Modeling and Evaluation of dv/dt Filters for AC Drives with High Switching Speed

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Abstract

Recent advances in power electronic switching device technology have resulted in dramatic improvements and cost reduction of pulse-width modulated AC adjustable speed drives. Concomitant with the better performance enabled by the high switching speed and increased switching frequency they have also raised several concerns related to the consequences of high speed switching. One of these concerns is the over-voltage that appears at the motor terminals due to the impedance mismatch between the power cable and the motor. This paper develops accurate simulation models for power cables and motors that allow a better understanding of the over-voltage problem. The models can be readily implemented using computational tools like Matlab, thereby providing a convenient method to develop the best dv/dt filter solution for a particular drive. The power cable is modeled using several lumped-parameter segments of a lossy representation of transmission line. An algebraic analysis is developed to choose an adequate number of lumped-parameter segments. The number of required segment is function of the pulse rise time, cable characteristic parameters and cable length. Simulation results are presented analyzing the over-voltage problem for a wide range of pulse rise times and cable lengths for 1hp, 10hp and 100hp motors. The most important filter network solutions are investigated using the simulation program and an optimized design is performed for the RC Filter at the motor terminals. Experimental results verifying the validity of the model for the over-voltage analysis are presented.

Introduction

As high switching speed and frequency are enabling adjustable speed drives with better performance, concerns have arisen related to certain unintended consequences of the same. One of these concerns, the over-voltage problem due to steep voltage fronts and short pulse rise time from the inverter traveling along long power cable feeding the motors, has become an important research area in the last ten years [1,2,3]. The over-voltage is explained as a voltage pulse, initiated at the inverter, traveling along the cable and being reflected at the motor terminal due to the mismatch between the surge impedance of the motor and the cable. Its behavior is dependent, however, on the characteristics of voltage pulse rise time and of the cable. The objective of this paper is to present a definitive study of the motor over-voltage phenomena by developing accurate and fast simulation models for power cables and motors that allow a better understanding of the over-voltage problem. The models can also be used to provide a convenient tool to benchmark the best dv/dt filter solution for a particular drive.

Transmission lines with lossless characteristics have been commonly utilized to represent the power cable [4,5,6], which typically leads to a large amount of inaccuracies. The use of distortion-less line representation was proposed in [7], which is a much better approximation than the lossless line. However, it is still not sufficiently accurate to investigate the over-voltage problem, especially for drives with long feeders, when the distortion of the line becomes more important. In this paper, it is shown that representing the industrial power cable as a lossy transmission line, better results can be achieved compared to the ones existing in the literature.

The induction motor model for the purpose of studying the over-voltage phenomenon has been modeled using a simple RL circuit in most of the papers in the literature [4,5,6]. This model is unable to capture all the high frequency content that is present in PWM voltage pulse. Some references have shown the necessity to have a different model for the induction motor other than simple a RL circuit [7,8,9]. Among them, a satisfactory high frequency model of the induction motor to evaluate high frequency leakage currents in EMI applications is suggested in [8,9]. The applicability of this model is thus extended in this paper for the over-voltage problem investigation.

The simulation program developed in Matlab including the aforementioned cable and motor models are described in the subsequent sections. Several simulation results are presented showing the suitability of the simulation program in the over-voltage calculation. Selected experimental results from a 3 hp drive come along for comparisons. The most interesting dv/dt filter topologies, including RC and RLC filters ate the motor terminals and RLC and LC+CLAMP filters at the inverter output, are evaluated in the simulation program. An optimized design of a RC Filter for the 3 hp drive is proposed based on simulation analysis and the applicability of the filter is verified through simulation and experimental results.

System Description

Transmission Line Representation of the Power Cable

The power cable as a transmission line can be modeled either as a lumped-parameter network or as a distributed-parameter circuit. Some of references in the literature favor the distributed-parameter representation over the lumped parameter representation [7]. Distributed-parameter representation provides more accurate results in the study of high frequency transients than the lumped-parameter models [10]. However, distributed parameter representation typically leads to a heavy computational burden from the point of view of simulation. Indeed, the lumped parameter representation with an adequate choice of the number of segments can produce accurate results just as well, which will be demonstrated in this paper.

One important consideration, discussed in [10], is the inclusion of “distortion effects” in the distributed-parameter models. On the other hand, although the potentially more accurate distributed parameter line model is used [7], the accuracy of the results is weakened by the use of distortionless characteristics. Simulation of distributed-parameter transmission lines including distortion effects is not straightforward [11]. One technique to calculate transmission line waveforms is to use transport time-delay computation, which assume very simple form if the transmission line characteristics are consider to be either lossless or distortionless [12]. Since it is relevant to use a transmission line with lossy characteristics, it has been decided herein to use the lumped-parameter representation using an adequate number of lumped segments that will give an accurate characterization of the over-voltage at the motor terminals.

If a pulse of rise time τ_{rise} is applied at the sending-end of a pair of parallel wires, and if at the receiving-end of the wires there is a load impedance that does not match the cable surge impedance, then the pulse will travel along the wires and will be reflected at the termination, and then travels back towards the sending-end taking an out-and-back time of flight t_d. The relation between τ_{rise} and t_d can be used to establish a condition to represent the wires as various lumped-parameter segments as follows:

1. *Wires of short length, (t_d < τ_{rise})* – In this case, the leading edge of the reflected pulse will arrive back at the sending-end of the line before the outgoing pulse has risen. Particularly, if $t_d << \tau_{rise}$, then the reflected pulse is slightly delayed compared with the outgoing pulse. This implies that, for the duration of the pulse rise time, the voltage between the wires, and hence the associated electric field, at all positions along the system can be considered to behave as a single lumped element;
2. *Wires of long length, (t_d > τ_{rise})* – In this case, which is the most common for long cable drives with very fast pulse rise times, the outgoing and reflected pulse must be resolved at the sending-end. Therefore, at any instant of time the voltage is not the same at all positions along the system, the electric field between the wires varies with distance along the wires. As a consequence, the system cannot be treated as a single lumped element, but either as a distributed circuit, or as a several lumped segments.

