedance of a cable, in terms of its modal parameters, can be obtained by

$$v_i = \frac{1}{\sqrt{L_i \cdot C_i}} \quad (3)$$

$$Z_i = \sqrt{\frac{L_i}{C_i}} \quad (4)$$

where:

- v_i is the propagation speed of the cable "*i*"-mode;
- Z_i is the surge impedance of the cable "*i*"-mode;
- C_i and L_i are the cable "*i*"-mode capacitance and inductance, respectively.

In a cable system, as the relative position of the conductors is changed (in relation to each other or to the ground), the mutual resistances and inductances of the cable series impedance matrix are directly affected. This also influences the on-diagonal elements, but indirectly. The cable phase-to-phase and phase-to-ground capacitances changes too. Thus, having in mind the information of the last paragraphs, along with (3) and (4), different cable geometric dispositions will lead to different cable propagation speed and surge impedance. Since transient overvoltages, at first place, are function of these quantities, the peak voltages at motor terminals will be affected by the cable arrangement. The amount of generated common mode currents during inverter operation will change too, once the zero-sequence impedance will modify as well.

In this context, the idea is to investigate the possibility of reducing the overvoltages and earth-return currents by means of appropriate cable geometry, specially in the cases where more than one conductor per phase is used. Issues concerning the uneven current distribution within cables due to phase impedance unbalancing and the associated voltage unbalance at the cable endings, among others, will also be addressed. In this paper, the proposed study is thus initiated, (i) presenting some important information on cable parameters and the relevant quantities in respect of this subject and (ii) showing preliminary experimental results regarding the transient overvoltage reduction issue.

A. Influence of the distance between conductors on the cable system parameters

Using the ATP "Cable Constants" routine, two differents arrangements of a three-phase, 4 mm^2, PVC insulated cable were analyzed. The first one correspond to a planar geometry, being the conductors apart from each other with 1, 5, 10 and 30 cm. The second case is a triangular arrangement, with the cables touching each other, similar to the commercial available ones. Table I shows the modal speed propagations (v_i) and surge impedances (Z_i) obtained for the five different cases. Mode "1" is the common mode and modes "2" and "3" are the differential modes.

TABLE I
Values of v_i and Z_i for the studied cable geometries

	Mode	v_i (x 10^8) (m/s)	Z_i (Ω)
Planar geometry, 30 cm apart	1	0,687	77,2
	2	1,080	67,6
	3	1,169	79,5
Planar geometry, 10 cm apart	1	0,644	80,8
	2	1,180	61,6
	3	1,307	71,9
Planar geometry, 5 cm apart	1	0,673	80,8
	2	1,270	57,4
	3	1,422	65,8
Planar geometry, 1 cm apart	1	0,605	86,8
	2	1,390	52,1
	3	1,590	58,7
Triangular geometry	1	0,992	139,0
	2	2,110	35,7
	3	2,420	111,2

Based on table I, two important conclusions can be drawn:

1 – Although there is a variation in the values of Z_i for the different cases, changes in the reflection coefficient at motor terminals can be neglected, since the surge impedance of the motor is much higher than the cable in all cases. So, there will be no influence on motor terminal peak voltage due to the variation of Z_i, when changing the cable geometry.

2 – The closer the cables are placed from each other, the higher the wave propagation speed becomes. As far as the transient overvoltages are concerned, this is very desirable. Higher propagation speeds result in lower motor peak voltages for the same length of cable, or, in other words, increases cable critical length.

Extending the investigation, the influence of the soil resistivity "ρ_G" (varying from 30 to 1000 Ω.m) and also of the frequency (from 60 Hz to 2 MHz) were included in the study. For this initial analysis, the mutual impedances were assumed as being the average value among all phases. Thus, all the on-diagonal elements in (1) present the same value and will denoted by "Z_S" ($Z_{ii} = Z_S$). Likewise, the off-diagonals will be written as "Z_M" ($Z_{ij} = Z_M$). In the case of the capacitances, "C_T" will represent the conductor capacitance to ground and "C_M" the capacitance between conductors ($C_M = C_{ik}$).

