DESIGN OF FILTER NETWORKS FOR LONG CABLE DRIVES THROUGH SIMULATION AND ANALYSIS

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Abstract— **Filter networks for long cable drives have been studied in the last decade to solve the over-voltage problem at the motor terminals. However, little research has shown good results in the optimization of the filter operation. In this paper, the project of dv/dt filters through simulation and analysis from previous works is done in such a way that the decision can be the best one for a particular drive system. Simulation and experimental results are presented demonstrating the usefulness of the filter networks on the motor over-voltage mitigation. Three filter topologies will be discussed and compared here: RLC Filter at the motor terminals, the RLC Filter at the inverter output and the Reactor Filter, which is extensively used in the industry.**

KEYWORDS

Industrial Drives; Electrical Drive Systems Design and Applications; Over-voltage and dv/dt Filter Design.

I. INTRODUCTION

Passive dv/dt filters have been fully exploited in previous works [1], [2], in which a convenient simulation tool has been suggested to design filter networks. The main goal of this paper is to demonstrate that the simulation program is the most interesting tool for the designing passive solutions to mitigate the existent over-voltage problem in the actual adjustable speed drives [3], [4], [5]. To reach this goal, three topologies of passive networks will be designed through simulation and analysis and implemented.

Early papers have derived design equations for the filter networks design [6], [7], [8]. Such design equations can be successfully used to derive filter topologies but they are not sufficient when an optimized filter design is required. What is understood to be an optimized filter is the one that presents minimal losses and minimal overvoltage at the motor terminals. It will be shown that what is possible is to achieve a good agreement between these two goals, since they are conflicting ones, and that the RLC Filter at the inverter output that presents the best agreement.

The dv/dt filter topologies are designed for two 3 hp induction motor drive systems: one with 20 meters and other with 250 meters of power cable length. Selected simulation and experimental results are presented showing the usefulness of the filters and how adequate the simulation program is.

II. FILTER DESIGN THROUGH SIMULATION AND ANALYSIS

It's known that the main philosophies utilized to solve the over-voltage problem are: to match the load to the cable characteristic impedance and to increase the voltage pulse rise time [2], [7], [8]. The networks placed at the motor terminals follow the first philosophy, while the networks placed at the inverter output follow the second one. In this last case, although the reflection phenomenon exists the over-voltage does not appear because the voltage pulse rise time is somehow kept bigger than the voltage pulse traveling time.

The design process through simulation and analysis of the RC Filter placed at the motor terminals was analyzed in a previous work [2]. Now, the design process for the RLC Filter placed at the motor terminals and the RLC Filter placed at the inverter output will be presented.

Practical concerns like switching frequency and the implementation of the both topologies will be treat later in a particular section.

A. RLC Filter at The Motor Terminals

The first thing in designing the RLC Filter at the motor terminals is to determine the filter resistance, which is chosen to achieve the matching characteristics between the cable characteristic impedance and the motor input impedance. This happens when we make the filter resistance equals to the characteristic cable impedance when the frequency tends to infinite, like one can see on the Equation 1, where ls and cp_1 are parameters of the high frequency cable model [9].

$$Rf \;=\; Z_{characteristic,cable}\Big|_{f\rightarrow\infty} \;\approx\; \sqrt{\frac{ls}{cp_1}} \tag{1}$$

For the case studied in this research, 3 hp motor and ♯6 AWG cable, the filter resistor is designed to be:

$$R_{filter} \;\approx\; 42\ \Omega \tag{2}$$

With the purpose of verifying how worthy is this calculus the Figure 1 shows the result of the simulation of the reflection coefficient for three values of the filter resistance.

Readily one can notice that the filter resistance calculated using Equation 1 is a very good choice since it provides the lowest magnitude for the voltage reflection coefficient. The calculus was made in that way based on two facts:

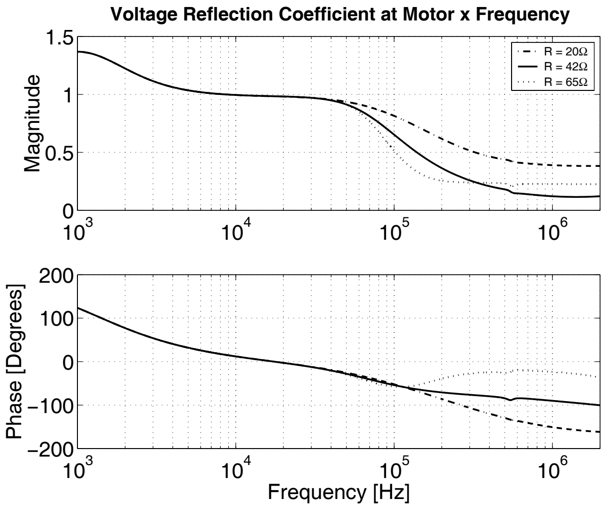

Fig. 1. Voltage reflection coefficient as a function of frequency for various filter resistors (Cable: ♯ 6 AWG. Motor: 3 hp. $C_{filter} = 20nF$; $L_{filter} = 130\mu H$).

