AN EFFICIENT CABLE MODELING TECHNIQUE FOR TRANSIENT OVERVOLTAGE STUDIES IN PWM MOTOR DRIVE SYSTEMS

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***Abstract* – Induction machine drive systems based on PWM inverters are widespread nowadays. Each pulse of the PWM output waveform represents a voltage surge applied to the cable. With fast hard-switching devices, 2 p.u. transient overvoltages are generated in the motor terminals even with motor-inverter connecting cables as short as five meters. 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 proposed model can be arranged in cascade-associated "pi" cells, in a number high enough to adequately represent the wave propagation and reflection dynamics, being thus fully appropriate to simulate the transient overvoltage phenomenon. Simulations using the proposed methodology are conducted and the obtained results are compared with measurements, showing very good agreement, despite the simplicity of the model.**

***Keywords* - Cable modeling, induction motor drives, long cables, PWM drives, skin effect, transient overvoltages.**

I. INTRODUCTION

The use of inverters based on the PWM technique represents an efficient and vastly employed solution for the induction motor speed control. Historically, the main concerns related to the induction motor in ASD's were the additional losses and torque oscillations due to the non-sinusoidal voltage supply. However, in the last decade, new issues came along, mainly because of the IGBT consolidation as the preferred switching device used in the converters. The focus has been the generation of transient overvoltages at motor terminals and possible premature motor failures.

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).

Voltage peaks of this magnitude are very harmful to the winding insulation and should 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. Partial discharges can 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].

These issues point out the importance of the study and investigation of the transient overvoltage phenomenon, being the computational analysis an attractive tool for its prediction and evaluation. To accomplish this, appropriate modeling for high frequency studies must be employed to represent the motor and the cable. Several papers found in literature have proposed models for the induction machine that 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.

In relation to 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 unavaible due to the high cost of the equipment.

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 tipically voltage/current harmonics under study are limited to the fifth harmonic order. In order to be applicable in the transient overvoltage study, this model was evaluated in a much wider frequency range. Additionally, an attractive feature was included in the model parameter calculation process, that is: a data adjustment routine to reduce errors in the output of the model, then producing more accurate results.

II. THE “N-BRANCH” CABLE MODEL

Assuming that a conductor can be considered as an association of infinite shunt-connected concentric tubular sub-conductors (fig. 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 a equivalent circuit of infinite RL branches [13].

This circuit comprises RL elements that do not vary with frequency, but are properly connected resulting in an equivalent impedance that represents the conductor resistance and inductance frequency variation (fig. 2). The procedure for determination of the “N-Branch” circuit is described as follows.

Considering the particular case of a two-branch model, the determination of its parameters is straightforward; for this, (1)-(6) must be followed.

$$\Delta R = R_{C2} - R_{C1} \tag{1}$$

$$\Delta L = L_{C1} - L_{C2} \tag{2}$$

$$L_2 = L_{C1} - \frac{\Delta L\left(\frac{\Delta R^2}{\Delta L^2} + \omega_2^2\right)}{\left(\omega_2^2 - \omega_1^2\right)} \tag{3}$$

$$R_2 = \frac{\Delta R}{\Delta L}(L_{C2} - L_2) + R_{C2} \tag{4}$$

$$L_1 = \frac{R_2^2(\omega_2^2 - \omega_1^2)}{\Delta L\left(\frac{\Delta R^2}{\Delta L^2} + \omega_1^2\right)\left(\frac{\Delta R^2}{\Delta L^2} + \omega_2^2\right)} \tag{5}$$

$$R_1 = L_1\frac{\Delta R}{\Delta L} - R_2 \tag{6}$$

Where:

- R_1, L_1, R_2, L_2 are the resistance and inductance of the first and second branches of the model, respectively;

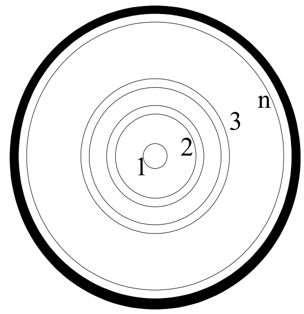


Fig. 1. Transversal section of a cable sub-divided in “n” concentric tubular conductors.