In this way, the positive and zero-sequence values for the cable resistance, inductance and capacitance can be written as

$$R_{pos} = R_S - R_M \tag{5}$$
$$R_{zero} = R_S + 2 \cdot R_M \tag{6}$$
$$L_{pos} = L_S - L_M \tag{7}$$
$$L_{zero} = L_S + 2 \cdot L_M \tag{8}$$
$$C_{pos} = C_T + 3 \cdot C_M \tag{9}$$
$$C_{zero} = C_T \tag{10}$$

where the subscripts "*pos*" and "*zero*" refer to positive and zero sequence.

Thus, from the conducted study, many results could be obtained; figs. 3 – 7 depict some selected ones. Important conclusions could also be drawn, which are shown in the sequence.

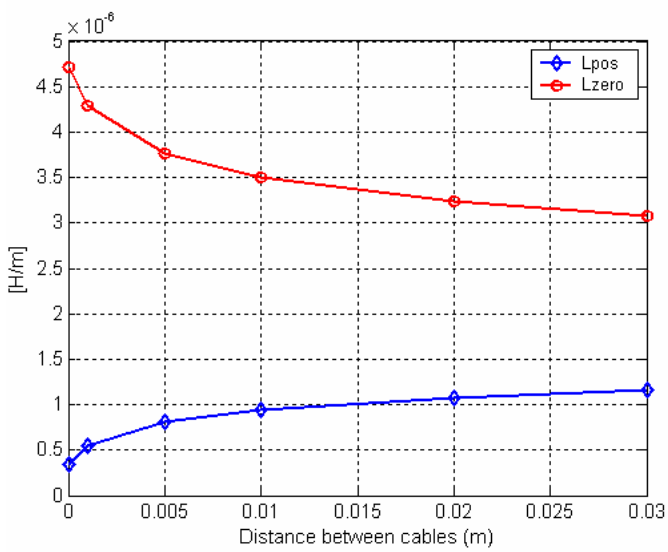

Fig. 3: L_{pos} and L_{zero} variation as a function of the distance between conductors (ρ_G = 100 Ω.m and f = 500 kHz).

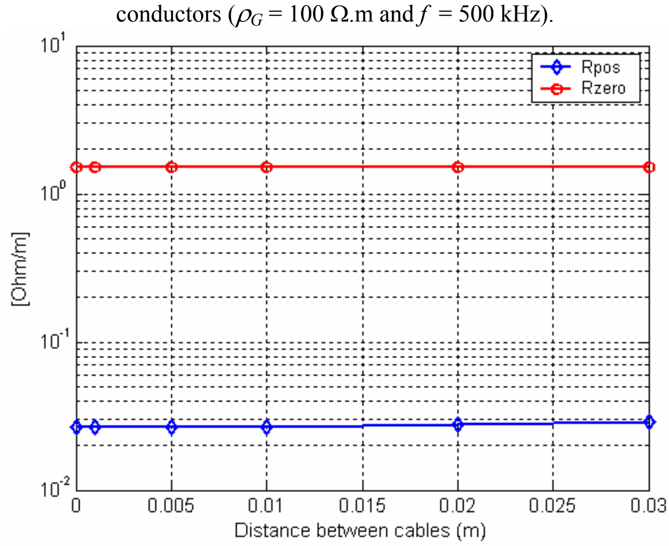

Fig. 4: R_{pos} and R_{zero} variation as a function of the distance between conductors (ρ_G = 100 Ω.m and f = 500 kHz).