- The main frequencies that cause the reflection wave phenomenon are the highest ones found in the spectrum of the PWM pulse. The smaller the pulse rise time, the higher the maximum frequency found in the spectrum;
- The input motor impedance is very high, so the parallel association with the filter resistance gives an equivalent impedance practically equals to the filter resistance, giving us the control of the one of the characteristics of the terminal impedance for good matching.

The choice of the filter capacitance is made by using the MATLAB simulation program. It allows one to choose the adequate capacitance in order to establish the optimal point in one plane of interest: the line-to-line peak voltage vs. the filter losses, both parameterized by the cable length and calculated for several values of capacitance. The influence of the capacitance is evident. This is summarized in the Figure 2 that follows:

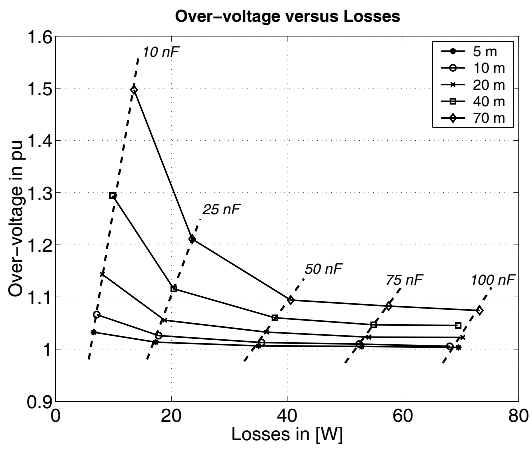

Fig. 2. Minimum line-to-line peak voltage as a function of filter losses for various numbers of filter capacitance. Cable length: Star: 5 m; Circle: 10 m; Cross: 20 m; Square: 40 m; Diamond: 70m. Motor: 3 hp.

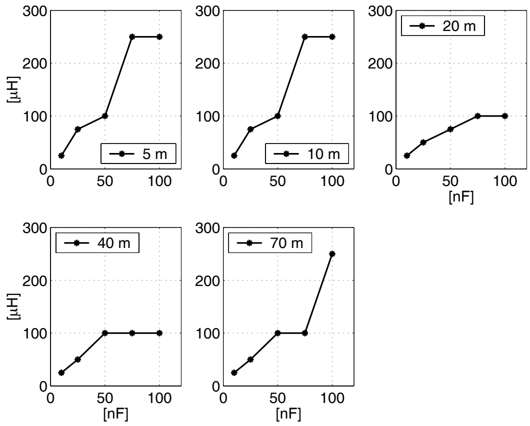

Fig. 3. Suggested pairs for filter inductance and capacitance for various lengths of cable. Filter topology: RLC Filter at the motor terminals. Motor: 3 hp.

The inductance has none or minimal influence on the filter losses, as it was observed utilizing the simulation program, but the joint effect of the pair capacitance-inductance is very important to achieve the best results [10]. So the choice of the inductance utilizing the abacus shown in Figure 3 is an easy way of finishing the filter design, matching the inductance to the capacitance chosen in the last step. Figures 2 and 3 show how two of the conflicting goals are related and how simple it is to develop the design.

B. RLC Filter at The Inverter Output

The design of the RLC Filter at the inverter output is made exactly in the same way used for the RLC filter at the motor terminals. The first step is to design the filter resistance, which was chosen to be equal to the cable characteristic impedance at very high frequencies. It remains in the same value (42Ω) since the cable is the same.

The reactive components are chosen through many calculations using the over-voltage simulation program. Figure 4 shows the variation of the line-to-line peak voltage as a function of filter losses demonstrating the influence of the filter capacitance for this topology. Figure 5 shows the values of filter inductance that provides the lower line-to-line voltage as a function of filter capacitance.