The number of lumped segments that leads to an accurate characterization of the over-voltage can be determined from a consideration of the behavior of the electric field [13]. For instance, consider the electric field E at an arbitrary point x of the system written as

$$E = E_{max} \sin\left(\omega t - \frac{2\pi}{\lambda}\right) \tag{1}$$

representing a wave with angular frequency ω and wavelength λ traveling in the +x-direction. The variation of the electrical field δE over an increment of distance δx is given by:

$$\delta E = \frac{\partial E}{\partial x}\delta x = -\frac{2\pi E_{max}}{\lambda}\cos\left(\omega t - \frac{2\pi}{\lambda}\right)\delta x \tag{2}$$

Therefore,

$$\frac{|\delta E|_{max}}{E_{max}} = 2\pi\frac{\delta x}{\lambda} \tag{3}$$

Equation 3 can be used as a basis to calculate the number of lumped circuit elements necessary for accurate characterization of the voltage distribution. Knowing the desired value of the ratio $|\delta E|_{max}/E_{max}$, the length of each lumped segment across which there is negligible variation of E may be determined. This length is dependent on the value of the voltage pulse wavelength λ. Once this characteristic length is known, the entire length of the cable may be represented by an appropriate integral number of lumped parameter segments. The remaining task is to define the wavelength λ. From the electromagnetic theory the wavelength can be related to the phase constant β of the traveling wave by the expression:

$$\lambda = \frac{2\pi}{\beta} \tag{4}$$

The phase constant β can be calculated knowing the angular frequency ω and the electrical parameters of the power cable per unit length as follows:

$$\beta = \Im\left\{\sqrt{(r + \omega l)(g + \omega c)}\right\} \tag{5}$$

where *r*, *l*, *g*, and *c* are respectively the resistance, inductance, conductance, and capacitance of the line per unit length. The voltage pulse is a summation of many harmonic components that contribute to the formation of the electric field across the length of the cable. It is also known that the minimum frequency at which dv/dt related phenomenon of overvoltage is related the rise time of the pulse. From the Fourier analysis of the PWM pulse, the frequency associated with the pulse rise time τ_{rise} can be calculated as [7,14]

$$f_{HF} = \frac{1}{\pi \tau_{rise}} \quad (6)$$

Therefore:

$$\omega = 2\pi f_{HF} \quad (7)$$

The next step is to define the maximum value of the ratio $|\delta E|_{max}/E_{max}$, which represents a negligible variation of the electrical field. A reasonable value could be 1×10^{-3}, which will generally lead to quite short lengths of the lumped circuit as will be verified. However, this can become prohibitive, since it will increase too much the computational effort. Most of the simulation results, which will be shown later, have used a value of the lumped segment length that gives a ratio of 1×10^{-2}. For very fast rise time, such as τ_{rise} = 50 ns or τ_{rise} = 100 ns, even higher ratio value was used, being around 0.1 or 0.2. Using Equations (4) to (7), and fixing the ratio in Equation (3) at the values 1×10^{-3}, 1×10^{-2}, 1×10^{-2}, and 2×10^{-1}, various lengths of the lumped circuit were calculated for different voltage pulse rise times and for different AWG gauges for the conductor. Figures 1 to 4 show the behavior of the critical length as a function of rise time for various ratios of $|\delta E|_{max}/E_{max}$.

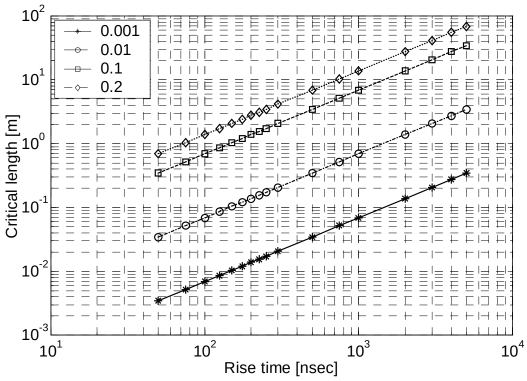


Fig.1: Critical length as a function of rise time for different ratios $|\delta E|_{max}/E_{max}$. #8 AWG cable.

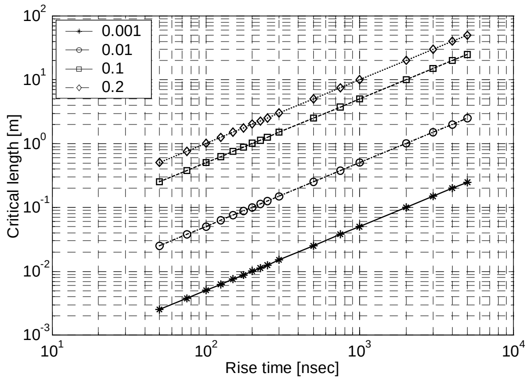


Fig.2: Critical length as a function of rise time for different ratios $|\delta E|_{max}/E_{max}$. #10 AWG cable.

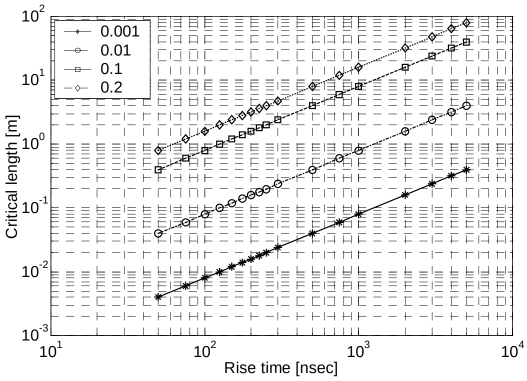


Fig.3: Critical length as a function of rise time for different ratios $|\delta E|_{max}/E_{max}$. #12 AWG cable.