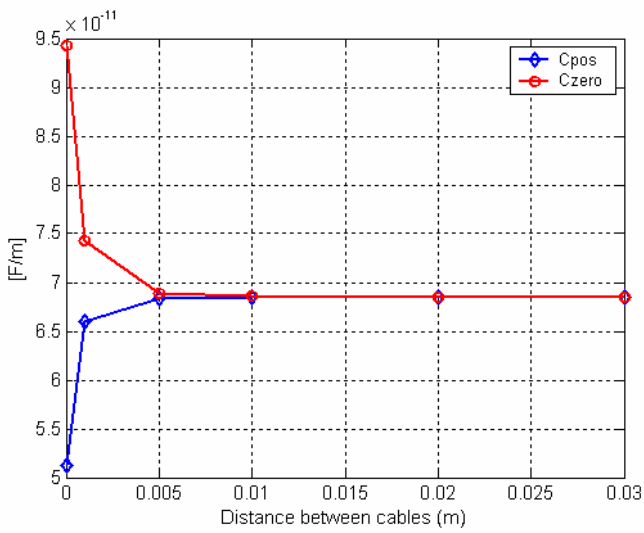

Fig. 5: C_{pos} and C_{zero} variation as a function of the distance between conductors (ρ_G = 100 Ω.m and f = 500 kHz).

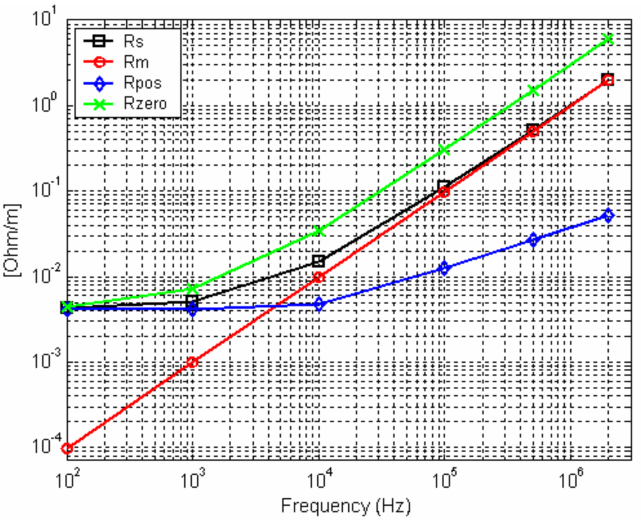

Fig. 6: R_S, R_M, R_{zero} and R_{pos} variation as a function of the frequency (ρ_G = 100 Ω.m and triangular geometry).

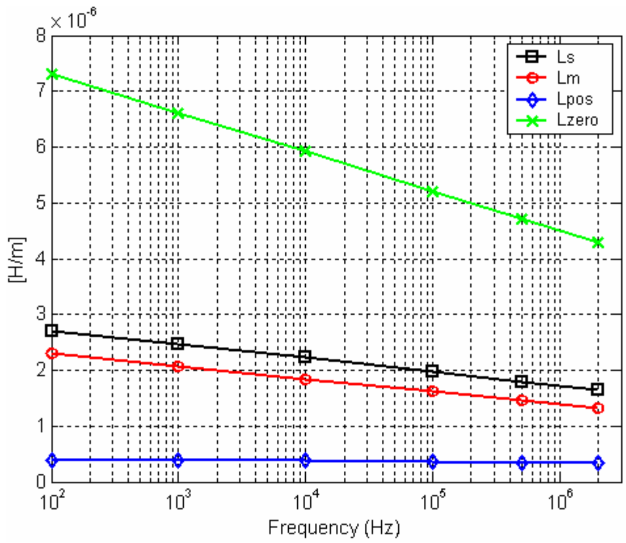

Fig. 7: L_S, L_M, L_{zero} and L_{pos} variation as a function of the frequency (ρ_G = 100 Ω.m and triangular geometry).

- In relation to frequency:

i) Comparing the values at 2 MHz with the corresponding 60 Hz ones, the conductors resistance have increased 500 times; R_M and R_{zero} became 20.000 and 1350 times higher, respectively (the skin effect in the earth return path is much more intense than in the cable). However, R_{pos} at 2 MHz is just 13 times bigger than at 60 Hz.

ii) Considering the same frequency range above mentioned, it was observed that L_S have decreased about 40 %, while the reduction of L_M was within 40 % and 70 %, depending on the cables disposition and the earth resistivity value. However, the effect on L_{pos} is a reduction of just 12 %, in the case of the triangular arrangement, and 4 % for the planar geometry. L_{zero} decreases about 40 % in the triangular geometry and about 50 % when the cables are displaced by 30 cm, in the planar arrangement.