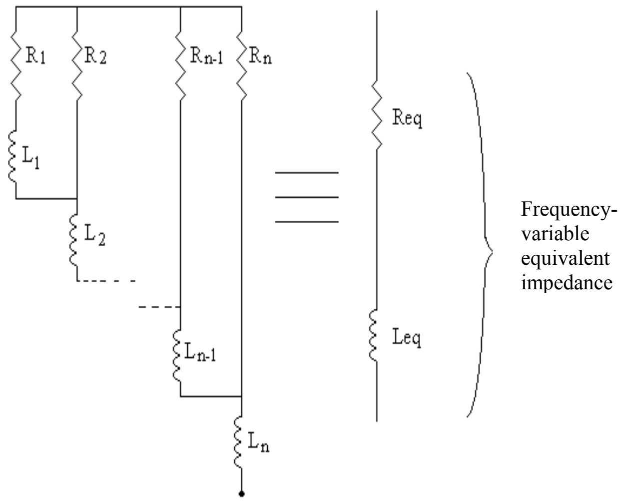


Fig. 2. “N-Branch” circuit and the corresponding equivalent RL impedance.

- $R_{C1}, L_{C1}, R_{C2}, L_{C2}$ are the resistance and inductance of the cable at frequencies ω_1 and ω_2, previously known, as input data.

From (1)-(6), with two known values of resistance and inductance of the cable for the two corresponding frequencies, it is possible to directly determine the parameters of a two-branch model. However, the calculation of models with three or more branches is impossible to be made in this direct way. Nevertheless, it can be performed by means of an approximate method, based on the two-branch model, as following described.

Let “*n*” be the number of frequencies where the corresponding cable parameters are known. The “N-branch” model is obtained as

i – From the data of the two highest frequencies *(ω_n* and *ω_{n-1})*, the resistance and inductance of the highest order branch (n^{th} branch, L_n and R_n) are calculated, by means of (1)-(4).

ii – Knowing the parameters of the n^{th} branch, an order reduction of the equivalent circuit is made, eliminating the branch of order “*n*” of the input data by using (7) and (8), for all frequencies ω_i, where “*i*” goes from 1 to “*n-1*”.

$$L'_{Cwi} = \frac{R_n^2(L_{Cwi} - L_n)}{(R_n - R_{Cwi})^2 + \omega_i^2(L_{Cwi} - L_n)} \tag{7}$$

$$R'_{Cwi} = \frac{R_n(R_{Cwi}R_n - R_{Cwi}^2 - \omega_i^2(L_{Cwi} - L_n)^2}{(R_n - R_{Cwi})^2 + \omega_i^2(L_{Cwi} - L_n)^2} \quad (8)$$

Where:

- R_{Cwi} and L_{Cwi} are the resistances and inductances of the cable at frequencies ω_i, with "i" varying from 1 to "n".

- R'_{Cwi} and L'_{Cwi} are the resistances and inductances of the "N-Branch" circuit without the "n" branch, for "i" varying from 1 to "$n-1$".

iii – With the values of R'_{Cwi} and L'_{Cwi}, the branch of "$n-1$" order can be determined for the frequencies ω_{n-1} and ω_{n-2}, using (1)-(4). Then, another order reduction is made and, from this point on, the process becomes repetitive until the second branch is calculated, corresponding to frequencies ω_2 and ω_1. The first branch will be calculated using (5) and (6).

Based on experience, it is recommended that the input frequencies follow a geometric separation. The first (f_1) and the last (f_n) frequency are the limits of the range where it is desired the model to respond; the intermediate frequency points (f_i) should be determined following a geometric sequence

$$f_{i+1} = f_i \cdot q \quad (9)$$

where :

- $q = \sqrt[n-1]{\frac{f_n}{f_1}}$;
- n is the number of branches of the model.

A. Data adjustment routine for model improvement

In general terms, concerning the "N-Branch" model, the higher the number of branches, the more accurate it becomes. However, an exaggerated quantity of branches implies in high quantities of nodes, resulting in undesirable computational effort. This highlights the importance of finding an optimum point relating the number of branches and the desired accuracy.

Having this in mind, a computational program was elaborated in order to allow the determination of optimized models. Firstly, it calculates "N-Branch" models for various values of "n" and selects those that are in accordance with the maximum errors previously stated. Then, there is a data adjustment routine: the errors in the resistance and inductance outputted by the model are calculated for all the frequencies used as input data; at the frequency where the maximum error occurred, the corresponding input data (resistance/inductance) is modified proportionally to the error found, and the model is calculated again. The new model will then present lower error at this specific point and in a great range around it, leading to better results. Finally, the output of the modified models are shown, together with the average and maximum errors, making the choice of the most appropriate model an easy task for the user.