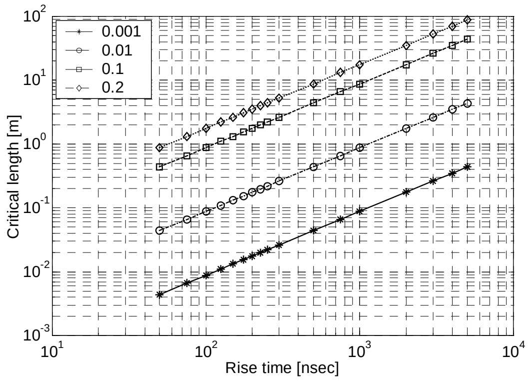


Fig.4: Critical length as a function of rise time for different ratios $|\delta E|_{max}/E_{max}$. #16 AWG cable.

Performing curve fit in these plots, general equations to calculate the critical length of the lumped segment are obtained for each cable gauge as a function of rise time, as shown in Equations (8) to (11). These expressions can be promptly utilized to calculate the length of the lumped segment, or the number of lumped segments, that produces a sufficiently accurate calculation of the over-voltage.

$$\#8\ \text{AWG} \Rightarrow L_{crit} = \left(\frac{|\delta E|_{max}}{E_{max}}\right)_{desired} \times [0.0679 \times \tau_{rise}(ns) + 0.1041] \quad (8)$$

$$\#10\ \text{AWG} \Rightarrow L_{crit} = \left(\frac{|\delta E|_{max}}{E_{max}}\right)_{desired} \times [0.0501 \times \tau_{rise}(ns) + 0.1483] \quad (9)$$

$$\#12\ \text{AWG} \Rightarrow L_{crit} = \left(\frac{|\delta E|_{max}}{E_{max}}\right)_{desired} \times [0.0796 \times \tau_{rise}(ns) + 0.0047] \quad (10)$$

$$\#16\ \text{AWG} \Rightarrow L_{crit} = \left(\frac{|\delta E|_{max}}{E_{max}}\right)_{desired} \times [0.0878 \times \tau_{rise}(ns) + 0.0671] \quad (11)$$

High Frequency Model of the Induction Motor

Another key factor for an accurate over-voltage analysis is the high frequency representation of the ac motor input impedance, which must be valid over a broad range of frequency. It is not necessary to verify how voltage will distribute inside the AC machine winding in order to calculate the over-voltage at the terminals. It is important, rather, to know the value of the ac motor input impedance and how it varies as a function of frequency. The ac motor model adopted here is based on the approach presented in [8,9]. Figure 5 shows the schematic of the proposed model that is implemented in the simulation program to evaluate the over-voltage analysis. The model conjugates low and high frequency representations of the motor. Parameters R_e, R_f, and C_g represent the high frequency part of the model and the dq model captures the low frequency dynamics. The parameter R_e represents eddy current losses inside the magnetic core and the frame. The parameter C_g represents the winding to ground capacitance, and together with element R_f, is responsible to represent the motor surge impedance. Table I shows typical component values for the high frequency motor model obtained from references [7,9].

Motor Rating [hp / V_{LL}]	R_e [kΩ]	R_f [kΩ]	C_g [pF]
1 / 230	17.49	1000	190
2 / 230	15	1000	221.06
7.5 / 230	5	600	750
10 / 230	3.69	400	1000
50 / 460	530	250	1650
100 / 460	250	100	6480

Table I: High frequency parameters of the AC motor model for various power ratings.

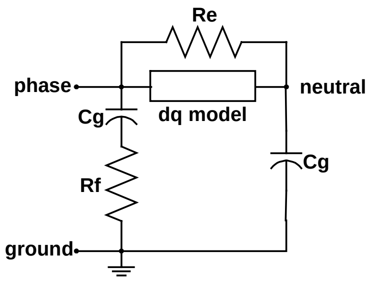


Fig.5: High frequency motor model including the dq low frequency representation.

Description of the Simulation Program

The propagation of the voltage through the three-phase cable is analyzed by evaluating the solutions of the differential equations of the several lumped network segments that represent the power cable. A simulation of such three-phase systems would be involved in solving numerous differential equations. A dq representation of the system reduces the number of differential equations and makes the simulation procedure easier. The entire system simulation, i.e., PWM voltage pulse generation, transmission line differential equations, high frequency motor model differential equations, and dv/dt filter differential equations are thus simulated using the dq representation of the system.

Figure 6 shows the per-phase representation of one segment of the three-phase lumped-parameter representation of the power cable that is suggested to realize the over-voltage analysis. Transposition of the phases has been assumed for the power cable. The dq differential equations of the power cable are suggested as follows:

$$\begin{pmatrix} v_q \\ v_d \end{pmatrix}^i = r_s \begin{pmatrix} i_q \\ i_d \end{pmatrix}^i + \omega_{ref} l_s \begin{pmatrix} i_d \\ -i_q \end{pmatrix}^i + l_s \frac{d}{dt} \begin{pmatrix} i_q \\ i_d \end{pmatrix}^i + \begin{pmatrix} v_q \\ v_d \end{pmatrix}^{i+1} \quad (12)$$

$$\begin{pmatrix} i_q \\ i_d \end{pmatrix}^i = \frac{1}{r_p} \begin{pmatrix} v_q \\ v_d \end{pmatrix}^i + \omega_{ref} c_p \begin{pmatrix} v_d \\ -v_q \end{pmatrix}^i + c_p \frac{d}{dt} \begin{pmatrix} v_q \\ v_d \end{pmatrix}^i + \begin{pmatrix} i_q \\ i_d \end{pmatrix}^{i+1} \quad (13)$$

where the parameter ω_{ref} is the rotating reference frame angular velocity. The indexes "i" and "i+1" are associated with sending-end and receiving-end nodes, respectively, for each segment. The differential equations are solved using Rung-Kutta method order 4.

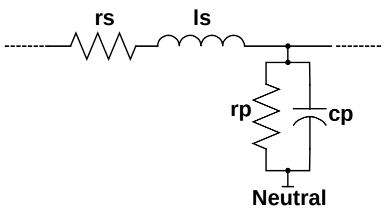


Fig. 6: Per-phase representation of one lumped-segment of the power cable

Simulation Analysis of the Over-voltage

Using the high frequency models presented in the preceding sections, a simulation program has been developed in Matlab to calculate the over-voltage in a range of voltage pulse rise times (from 50 ns to 5 µs) driving three different induction motor power ratings (1, 10, and 100 hp). Figure 7 shows the maximum line-to-line voltage at the motor as a function of voltage pulse rise time for different cable lengths for a 1 hp motor, while Figure 8 shows the behavior of the motor voltage for the case of 200 m cable length and 250 ns rise time. Figures 9 and 10 show similar plots for the 10 hp motor, and Figures 11 and 12, for 100 hp motor respectively.