- In relation to the earth resistivity (ρ_G):

i) The variation of R_S, R_M, R_{zero} and R_{pos} with the earth resistivity is negligible.

ii) Although L_S and L_M increase for higher values of earth resistivity, L_{pos} remains unaffected. The increase of L_{zero} in relation to ρ_G is situated in the range of 13 % to 31 %, depending on the cable arrangement and the frequency analyzed.

iii) Information about the earth resistivity is not always available. However, as can be seen from i) and ii), its influence on the cable parameters is minor, and thus not much concern needs to be addressed for its determination. The average ρ_G value of 100 Ω.m [20] should probably lead to satisfactory results in most cases.

- In relation to the distance between cables:

i) The closer the cables are placed, the lower L_{pos} become; R_{pos}, however, does not change, except in very high frequencies (near the MHz range). Therefore, when placing the phases near each other, the voltage drop in the cable reactance is reduced, but not in its resistance. Thus, the power losses keep the same.

ii) Approximating the phases, both L_{pos} and C_{pos} decrease, which in turn increases the wave propagation speed in the cable. The cable critical length is thus increased, as mentioned earlier.

iii) Both C_{zero} and L_{zero} increase when the distance between the cables is reduced, while R_{zero} remains the same. Such parameters compose the common mode path of the cable. However, it is not possible yet to correlate the amount of common mode current that will flow with the cables disposition, once the relative importance of C_{zero}, L_{zero} and R_{zero} impedance values, over the frequency range, was not analyzed. It should be remembered that the common mode circuit also comprises other elements, such as the converter-to-ground capacitance, transformer, the cable connecting the transformer to the frequency converter, etc, which need be evaluated as well.

B. Influence of different cable insulation on the wave propagation speed

The values presented in table I refer to PVC-insulated cables, whose relative dielectric permittivity was considered as $\varepsilon_r = 5$. In order to evaluate the influence of a lower ε_r on the cable propagation speed, the insulation material was exchanged to EPR ($\varepsilon_r = 3$). The results are shown in table II.

TABLE II
Wave propagation speed for different cable geometries and insulation permittivities (ρ_G = 100 Ω.m and f = 500 kHz)

v_{mode} (m/s)	Insulation type	Triangular geometry	Planar geom., 10 cm	Planar geom., 30 cm
v_1	PVC	7,433 x 10^7	6,443 x 10^7	6,866 x 10^7
	EPR	7,743 x 10^7	6,764 x 10^7	7,210 x 10^7
v_2	PVC	1,800 x 10^8	1,185 x 10^8	1,079 x 10^8
	EPR	1,918 x 10^8	1,244 x 10^8	1,133 x 10^8
v_3	PVC	2,401 x 10^8	1,307 x 10^8	1,117 x 10^8
	EPR	2,490 x 10^8	1,372 x 10^8	1,228 x 10^8

It can be observed that the speed propagation of the differential modes (2 and 3) increased about 3,5 % to 6,5 % when the PVC insulation was replaced by the EPR. This slight increase will probably not result in a significant reduction of the expected transient peak voltage at the motor terminals.

III. EXPERIMENTAL RESULTS

Some measurements were done to experimentally verify the influence of the cabling on the transient overvoltages. The system under analysis is comprised of a commercially available frequency converter, a 3 h.p., 220/380 V induction motor and various pieces of single-phase, 4 mm^2 cable, appropriately associated in order to compose the desired arrangements. Planar geometries, with 5 and 15 cm of distance between cables, and triangular geometry, with no distance between cables, were studied.

Figure 8 shows the obtained results. As expected from table I, the triangular cable disposition resulted in the lower transient peak voltages at motor terminals. Taking as example the 15-meter cable, the difference between the triangular and the planar geometry with the cables being 15 cm apart, was about nine percent. As stated before, such slight decrease in the peak voltage can significantly increase the life expectancy of standard-insulated motors applied in long cable-PWM drive systems [19], at no cost or other disadvantages usually associated with other alternatives.

