Minimizing Overvoltages in Adjustable Speed Drives with Long Cables

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***Abstract* - This paper analyses different solutions found in the literature to mitigate overvoltages in an adjustable speed drive when a long cable connects motor and converter. The converter harmonics can excite several resonance frequencies in the cable leading to a motor terminal voltage with extreme high overvoltages, greater than 2pu. This case is a typical configuration in several industrial applications where an induction motor is fed by means of a cable using a VSI-PWM (Voltage Source Inverter - Pulse Width Modulation). Simulations as well as experimental results are presented to illustrate the analysis.**

I. Introduction

Nowadays there is a need for industrial applications to optimize performance and flexibility. An Adjustable Speed Drive (ASD) enables the machine to work even in open loop in several frequencies and loading, eliminating problems such as high starting current and motor overloading. However, in some applications, a long cable connecting motor and converter is needed. In applications, such as mining or oil exploitation, the length reaches its maximum [1], nevertheless, other process has a cable length of hundred of meters which can be dangerous in terms of overvoltage depending on the converter switching strategy. Fig. 1 presents a schematic of the system.

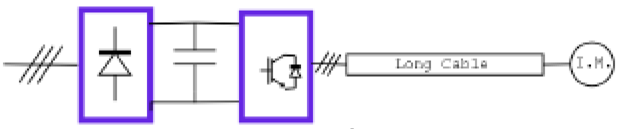


Fig. 1. System Schematic

In power electronic systems one has a steady state which is a sequence of consecutive transients, and therefore the load has to withstand overvoltages constantly. This stresses the importance to reduce as much as possible the overvoltage at the load terminal. There are several solutions to mitigate motor terminal overvoltages such as: Passive filters at the inverter output, impedance matching at the motor terminal, multi-level converter and optimum switching frequency. This paper will present and compare these methods. Fig. 2 shows a converter output voltage and the motor terminal voltage for a experimental prototype. The cable length is 200m, the inverter fundamental frequency is 60Hz with a switching frequency of 5kHz, the motor is 1HP and it is operating without load. The voltage pick value is affected by the presence of the cable, without it the pick value should be around 315 V, while the results show a pick value around 400V (27% overvoltage), at motor terminals it reaches almost 600V, around 90% overvoltage. This situation is extremely harmful for the motor, and can cause isolation failure in the motor. In order to assess the overall impact of the driving system a simulation model of the complete system was implemented in EMTP to better analyze all the aforementioned solutions.

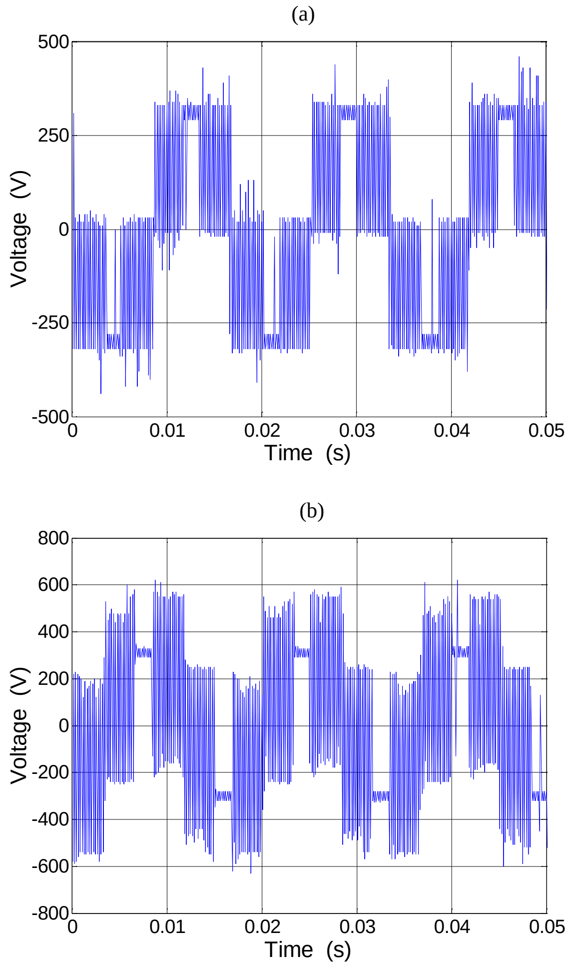


Fig. 2. Typical Voltage in Driving System with long cables (a) converter output, (b) motor output (time scales are not synchronized)

II. Theoretical Background

The problem of the overvoltage is a consequence of wave reflection at the cable terminals [2], [3].