Since the way of designing the filters is the same and follows the same procedure, using the same simulation program, one can ask what the real deference among these topologies is. Although the axes scales of the four figures are different, this is not the main and so important point.

The feature that must observed to make the choice among the topologies will be presented in the up coming section: the filter losses variation with the filter capacitance and the overvoltage achieved with one specific filter capacitance.

III. Practical Implementation and Results

This section presents selected experimental results that bases further analysis and support the choice of the RLC Filter topology at the inverter output as the most interesting one. Through simulation and analysis, the three main topologies of passive filters were designed for a 3 hp motor drive system

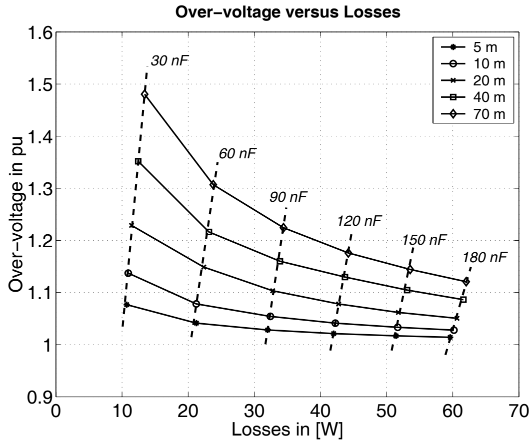

Fig. 4. Minimum line-to-line peak voltage as a function of filter losses for various numbers of filter capacitance. Cable length: Star: 5 m; Circle: 10 m; Cross: 20 m; Square: 40 m; Diamond: 70m. Motor: 3 hp.

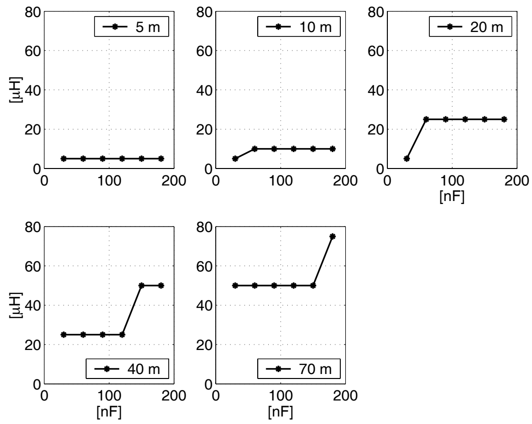

Fig. 5. Suggested pairs for filter inductance and capacitance for various lengths of cable. Filter topology: RLC Filter at the inverter output. Motor: 3 hp.

with 20 meters of power cable length: RC Filter and RLC Filter at the motor terminals and RLC Filter at the inverter output.

We can first analyze how adequate the simulation program output was due to the practical results achieved. Figure 6 shows the waveforms obtained with the simulation program and the ones obtained experimentally. Figure 7 shows the terminal voltages and the filter current waveform. Additionally, one can see that the overvoltage has been reduced considerably with the usage of the RC Filter at the motor terminals.

Figures 8 and 9 show experimental results for the RLC Filter at the motor terminals. Figures 10 and 11 for the RLC Filter at the inverter output.

Important experimental results are presented in Figure 12: filter losses as a function of filter capacitance for the three filter topologies. It might be noticed that the inverter switching frequency is also a key parameter in the determination of the filter losses. The experimental results presented in Figure 13 confirm that the filter losses increases if the inverter switching frequency increase. Therefore, an adequate choice of the

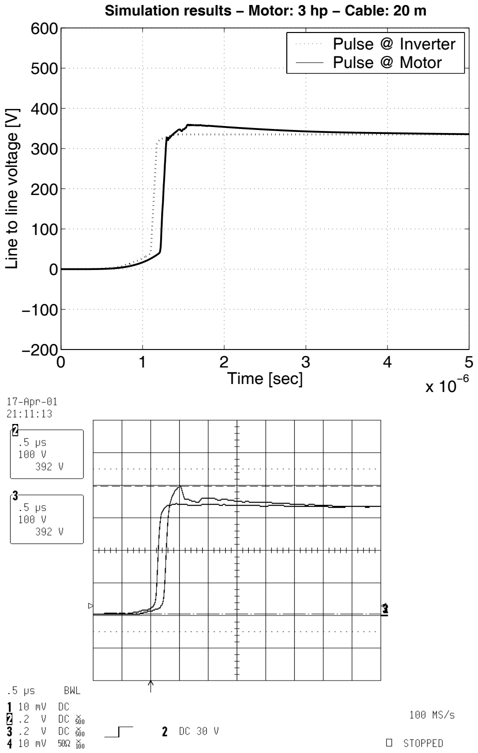

Fig. 6. Line-to-line voltage at inverter output and at motor terminals. Motor: 3 hp. Cable length: 20 m. $R_{filter} = 126\Omega$. $C_{filter} = 10nF$. Simulation: upper plot. Experimental: lower plot.