This program was successfully applied to several cable systems with very good results, particularly for higher gauge cables. In the case of smaller diameter cables, in which the skin effect is less severe, a large number of branches resulted in negative parameters for the calculated model; to avoid this problem, the maximum quantity of branches had to be limited, leading to less satisfactory results. Selected results from a 3 x 4 mm^2 cable are shown in the following, where a limit of five branches was imposed to the program. This cable, together with its 5-Branch model, was used in the simulation and experimental analyses conducted in section 4.

Top and bottom curves of fig. 3 show the cable resistance and inductance variation as function of frequency. The black, blue and green curves correspond respectively to 3, 4 and 5 branches used in the model, while the "*" refers to the reference values (from the ATP "Cable Constants"). From figure 4, it is noted that the higher the quantity of branches used, the more accurate the results are, as expected. As explained before, small gauge cables lead to somewhat higher errors, but the results are still satisfying. Errors like 6,2 %, at 100 kHz, 16 %, at 1 MHz, and 3,7 %, at 2 MHz, can be observed from figure 4, for the "5-Branch" model. After the data adjustment routine, whose results are depicted in the bottom curve of figure 4, it can be observed that for the "5-Branch" model the changes led to quite good improvements, while for the other two the benefits of this additional routine were not clear. In the case of the "5-Branch" model, even though with an increase in the error around 2 MHz, the new model showed to be quite more accurate after the adjustment, since there was a drastic reduction in the error around 1 MHz and also in the average error. For the models with 3 and 4 branches, the error was nullified at 2 MHz, but became even worse around 1 MHz. As this frequency was not used as an input data, changing the corresponding input resistance and inductance would not affect the model.

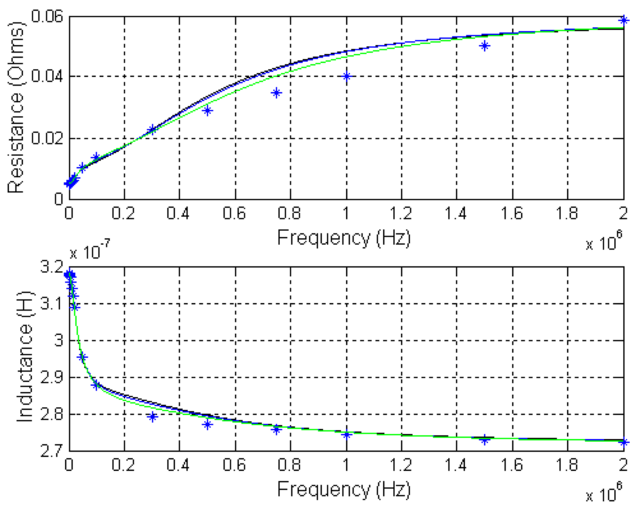


Fig. 3. Resistance (top) and inductance (bottom) variation in relation to frequency. Results from models with 3 (black), 4 (blue) and 5 (green) branches. The "*" represents the values from the ATP cable constants.

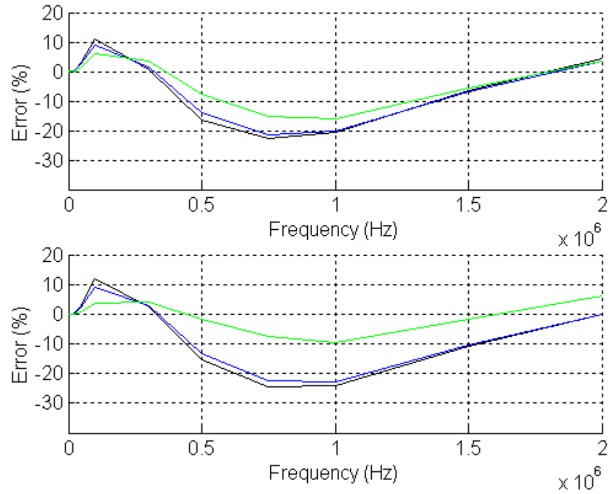


Fig. 4. Errors in the equivalent resistance of the analyzed “N-Branch” models: before data adjustment routine (top graphic) and after it (bottom graphic).

As mentioned earlier in relation to the “N-branch” model, the higher the cable gauge is, the better the obtained results are. This occurs because a greater number of branches can be used when the skin effect is more severe, which is the case of higher-gauge cables. To illustrate this, a 3 x 240 mm^2 submarine cable was modeled. Due to the much more complex structure of this cable, parameter estimation is more difficult and was not used here. Thus, the upper limit of the frequency range studied in this case is restricted to 100 kHz, since measurements for this cable were available only up to this frequency.