A very important factor for the value of the voltage at the cable output is the relation between the cable characteristic impedance, $Z_{C,\ and}$ the load surge impedance, Z_L [3]. This can be summarized, for a lossless cable, as:

- whether $Z_L > Z_C$, the maximum voltage on the load will be larger than the voltage in the inverter output;
- whether $Z_L = Z_C$, the maximum voltage on the load will be the same in the inverter output;
- whether $Z_L < Z_C$, the maximum voltage on the load will be smaller than the voltage in the inverter output.

The reflection coefficient ρ_S is given by:

$$\rho_s = \frac{Z_L - Z_C}{Z_L + Z_C} \tag{1}$$

A lossless single-phase cable is considered to illustrate this phenomenon. This system has a step voltage of 100% at t = 0, at t = T where T is the cable travel time or travel constant since in this example a lossless model is considered. The voltage at the cable output will then be a function of the load. Fig. 3 shows the output for two distinct load 90Ω and 10Ω respectively. The cable surge impedance is Z_C = 30Ω. One can see that the overvoltage increases with Z_L, as suggested also by (1).

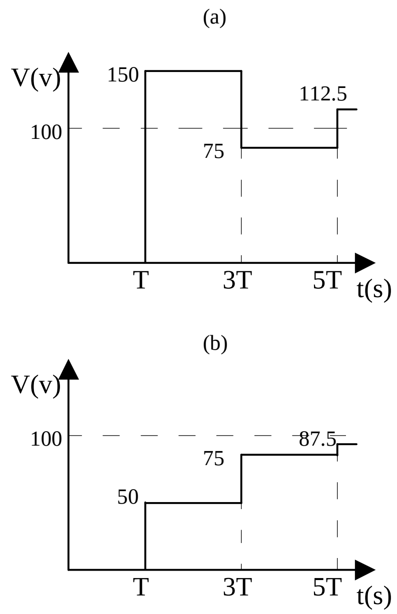


Fig.3. Load voltage for (a) Z_L=90Ω, (b)Z_L=10Ω

For an inverter the input voltage is not a ideal dc source, it is instead a switched voltage. In most of actual inverters configuration, the voltages changes drastically from -*vdc* to *vdc*, where *vdc* is the voltage at the inverter dc link. This switched voltage can be considered in a very simplified manner as a train of pulses which one being of 2pu amplitude either positive or negative (to cause the voltage from 1pu to reach -1pu one a -2pu voltage). For an open-circuit configuration these 2pu pulses will cause a 4pu voltage at the cable terminal. Furthermore, the inverter switching frequency, around some kHz, is much smaller than the cable oscillating frequency, around some MHz(1/2T). Distinct switching pulses will add up causing overvoltages over 4pu, an ideal case with a very high switching frequency can reach up to 6pu. A more precise expression can be developed considering an open circuit configuration and the cable with distributed and frequency dependent parameters. If the voltage at the cable input can be represented by a Fourier series such as:

$$V_{in} = \sum_{n=1}^{\infty} \sin\left(n \cdot \omega \cdot t + \phi_n\right) \tag{2}$$

the output will be given as:

$$V_{out} = \sum_{n=1}^{\infty} \frac{\cosh(\gamma \cdot l)}{\sinh\left(\frac{\gamma \cdot l}{2}\right) \cdot \sinh(\gamma)} \cdot \sin\left(n \cdot \omega \cdot t + \phi_n\right) \tag{3}$$

Where $\gamma = -(ZY)^{1/2}$ is the propagation factor and Z = Z(ω), and Z and Y are respectively the series impedance and shunt conductance per unit of length and l is the cable length. The function in (3) is unbounded, however, in practical applications the switching frequency is limited and so is the output voltage. For a 15kHz switching frequency the maximum output voltage is 3.85pu.