Since most of the models that are common in the literature analyze the over-voltage problem without using a lossy representation of the power cable, they found the voltage at the motor terminals becoming higher (approaching to two times the DC bus voltage) as the length of the cable increases [2,3,4,5]. This generalization tends to be true for smaller cables where the losses in the cable are negligible, and for slower rise times as well. However for fast rise times, it may be observed from Figures 7, 9, and 11, that the opposite is true. For example, the peak line-to-line voltage for the 100 hp motor @ 50 ns rise time (illustrated in Figure 11) becomes lower as cable length increases. Thus, a more realistic model for the cable brings forth this behavior accurately.

Moreover, many models only consider the cable length and the pulse rise time to define the edge for over-voltage starts to happen. However the results shown here indicate that the motor rating plays a very important role, leading to different over-voltage magnitudes for different hp ratings. For low power motors the over-voltage is about 1.8 pu (Figures 8 and 10), while for high power motors it is about 1.5 pu (Figure 12). Such behavior is due to different degrees of matching of the cable surge impedance to the motor input impedance occurring at different motor power ratings. Therefore it is of utmost importance to have an accurate motor model for the analysis of the high frequency phenomena.

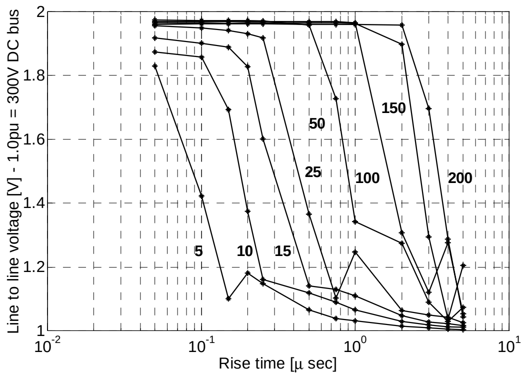


Fig. 7: Line-to-line voltage peak versus Rise time for a range of cable length in [m]. Motor: 1 hp / 230 V_{LL}

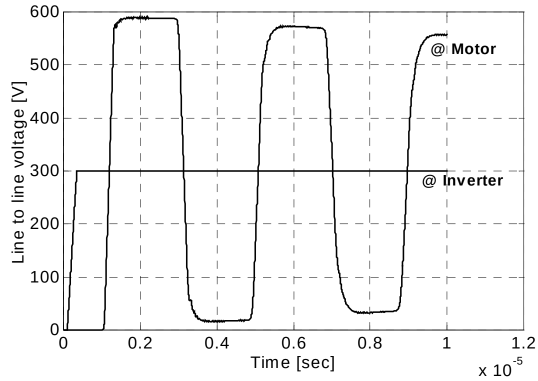


Fig. 8: Line-to-Line voltage at motor terminals. Motor: 1 hp; Cable: 200 m; Rise time: 250ns.

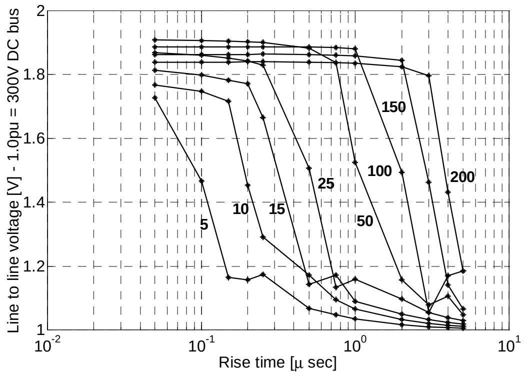


Fig. 9: Line-to-line voltage peak versus Rise time for a range of cable length in [m]. Motor: 10 hp / 230 V_{LL}

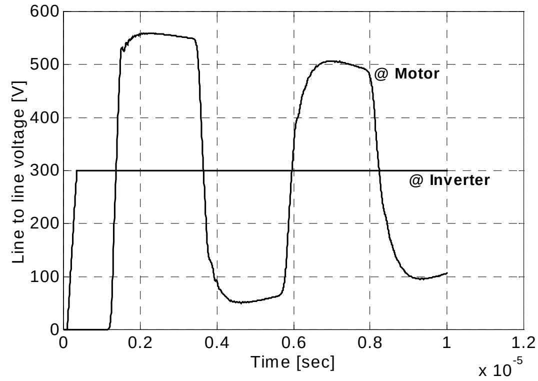


Fig. 10: Line-to-Line voltage at motor terminals. Motor: 10 hp; Cable: 200 m; Rise time: 250ns.

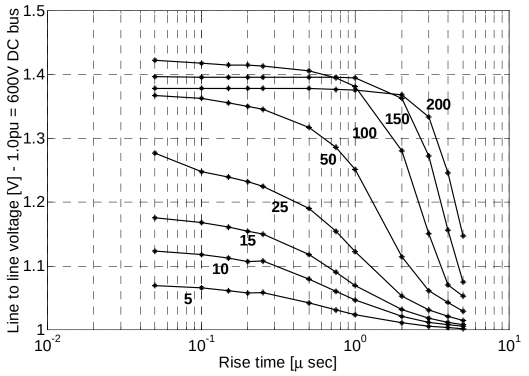


Fig. 11: Line-to-line voltage peak versus Rise time for a range of cable length in [m]. Motor: 100 hp / 460 V_{LL}

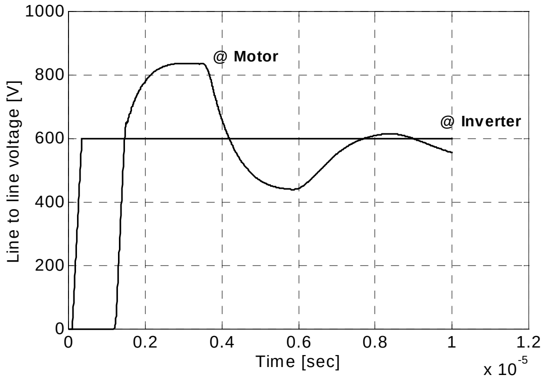


Fig. 12: Line-to-Line voltage at motor terminals. Motor: 100 hp; Cable: 200 m; Rise time: 250ns.

