CABLE PARAMETER ESTIMATION AND MODELING FOR HIGH FREQUENCY PHENOMENA STUDIES IN PWM MOTOR DRIVES

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Abstract - Induction machine drive systems based on PWM inverters are widespread nowadays. Each pulse generated by the inverter represents a voltage surge applied to the cable. In many applications, the motor is required to be installed far away from the converter, resulting in long cables. This leads to transient overvoltages in the motor terminals, produced by the pulse reflections in the cable endings. The computational analysis of such phenomenon in a motor drive system comprises a wide frequency range, which starts with the low values corresponding to the motor speed, includes the switching harmonics, which can reach up to few hundreds of kHz, and also the cable resonant frequency, which value can be in the MHz range, depending on the cable length. In this context, this work presents a time domain methodology for cable modeling able to represent the cable parameters variation due to skin effect in this broad range of frequencies. The frequency-dependent cable earth-return model is also included, allowing the computation of the zero-sequence currents generated by the common-mode voltage produced by the inverter. Simulations using the proposed methodology are conducted and the obtained results are compared with measurements, showing very good agreement.

Keywords - Cable modeling, common-mode currents, induction motor drives, long cables, skin effect, transient overvoltages.

SYMBOLS

N Number of branches used in the cable model.
L1, L2 Resistance and inductance of the branches.
Req, Leq Equivalent resistance and inductance of the cable at a specific frequency.

I. INTRODUCTION

As it is well known, the output voltage waveform of a VSI-PWM converter is a series of pulses of equal amplitude and variable width, which are transmitted to the motor by the cable. Depending on the pulse rise time, the length and characteristics of the cable and the equivalent impedance of the motor in relation to the received pulse, a transient overvoltage can take place at motor terminals at each switching point, which can reach up to two times the converter dc link voltage. Depending on some factors [1], it can occur that the transient generated by a previous pulse has not been completely damped out when the next pulse reaches the motor; due to the superposition of both transients, voltage peaks higher than 3 p.u. may appear (1 p.u. = dc link voltage).

It is obvious that voltage peaks of this magnitude are very harmful to the winding insulation and must be avoided. It is improbable that the interturn insulation fail just after the impact of such a voltage surge; however, the damage caused by it is accumulated over the time. It is probable that partial discharges take place in specific regions of the windings, specially in the line end coils, accelerating the insulation degradation. The worst case is when these partial discharges form a fixed channel and eventually become even more dangerous. According to [2], the highest dv/dt permitted for a standard motor is 500 V/µs, while the operation with PWM inverters and long cables can lead to 7000 V/µs. Critical cases have been reported where groups of new motors failed after just few weeks of operation [3].

In face of this, the importance of the study and investigation of the phenomena readily comes along, being the computational analysis an attractive tool for its prediction and evaluation. Nevertheless, in order to produce reliable results, motor and cable modeling must be appropriate for high frequency studies. Several papers found in literature have proposed models for the induction machine which attend this requirement [4-7]. The basic idea is to elaborate an equivalent circuit whose frequency response approximates the measured one, in a wide frequency range. One of the crucial aspects of these models is the correct representation of the intrinsic capacitances of the motor, which, in high frequencies, represent low impedance paths for the current generated by the voltage pulses, since their fast rise times correspond to very high frequencies.

Regarding the interconnection cable, the key point is the correct inclusion of the skin effect in its modeling, in a range from tens of Hz up to MHz level. Several works attempted to reach this goal, but, in general terms, all of them present some limitation or disadvantage. Some are able to correctly represent the cable parameter dependence only in narrow ranges [8, 9], being then appropriate just for applications with very long leads, as those found in submarine systems. Others involve very complex mathematical procedures [10, 11], being thus of hard comprehension for the machine and drive engineer, who is not familiar with the specific topic of line and cable modeling. The method proposed in [12] is not very practical, since the parameters of the model are calculated in the basis of trial and error. An efficient model is presented in [4], which produces very good results, but it is not possible to calculate its parameters without measurements, frequently unavailable due to the high cost of the equipment.