In ASD drive systems the cable characteristic impedance is much smaller than the motor surge impedance. In fact, for most cases, the motor surge impedance can be considered infinite when compared with the cable characteristic one. Thus to analyze the overvoltages in ASD system rather simple motor models for the motor can be used in the simulations.

A. Frequency dependence modeling

The representation of the frequency dependence effect in a cable or transmission line can be carried out either in modal (eigenvector transformation) or phase coordinates. For the sake of simplicity the latter was chosen over the former, though there are no restriction to apply a phase domain model to represent the cable as shown in [1], [4], [5]. The behavior of a transmission line or electric cable is fully described by the first-order differential equations in the frequency domain shown in (4).

$$\begin{cases} -\frac{d}{dx} V = (R + j \cdot \omega \cdot L) \cdot I \\ -\frac{d}{dx} I = (G + j \cdot \omega \cdot C) \cdot V \end{cases} \tag{4}$$

where V and I are the voltage and current vectors, Z = R+jωL and Y = G+jωC are the line series impedance and shunt admittance matrices respectively. The frequency dependent parameters are R(ω) and L(ω). The single-phase model is a particular case where only scalars are involved.

The main advantage of a modal domain model is that each mode behaves like a single-phase line. So it becomes quite easy to extend single-phase models to multi-phase ones. This is also particularly useful when the frequency dependence of the propagation factor and characteristic impedance is modeled via rational-functions synthesis. In EMTP the S-transform Modal domain model is widely known as JMarti model and was developed in the early 80 by Jose Marti [6]. It uses a partial fraction representation of all the function involved, i.e. the propagation factor and the characteristic impedance. The expansion is in a series as follows:

$$H(s) = \sum_{i=1}^{m} \frac{K_i}{s + p_i} \qquad (5)$$

where H(s) can be either the propagation factor or the characteristic impedance. This procedure is equivalent to represent the characteristic admittance or the propagation matrix by a Foster circuit (several RC in parallel).

Due to the cable parameter variation the overvoltage at the cable output is damped and tend to vanish. The ringing effect created by the cable is a direct function of the cable parameters, in fact it is the cable propagation factor that defines this ringing frequency. Fig.4 shows the overvoltage decaying as well as it repeat pattern. This stresses the importance to reduce as much as possible the overvoltage at the load terminal.

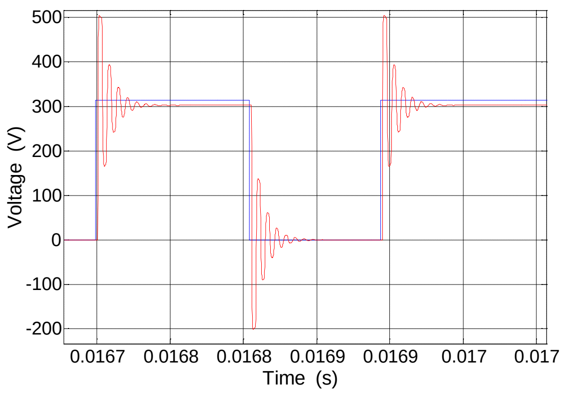


Fig. 4. Drive system voltages.
Blue = inverter output; Red = cable output.

III. Simulation Tests

The system was implemented in the ATP version of the EMTP having as a load a high resistance, induction motor representation. The cable parameters were simulated considering the frequency dependence of its parameters as well as the distributed nature. Although the actual cables used for this application are three-phase pipe types cables, here they were considered to be accurately represented by single-phase models. The cable models uses a frequency dependent line model called JMARTI, where both the characteristic impedance and the propagation factor are represented as function S (Laplace transform) in the modal (eigenvector) domain. Fig. 5 presents the inverter output and the motor voltage. Fig. 4 shows in more detail the rise time and the pick voltage for this case.