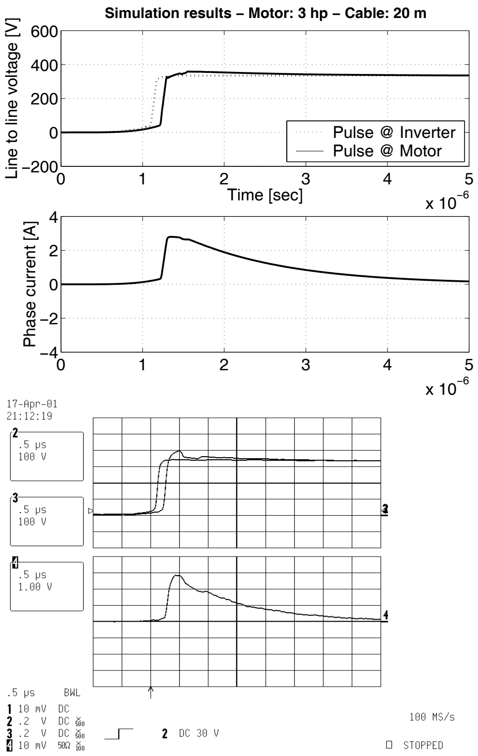

Fig. 7. Line-to-line voltage at inverter output and at motor terminals (upper plot) and phase current (lower plot). Motor: 3 hp. Cable length: 20 m. $R_{filter} = 126\Omega$. $C_{filter} = 10nF$. Simulation: upper two plots. Experimental: lower two plots.

inverter switching frequency can cause a positive impact in

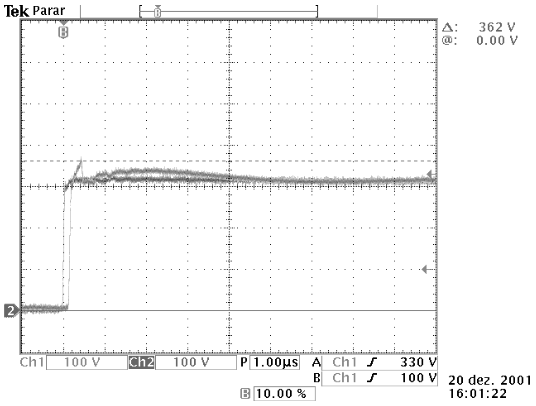

Fig. 8. Experimental results: line-to-line voltage at motor terminals and at inverter output using a RLC Filter (Δ-connected) at the motor terminals: $R_{filter} = 126\Omega$, $L_{filter} = 150\mu H$, $C_{filter} = 10nF$; Cable length = 20 m; Motor: 3 hp.

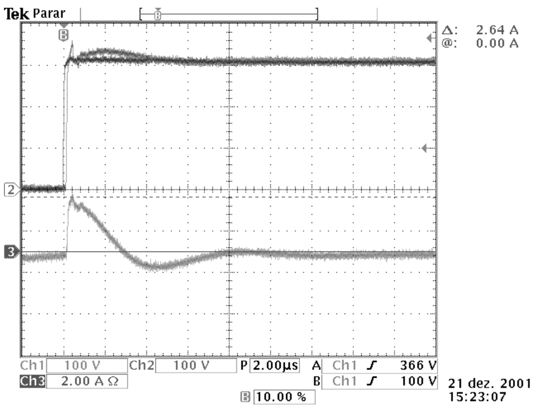

Fig. 9. Experimental results: line-to-line voltage and filter leg current using a RLC Filter (Δ-connected) at the motor terminals: $R_{filter} = 126\Omega$, $L_{filter} = 150\mu H$, $C_{filter} = 10nF$; Cable length = 20 m; Motor: 3 hp.