The suitability of the simulation program can be promptly verified from the aforementioned over-voltage simulation results. It can be concluded that using adequate high frequency models for cable and motor, more accurate results can be derived regarding the amount of the over-voltage as a function of cable length and rise time.

Experimental Analysis of the Over-voltage

A 3 hp motor drive system was set up in laboratory to obtain experimental results of the over-voltage and to validate the simulation analysis. The motor parameters are shown in Appendix A. The setup was tested for various lengths of a #6 AWG cable and selected experimental results are shown here. Figures 13 and 14 show the simulation and experimental results, respectively, for 5 m cable length case. The rise time in this case is around 80 ns. It can be observed that 5 m is not a long cable indeed, but because the very fast voltage pulse rise time the over-voltage reaches about 60% above the DC bus voltage (around 520 V line-to-line). Figures 15 and 16 show the simulation and experimental results for the 70 m cable length case, respectively. In these results, the over-voltage has reached almost two times the DC bus voltage as theoretically predicted.

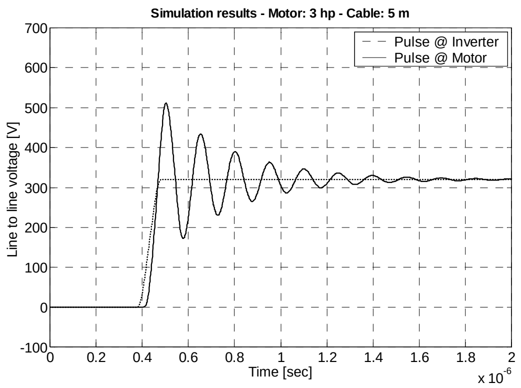


Fig. 13: Simulation results: Line-to-line voltage at the inverter output and motor terminals. Rise time: 80 ns; DC bus: 330 V; Motor: 3 hp; Cable: 5 m.

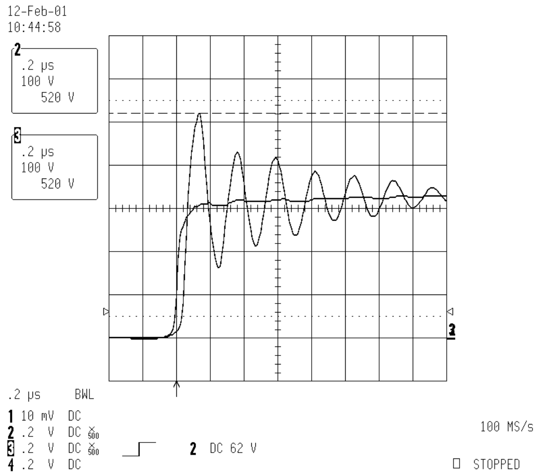


Fig. 14: Experimental results: Line-to-line voltage at the inverter output and motor terminals. Rise time: 80 ns; DC bus: 330 V; Motor: 3 hp; Cable: 5 m.

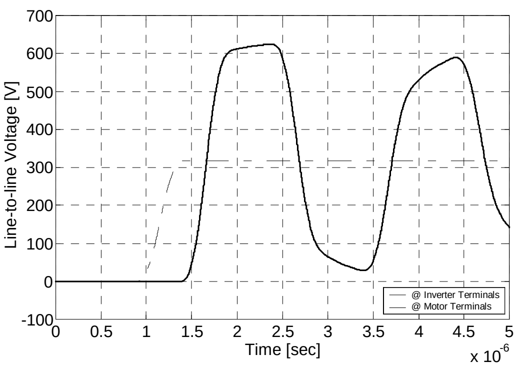


Fig. 15: Simulation results: Line-to-line voltage at the inverter output and motor terminals. Rise time: 80 ns; DC bus: 330 V; Motor: 3 hp; Cable: 70 m.

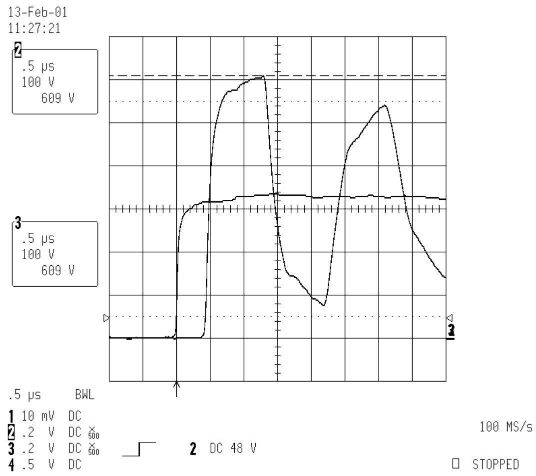


Fig. 16: Experimental results: Line-to-line voltage at the inverter output and motor terminals. Rise time: 80 ns; DC bus: 330 V; Motor: 3 hp; Cable: 70 m.

Although the simulation and experimental results have demonstrated to be in a reasonable agreement, there are some discrepancies mainly because of the following:

- The shape of the voltage pulse at the inverter output plays an important role on the characteristics of the over-voltage waveforms. This is certainly true since the harmonic content of the voltage pulse is dependent on the pulse waveform, and so does the over-voltage in the motor terminals. The voltage pulse initiated at the inverter has a shape that is not well modeled in the simulation, resulting in errors.
- It is also suggested that all cable parameters are frequency dependent. In the simulation, the parameters of the cable were chosen at a unique frequency associated to the voltage pulse rise time. However, the voltage pulse has harmonic content across a broad spectrum. Therefore, a more complex model for the cable may be required to improve the accuracy of the over-voltage analysis further.

The preceding items are currently under investigation and the over-voltage analysis including their effects will be presented in a later article.