Another aspect, which is illustrated in fig. 9, should be highlighted. One could expect that, as the cable length was being increased, the overvoltage frequency oscillation would decrease proportionally. This is what is vastly stated in literature concerning the overvoltage issue. In fact, among lots of papers studied, only in [21, 22] was pointed out that this is not wholly true. The fact is that the motor capacitance can substantially affect the oscillation frequency and, unless the cable becomes long enough, this will happen. Longer cables will present higher capacitances, which will predominate over the motor.

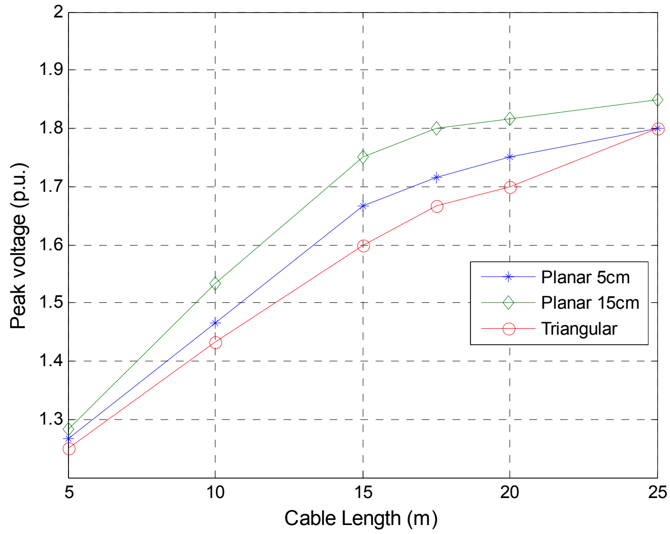

Fig. 8. Transient peak voltage at motor terminals as a function of cable length, for the studied cable geometries.

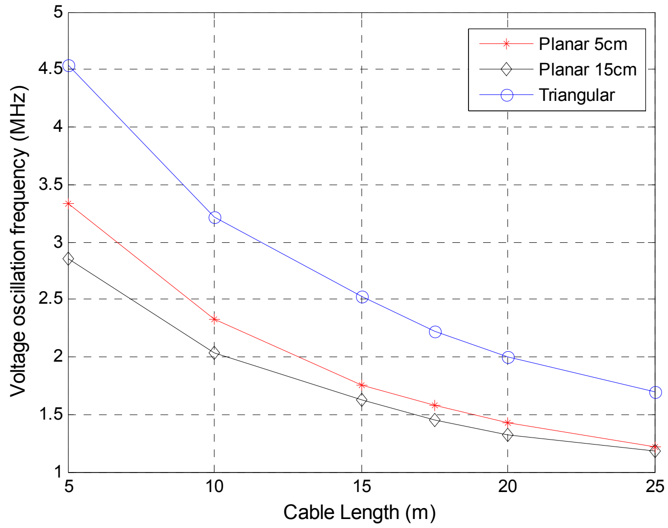

Fig. 9. Voltage oscillation frequency as a function of cable length, for the studied cable geometries.

IV. CONCLUSIONS

An investigation of the cabling influence on the generated overvoltages and common mode currents in a PWM motor drive system was outlined and initiated in this work. Important information regarding cable parameters and the relevant quantities related to the proposed study were presented. Measurements showed that the more coupled the conductors are, the higher the cable propagation speed becomes, thus increasing the cable critical length and reducing the transient peak voltages at motor terminals. Since more tightly-coupled conductors present lower differential mode inductance, the voltage drop in the cables also decreases. It was observed that the variation in the cable surge impedance due to different cable geometries is not great enough to affect the generated overvoltage level. The experiments also showed that, unless the cable is long enough to make its own capacitance predominant over the motor capacitance, voltage oscillation frequency will depend on the latter, in contrast to what is usually found in literature. The research initiated here is underway and will mainly focus the situations where more than one conductor per phase is used. Further results concerning the overvoltage reduction will be presented in the future, along with the common mode current issue. The possible uneven current distribution among cables due to phase impedance unbalancing and the resulting voltage unbalance at the cable endings will also be analyzed.

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