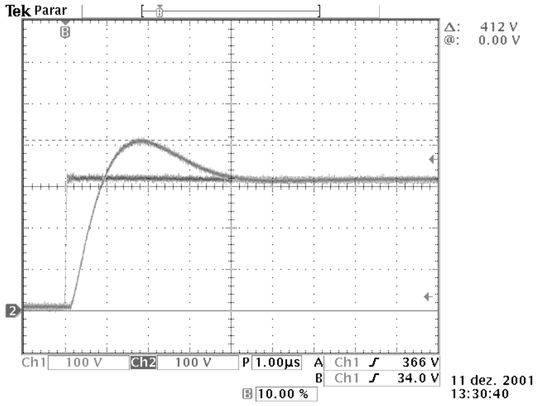

Fig. 10. Experimental results: line-to-line voltage at motor terminals and at inverter output using a RLC Filter (Δ-connected) at the inverter output: $R_{filter} = 126\Omega$, $L_{filter} = 25\mu H$, $C_{filter} = 10nF$; Cable length = 20 m; Motor: 3 hp.

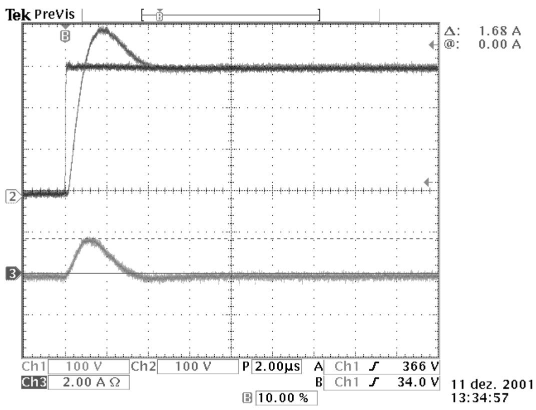

Fig. 11. Experimental results: line-to-line voltage and filter leg current using a RLC Filter (Δ-connected) at the motor terminals: $R_{filter} = 126\Omega$, $L_{filter} = 25\mu H$, $C_{filter} = 10nF$; Cable length = 20 m; Motor: 3 hp.

reducing the filter losses.

The passive filter topologies, RC Filter at the motor terminals and the RLC Filter at the inverter output, were also evaluated for a 3 hp induction motor-pump drive system with 250 m power cable length. The motor drive was a water pump installed at AÇOMINAS, a rolling mill company in the state of Minas Gerais, Brazil. The 5% reactor filter at the inverter output, a common industry practice, was also evaluated in this analysis.

Easily one can notice that the best response, taking into account the over-voltage reduction, is the one obtained with the RC Filter. However, to achieve this, the power drawn by the RC Filter is higher than that drawn by the other topologies,

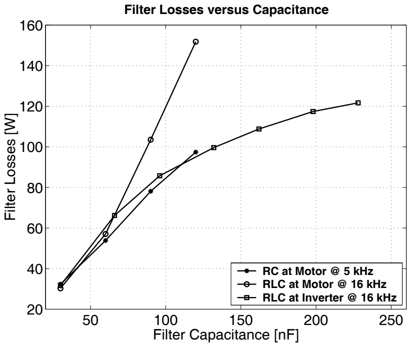

Fig. 12. Experimental results: filter losses versus filter capacitance. RC Filter at motor terminals at $f_{switching} = 5kHz$; RLC Filter at motor terminals and RLC Filter at inverter output at $f_{switching} = 16kHz$.

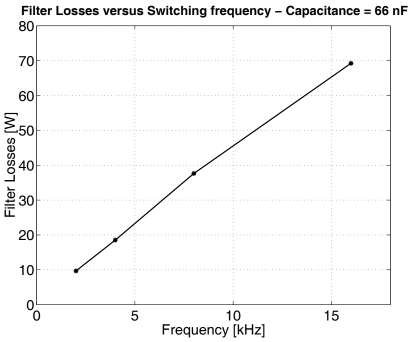

Fig. 13. Experimental results: filter losses versus switching frequency for the RLC Filter at inverter output. Filter capacitance: $C_{filter} = 66nF$.