*Artigo publicado na IV Conferência de Estudos em Engenharia Elétrica (IV CEEEL) realizada no período de 22 a 25 de Novembro na Universidade Federal de Uberlândia, Uberlândia MG.*
The methodology proposed in the present work makes use of the modeling initially developed in [13], employed so far mainly in energy quality studies, where typically voltage/current harmonics under study are limited to the fifth harmonic order. In order to be applicable in the transient overvoltage study, which is the goal of this paper, this model was evaluated in a much wider frequency range. Another contribution of this work is the inclusion, in the cable modeling, of a very simple and efficient methodology for the common-mode current calculation that does not require modal transformation, allowing the study of the differential and common-mode phenomena by means of a single circuit.

II. THE “N-BRANCH” CABLE MODEL

Assuming that a conductor can be considered as an association of infinite shunt-connected concentric tubular sub-conductors (figure 1), each one with its own value of inductance and resistance in such a way that the skin effect is represented, and considering that the current in each sub-conductor does not vary along its way, the expressions of the voltage drop in each sub-conductor, coupled to the others, lead to an equivalent circuit of infinite RL branches [13].

This circuit comprises R and L elements which do not vary with frequency, but are properly connected resulting in an equivalent impedance that represents the conductor resistance and inductance frequency variation (figure 2). The determination of the “N-Branch” circuit parameters is straightforward, requiring just the information of the cable parameters in “N” different frequencies, used as input data, which can be obtained by measurements or estimation methods. The procedure for the model parameters calculation is explained in details in [13].

Figure 3 shows the results obtained for the representation of a 3 x 4 mm$^2$ cable by means of “N-Branch” circuits using 3, 4 and 5 branches, in a range from 20 Hz up to 2 MHz. The “*” points represent the values used as input data, obtained by estimation methods. It can be observed that the results obtained from the models matched quite well the values used as input data.

III. CABLE PARAMETER ESTIMATION

As mentioned in section II, the determination of the “N-branch” model requires the information of cable resistances and inductances in conveniently chosen frequencies, as input data. Thus, it is very interesting to make use of parameter estimation methods if they show to be accurate. This makes the process of obtaining the cable model independent of measurements, which is very attractive and practical. At this point it is important to emphasize that this issue concerns not only the proposed model, but many others, as well. Having this in mind, three different estimation methods were studied and compared, in order to allow the choice of the one that could bring the best results considering the cable types, gauges and geometry evaluated. The cable systems studied comprise cables from 4mm$^2$ to 240 mm$^2$, arranged in plane and triangular geometries, mutually separated by 0 to 30 cm and constituted by conductor, insulation, shielding and external cover. It is believed that the majority of industrial cables fit these characteristics. It is important to highlight that the conclusions presented here are valid only for cables whose characteristics are found to be within the above mentioned.

The methodologies studied in this work are those proposed by Pollaczek [14], Semlyen et al. [15] and Klewe [16]. The difference among them is in the calculation of the cable series impedance terms related to the mutual coupling and representation of the earth as a current return path. The equations of these methods are not shown here due to the restricted space, but can be found in the corresponding references.

A very large quantity of results were obtained during the elaboration of this comparative analysis, since the
combination of the great variety of the studied cable characteristics turned out lots of possibilities. All the results were analyzed and compared in order to make possible providing answers like: which method is more accurate and in which cases, which of them presented best overall efficiency, and so on. As measurements were not available, the results produced by the “Cable Constants” routine of the ATP/EMTP simulator were used as reference. Selected results from the 3 x 4 mm$^2$ cable mentioned in the last section are found in the sequence.

Figure 4 shows that all the studied methods resulted in similar errors in relation to the estimation of the cable series resistance and inductance. In relation to the mutual components of the series impedance, which occupy the off-diagonal terms in the impedance matrix, the method proposed by Semlyen et al. presented more accurate results, as shown in figure 5.