Investigation of Filter Networks: RC Filter @ Motor Terminals

The models developed herein can also be used to evaluate the filter solutions for the over-voltage problem. Fig. 17 shows the four different solutions that have been presented in the past: RC filter @ motor [4,15], RLC filter @ motor [4], RLC @ inverter [5], and LC with Clamp @ inverter [6].

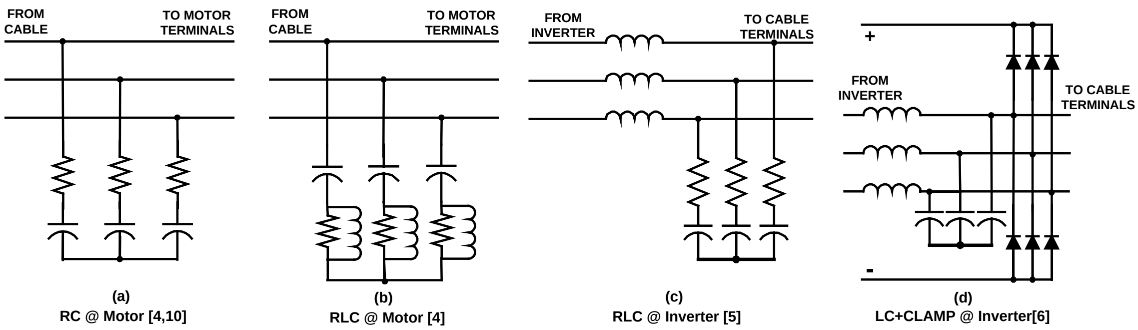
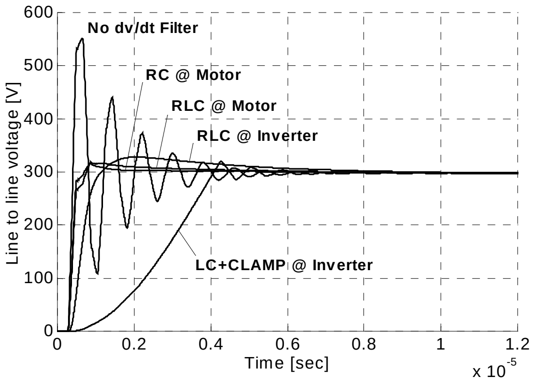


Fig. 17: Best filter topologies to solve the over-voltage problem. (a) RC placed at the motor terminals; (b) RLC placed at the motor terminals; (c) RLC placed at the inverter terminals; (d) LC+CLAMP placed at the inverter terminals.

Several simulation results were obtained for a 10 hp motor drive with 250 ns pulse rise time and 25 m cable length. Figure 18 shows preliminary results of the application of each filter network. The effectiveness of LC+CLAMP @ inverter in reducing the pulse rise time is readily observed from the figure. Observe that the solutions placed at the motor terminals are not able to reduce the dv/dt as much as the filters placed at the inverter terminals. This result happens because the filter networks at the motor terminals, which match the cable impedance, can only reduce the voltage to the dc bus value but cannot slow down the pulse rise time. In a different manner, the topologies placed at the inverter output can greatly reduce the dv/dt at the motor, since they decrease the pulse rise time before the pulse travels through the cable.

For each filter topology, design equations can be derived based on the principles of matching motor input impedance to the cable surge impedance and decreasing the voltage pulse rise time. If the design aim is to find filter parameters in order to give the system a certain behavior, the design equations are not sufficient. A closed form expression that gives the voltage peak in the motor terminal and losses in the filter as a function of the filter parameters is extremely complex. It would appear likely to involve many approximations that could compromise the peak voltage and loss evaluation.

A more practical approach to determine the losses and to verify the maximum voltage at the motor terminals involves the use of simulation. Thus, a filter benchmarking study can be performed and a best filter design can be evaluated. In this paper, such analysis is performed for the RC Filter placed at the motor terminals. The same approach can be applied for other filter topologies as well.



Filter Characteristics			
Filter Type	R [Ω]	L [μH]	C [μF]
RC @ Motor	75	—	0.05
RLC @ Motor	65	625	0.037
RLC @ Inverter	65	20	0.1
LC+CLAMP @ Inverter	—	0.125	0.045

Fig. 18: Line-to-Line voltage at motor terminals for each different filter type. Motor: 10 hp/230 V_{LL}; Cable: 25 m; 250ns

Applying a RC Filter to mitigate the over-voltage in the 3 hp drive system, several simulation results were obtained regarding filter losses and peak voltage at the motor terminals. These figures of merit were analyzed for various lengths of cable including 5, 10, 20, 40, and 70 m. A voltage pulse rise time of about 100 ns was used in all simulation studies. Figure 19 shows selected results of line-to-line peak voltage as a function of filter capacitance for 20 m cable lengths. Three different values of filter resistance were researched: 35, 42, and 50 Ω. The optimized value (what is the basis for optimization?) for the filter resistance was found to be roughly 42 Ω independent of the length of cable. Additional simulation studies were conducted to determine the filter losses for various values of filter capacitance, having fixed the filter resistance in 42 Ω. Figure 20 shows filter losses and line-to-line peak voltage normalized to the DC bus voltage ($V_{LL} - V_{DC}$). From the simulation results in Figure 20, an optimized design for the RC filter can be suggested such as the filter capacitance that results in the lowest peak voltage for the lowest filter losses.

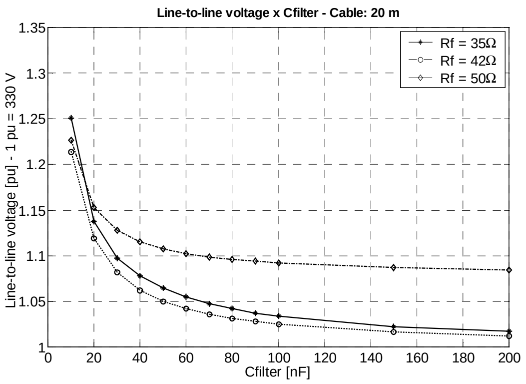


Fig. 19: Line-to-line voltage peak in pu (1pu = 330 V_{DC}) versus filter capacitance in [nF]. Motor: 3 hp. Cable length: 20 m. Plots: solid stars: 35 Ω; dotted circles: 42 Ω; and solid dotted diamonds: 50 Ω.