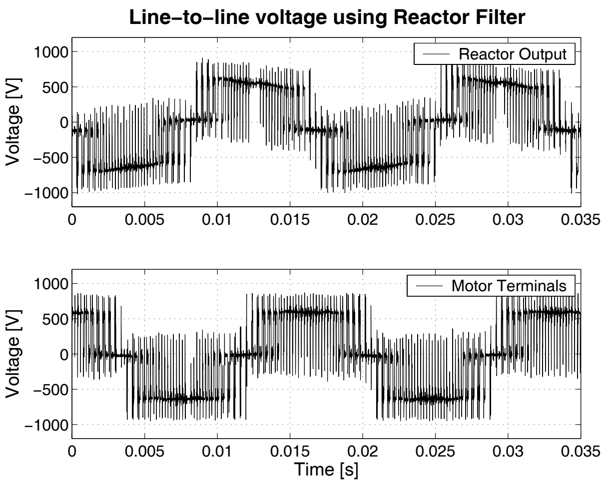

Fig. 14. Experimental results in a real industrial load: line-to-line voltage at the inverter output and at the motor terminals. 5% Reactor Filter applied. Cable length = 250 m; Motor: 3 hp.

for one selected switching frequency, as it can be seen on the Figure 12.

Another point to analyze is the distortion introduced when the reactor is utilized as the over-voltage filter. Figure 14 shows the voltage waveforms before and after the filter. Figures 15 and 16 show the same measurements when RC Filter at the motor terminals and RLC Filter at the inverter output are utilized, respectively. Readily one can notice that the widespread solution utilized in the industrial plants (the

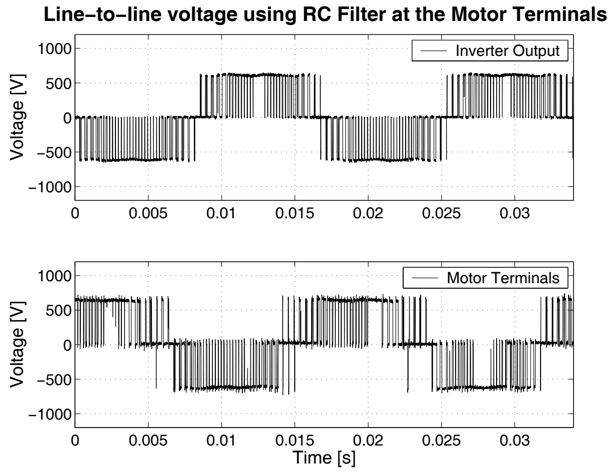

Fig. 15. Experimental results in a real industrial load: line-to-line voltage at the inverter output and at the motor terminals. RC Filter applied (Δ-connected): $R_{filter} = 126\Omega$, $C_{filter} = 66nF$. Cable length = 250 m; Motor: 3 hp.

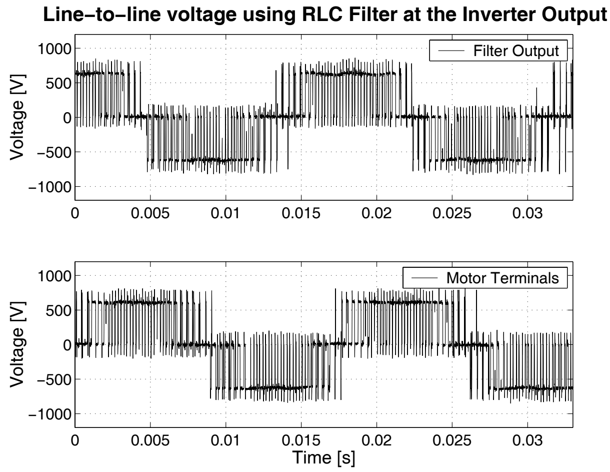

Fig. 16. Experimental results in a real industrial load: line-to-line voltage at the inverter output and at the motor terminals. RLC Filter applied (Δ-connected): $R_{filter} = 126\Omega$, $L_{filter} = 25\mu H$, $C_{filter} = 66nF$. Cable length = 250 m; Motor: 3 hp.

reactor) is the worst that could be take into account.

IV. CONCLUSION

This paper has proposed the design of dv/dt filter networks through simulation and analysis. The design charts that were developed for the suggested filter topologies are very useful for the filter design because they include the desired voltage stress at the machine terminals and the filter losses during the design process. Experimental results have been presented validating the suggested design technique and also demonstrating that the filter topologies can successfully eliminate the voltage stress.

Problems in Engineering generally can have too many solutions and some of then can lead to a good (or acceptable) result, that unnecessarily is the best one. What is presented here is an option of designing passive networks[1] with the purpose of solving the overvoltage problem caused by the

[1]The cheaper ones [10].

high dv/dt. This method certainly will lead to the best cost vs. benefit relation that is possible to achieve for a particular drive system.

Other issues concerning the design of the passive network filters are been studied and must be analyzed together with the other figures of merit presented in this paper. These issues are the common mode current that flows in the drive and the voltage distribution in the machine winding.

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