Models from five to eight branches were analyzed and the corresponding results are shown in figs. 5 and 6. Results from models with 5, 6, 7 and 8 branches are depicted by the black, blue, green and red curves, respectively, while the “*” represent the measured values. A very good agreement is observed between the model results and the measurements. Reporting to the “8-branch” model, for example, the maximum errors obtained are - 0.9 % for the resistance and - 0.8 % for the inductance.

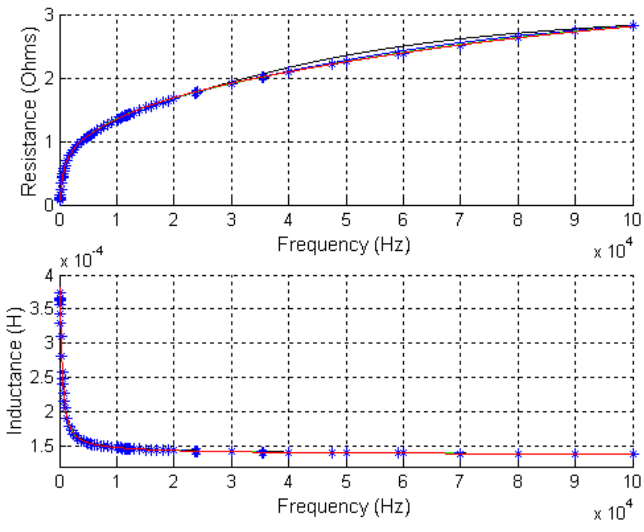


Fig. 5. Resistance (top) and inductance (bottom) variation in relation to frequency. Results from models with 5 (black), 6 (blue), 7 (green) and 8 (red) branches. The “*” represents the measured values.

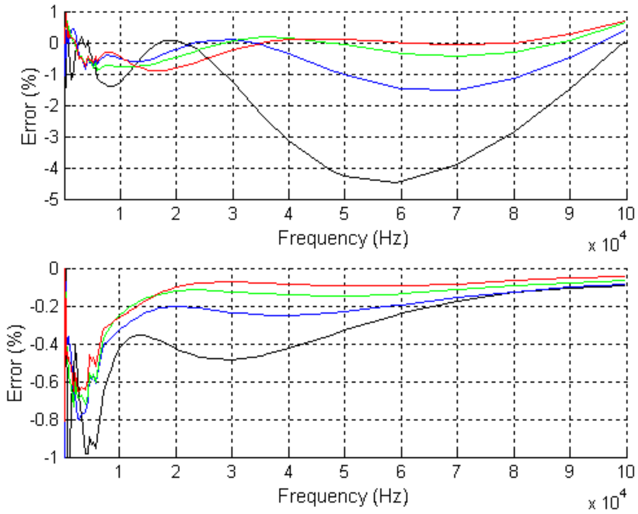


Fig. 6. Errors in the equivalent resistance (upper curve) and inductance (bottom curve) of the analyzed “N-Branch” models. Results from models with 5 (black), 6 (blue), 7 (green) and 8 (red) branches.

III. 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 2 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.

Figure 7 shows the simulation results. The motor was represented as a resistor of high ohmic value, resulting in a reflection coefficient near to 1. This was done to observe the progressive reduction of the oscillations amplitude due only to the effect of the resistance of the cable. A fixed-parameter cable model was used in the curves in the top and in the middle of fig. 7; in the former, parameters at 60 Hz were chosen, while in the latter the resistance and inductance refer to the cable resonant frequency, around 500 kHz. The result depicted by the bottom curve is from the use of the “5-Branch” model. It can be observed that the cable model with 60 Hz-fixed parameters resulted in very low attenuation of the transient overvoltage, thus being far from the expected result, represented by the 500 kHz-fixed parameter model. The “5-Branch” model produced a voltage damping very

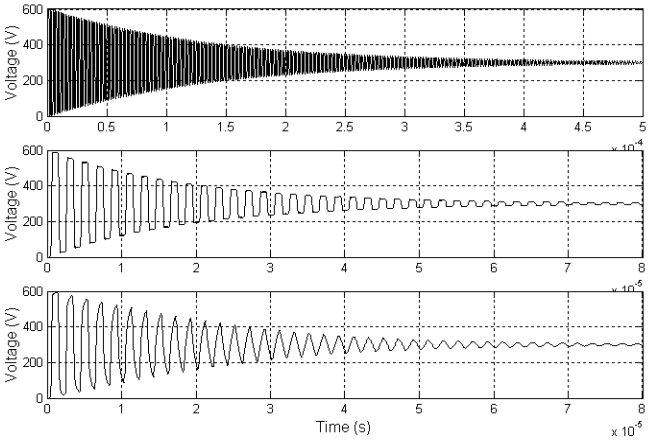


Fig. 7. Transient overvoltage simulated results obtained by modeling the motor as a high ohmic value resistor. The cable was modeled with 60 Hz-fixed parameters (top curve), 500 kHz-fixed parameters (curve in the middle) and by the "5-Branch" model (bottom curve).

close to the 500 kHz-fixed parameter model, proving its great accuracy. Besides, the proposed model was the only one that could reproduce the progressive "rounding" in the pulse edge during its propagations through the cable. This is because this model is able to provide the correct attenuation corresponding to each one of the harmonics that compose the PWM pulse.