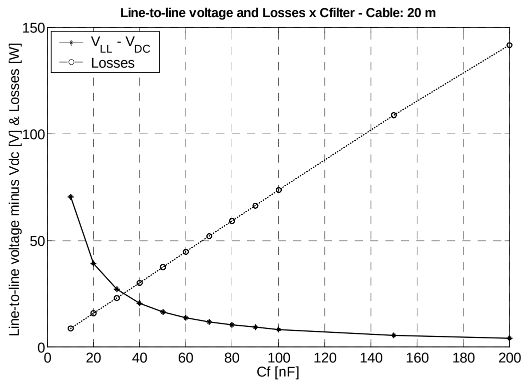


Fig. 20: Normalized line-to-line peak voltage and filter losses versus filter capacitance in [nF]. Motor: 3 hp. Rfilter = 42 Ω. Cable length: 20 m.

This design approach was applied for other lengths of cable. Figure 21 shows the simulation results for the proposed selection for the filter capacitance taking account losses and peak voltage for various cable lengths.

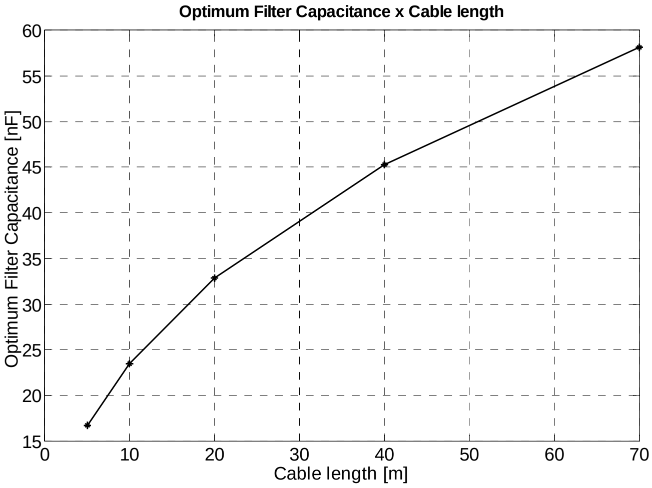


Fig. 21: Optimum filter capacitance as a function of cable length. Rfilter = 42 Ω. Motor: 3 hp.

The RC Filter was also implemented in laboratory to verify its performance. Selected experimental results are shown in this paper. Figure 22 shows simulation and experimental results for the RC filter in the case of 20 m. Figure 23 shows similar results for the case of 70 m cable. It can be verified from these plots that the peak voltage from simulation and from experimental results are in a good agreement. There is a difference in about 20 % between simulation and experimental results. As already pointed out in the over-voltage result analysis, this deviation can be explained due to discrepancies in the representation of the voltage pulse and in the modeling of the power cable.

Figure 24 shows additional comparisons between simulation and experimental results, analyzing losses and peak voltage for the 20 m cable case. The peak voltage is not well matched, confirming the deviation mentioned in the last analysis. However, the simulation program has provided suitable results for the filter losses. The main conclusion that can be drawn from these results is the necessity for better models for the voltage pulse initiated at the inverter and for power cable in order to have a more accurate evaluation of the over-voltage phenomenon.

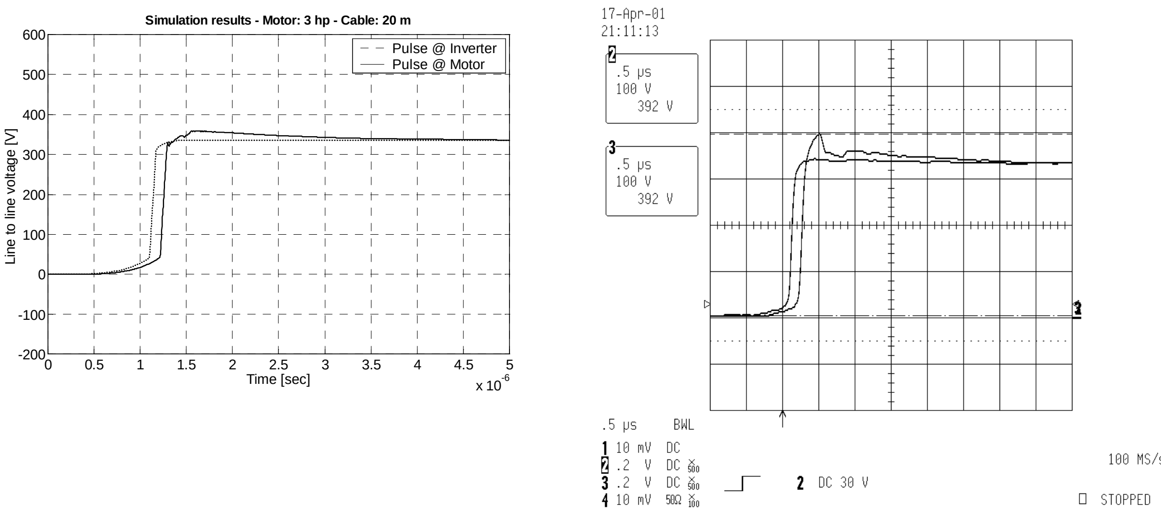


Fig. 22: Line-to-line voltage at inverter output and at motor terminals. Motor: 3 hp. Cable length: 20 m. Rfilter = 42 Ω and Cfilter = 33 μF. Left plot: simulation. Right plot: experimental.