From the above observations, it is seen that the most appropriate methodology for parameter estimation, regarding the types of cables studied, is the one developed by Semlyen et al. Thus, its equations were used in the calculation of the input data for the “N-Branch” model determination, and are recommended to be used whenever the parameters of cables similar to the analyzed here need to be obtained.

### IV – SIMULATED AND MEASURED RESULTS

The computational analysis of the transient overvoltages requires models that represent the frequency dependency and also the distributed nature of these parameters, reproducing the wave reflections that occur in the cable endings and the associated voltage/current oscillations.

Distributed-parameter models present this feature, but the inclusion of its dependence with frequency, in the time domain, is very complex to be implemented. An alternative solution is to use a lumped-parameter model associating its cells in a number high enough to “capture” the propagation phenomenon; additionally, these cells must comprise parameter-dependency in relation to frequency. This is the very case of the “N-Branch” model proposed in this work.

The system simulated in the ATP program represents a PWM inverter, the interconnection cable and a 1,5 h.p. induction motor. The PWM voltage pulse was approximated as a trapezoidal shape, with a rise time of 200 ns. The cable, which length is 95 m, was represented by a cascade-connection of “pi” circuits, which series impedance is the 5-Branch model shown in section 2. Each “pi” circuit was used to represent 0,5 m of the cable.

From figure 6 it can be noted that the cascade association of “N-Branch”-“pi” circuits led to an accurate representation of the overvoltage phenomena, whose results shown to be in quite good agreement with the experimental ones. The curve 4 represents the voltage measured at the inverter terminals, while the curve 3 depicts the corresponding voltage at motor terminals. The result from curve 1 refers to the modeling of the motor as a resistor, while the curve 2 was obtained with a high-frequency modeling of the motor [4], much more suitable for high-frequency studies.

The use of high-frequency models for the motor is also mandatory for transient overvoltage studies, since it brings additional accuracy for the analysis. The attenuation of the voltage oscillations were also reproduced quite well; the small difference observed between the simulated and experimental results in terms of voltage damping is probably due to the proximity effect, which is not included in the estimated parameters used as input data for the calculation of the cable model.

### CONCLUSIONS

This work presented an efficient methodology for cable modeling and simulation, suitable for the study of transient overvoltage in long cable-PWM motor drive systems. The model is able to correctly represent the cable parameter variation in a wide frequency range, from some tens of Hz up to MHz, thus being appropriate for this application. Three different estimation methods for cable parameters were also evaluated and compared, showing to be a very useful tool in the computational analysis, since the proposed model, as many others, require the cable parameters in some different
frequencies as previous information for the model determination. Considering the types of cables analyzed in this work, the methodology proposed by Semlyen et al. presented the best overall result, and then is suggested to be used whenever the parameters of cables similar to these ones need to be calculated. It was observed that the cascade-associated “N-Branches” “pi” circuits reproduced quite well the wave propagation and reflection phenomena. Besides, the simulation successfully represented the amplitude, shape and attenuation of the voltage oscillations, accurately characterizing the transient overvoltages present in long cable PWM drive systems.

![Figure 6: Voltage at the inverter terminals (measured): curve 4. Voltage at motor terminals: simulated representing the motor as a resistor (curve 1), simulated with a high-frequency model for the motor (curve 2) and experimentally obtained (curve 3).](image)

REFERENCES


AUTHOR’S BIOGRAPHY

Hélder de Paula was born in 27/12/1975, in Uberlândia, and graduated in electrical engineering from Universidade Federal de Uberlândia (UFU) in Dez/1998. He received his M.Sc. and Dr. degrees in 2001 and 2005, respectively, also from UFU. He is currently a teacher of Universidade de Uberaba (Uniuibe). His main fields of interest are induction machine drives and electromagnetic transients.

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