Measurements are presented in figs. 8 and 9. A transient overvoltage of nearly 2 p.u. can be observed at motor terminals in fig. 8. A more severe case is shown in fig. 9, where a 2.5 peak voltage takes place due to the small duration of the pulse generated by the inverter, as mentioned in section I.

A confrontation between the simulated and experimental results is shown in figure 10. 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 blue curve represents the voltage measured at the inverter terminals, while the green one depicts the corresponding voltage at motor terminals. The result in red refers to the modeling of the motor as a resistor, while the curve in cyan 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.

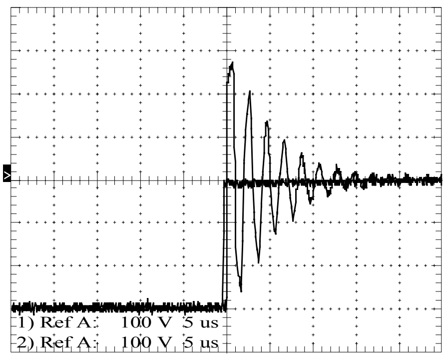
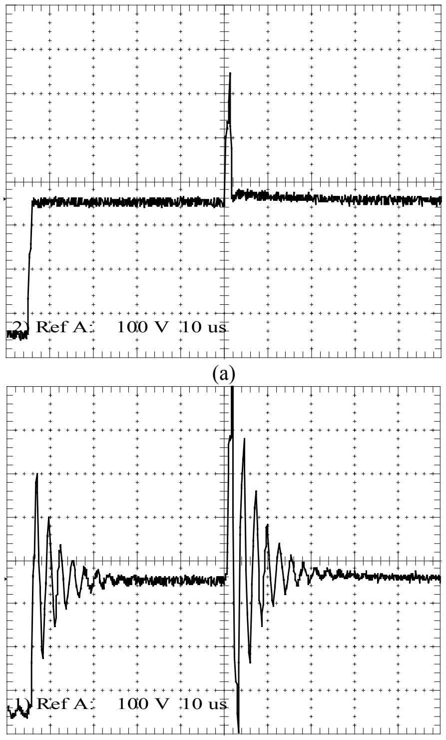


Fig. 8. Voltage at the inverter and motor terminals.



(b)

Fig. 9. Voltage at the (a) inverter and (b) motor terminals. A 2.5 p.u. transient overvoltage can be observed.

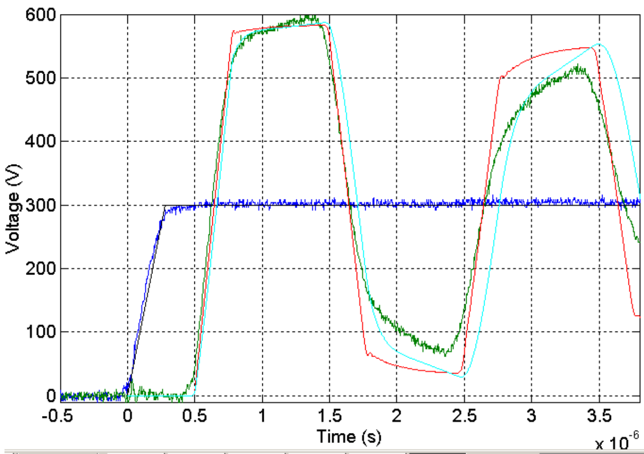


Fig. 10. Voltage at the inverter terminals: simulated (black) and experimental (blue). Voltage at motor terminals: simulated representing the motor as a resistor (red), simulated with a high-frequency model for the motor (cyan) and experimentally obtained (green).

Even better results can be expected if the pulse is more accurately represented, since the fast edges of the trapezoidal shape contain harmonics that are not present in the measured PWM voltage pulse. 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.

IV. CONCLUSIONS

This work presented an efficient methodology for cable modeling and simulation, suitable for the transient overvoltages study 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. It was observed that the cascade-associated "N-Branch" "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.

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