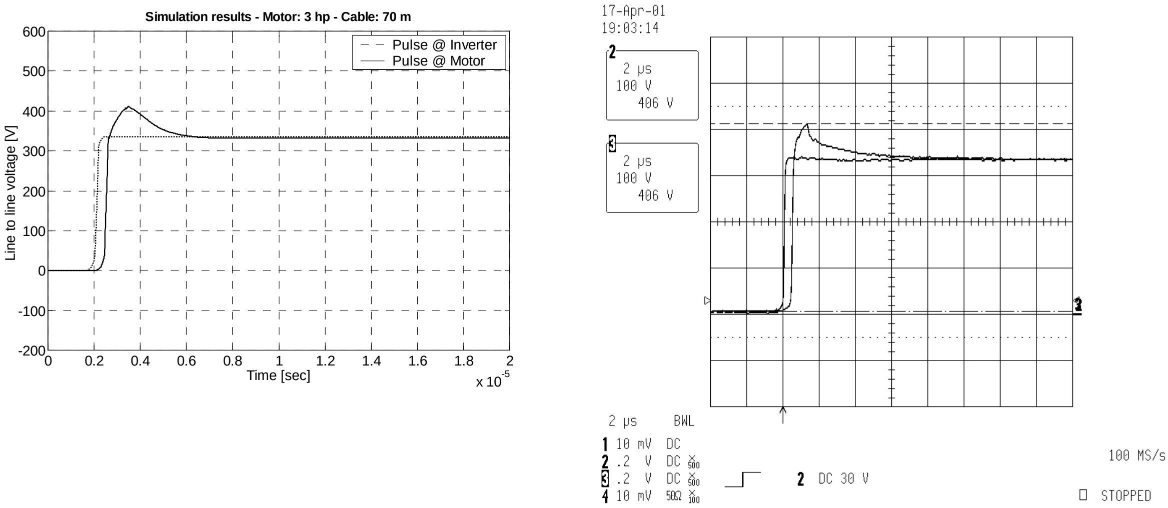


Fig. 23: Line-to-line voltage at inverter output and at motor terminals. Motor: 3 hp. Cable length: 70 m. Rfilter = 42 Ω and Cfilter = 60 µF. Left plot: simulation. Right plot: experimental.

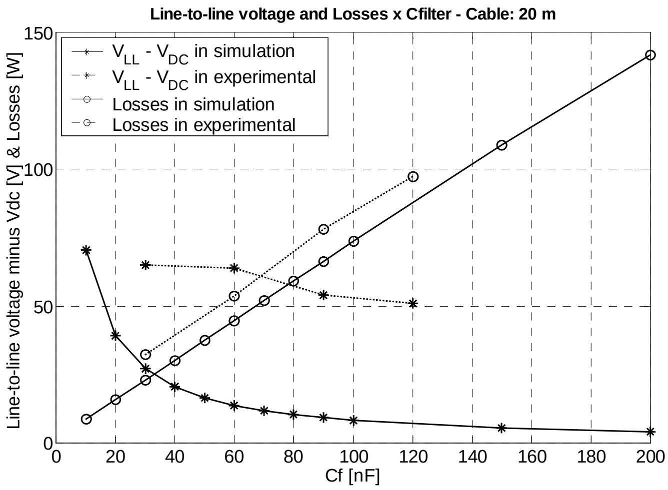


Fig. 24: Normalized line-to-line peak voltage and filter losses versus filter capacitance in [nF]. Motor: 3 hp. Rfilter = 42 Ω. Cable length: 20 m.

Conclusions

This paper has proposed a Matlab based program intend to the analysis of the over-voltage phenomena in long cable PWM drives. Two fundamental characteristics of the simulation package are:

- The power cable is represented as a transmission line with lossy characteristics and modeled using several lumped-parameter segments. An approach for calculating the adequate number of lumped segments in order to have accurate results is suggested.
- A high frequency model that works over a broad harmonic spectrum of excitation represents the ac machine stator winding.

Several simulation and experimental results have been presented demonstrating the suitability of the simulation package. In the case of the over-voltage analysis, the simulation program is useful for the generation of charts that gives the peak voltage in the motor terminals as a function of voltage pulse rise time and length of power cable. Using such over-voltage charts one can predict a priori the conditions under which the increased voltage stress will occur.

The most common dv/dt filter topologies for mitigating overvoltage problems were analyzed using the proposed simulation package. The main conclusion from this analysis is that the solutions placed at the motor terminals are not able to reduce the dv/dt as much as the filters placed at the inverter terminals. This occurs because the filters at the motor terminals, which match the cable surge impedance, can only reduce the voltage to the dc bus level but are not capable of reducing the pulse rise time. On the other hand, the filters placed at the inverter terminals can greatly reduce the dv/dt at the motor, since they decrease the pulse rise time before it travels through the cable. Detailed analysis of the RC Filter place at the motor terminals was performed and an optimized design was derived using the over-voltage simulation program. Experimental results from a laboratory set-up using a 3 hp motor drive confirm the applicability of the proposed models. Experimental results indicate that some residual inaccuracies are still persistent in the simulation models. The discrepancies have been identified to arise from two major causes and the following improvements are being pursued to address them.

- Because of the extended spectral content of the voltage pulse, a better representation of the pulse waveform is needed in order to have more accurate results of the over-voltage phenomenon;
- The power cable has frequency dependent parameters. Therefore, a better cable model is also needed in order to obtain a more correct analysis of the over-voltage.

In summary, the simulation program has demonstrated to be a convenient tool that allows one to study the over-voltage phenomena and to research dv/dt filter networks. Additional analysis is being realized on the abovementioned items and will be presented in a future paper.

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Appendix A

Table A-I shows the parameters of the 3 hp motor drive system.

Motor Nameplate Data 230/460 V – 3 phase – 60 Hz 9/4.5 A – 1755 rpm – 82.5% eff Insulation class B – Design B – 182T Frame					
Motor Base Values Vb = 187.8 V – Zb = 47.3 Ω – Ib = 3.97 A					
Cable Parameter per unit length		**Motor Low Frequency Parameters in [pu]**		**Motor High Frequency Parameters**	
rs	1.417 mΩ	r1	0.018	Cg	320 pF
ls	0.241 µH	r2	0.012	Rf	750 Ω
rp	50 MΩ	x1	0.043	Re	15 kΩ
cp	135 pF	x2	0.043		
		xm	0.556		

Table A-I: Parameters of the 3 hp motor drive system.