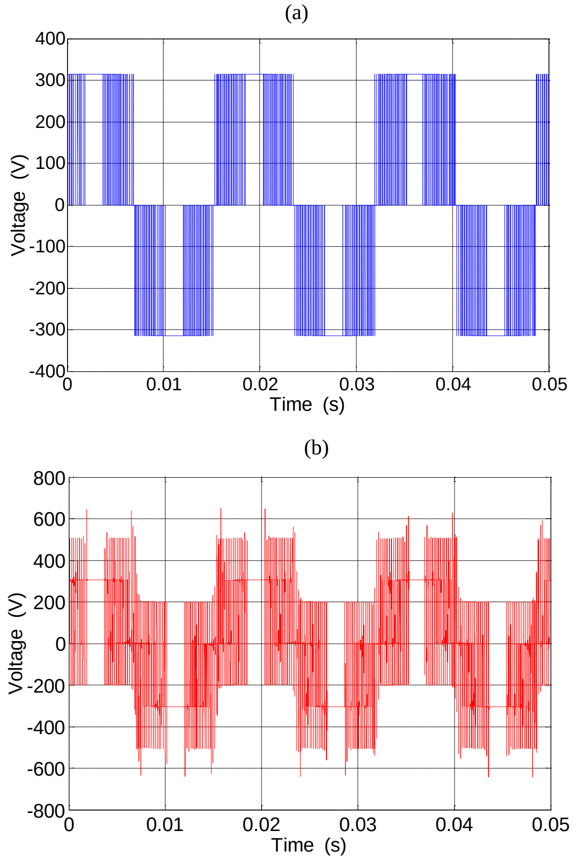


Fig. 5. System Voltage: (a) inverter output, (b) cable output

Fig. 4 shows the cable reflection with losses and should be compared with fig. 3.

A. Passive filters at the inverter output

The use of passive filter is the most common solution to avoid overvoltages [7]. The drawback of this solution is the high cost and the risk of unexpected resonance. Fig. 6 shows the voltage for this system. The value of the filter RC is determinate by approximation given for the ATPLcc program, surge impedance.

B. Impedance matching at the motor terminal

From (1), if Z_L is equal to Z_C then $\rho_S = 0$ and there is no reflected wave. This can be achieved with matching impedance in parallel or in series with the original load. Fig. 7, shows the voltage at the motor when an RC impedance in parallel with the motor terminals is used. The value of this impedance was obtained with the help of the ATPLcc program.

C. Multi-Level Converter

Although only used for high power applications, a multi-level converter is another feasible solution to minimize the overvoltage. It can provide lower *dv/dt* and harmonic content. It is more expensive than using filters since it needs a larger number of switches (semiconductor) which are far more expensive than passive elements. Fig.8 shows the voltage at the inverter output and at the load for a 5-level converter.

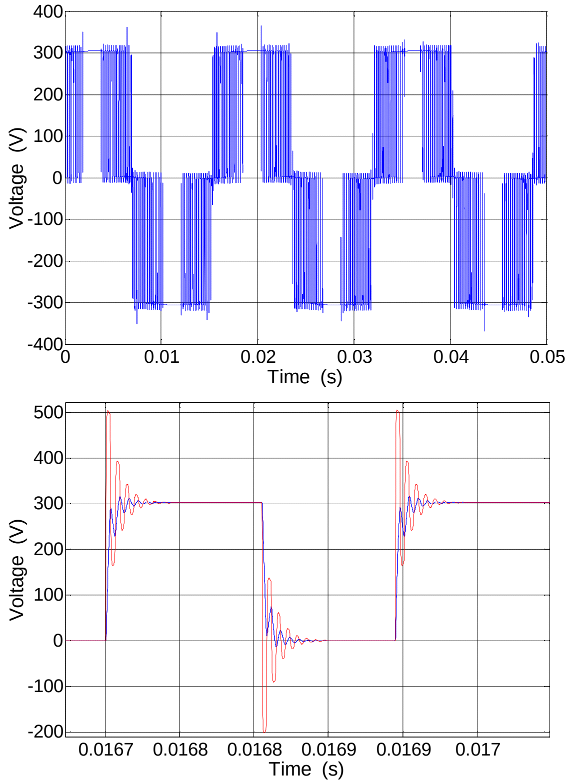


Fig. 6. Output Voltage for the System with Passive Filter RC (Red = without filter; Blue = with filter).

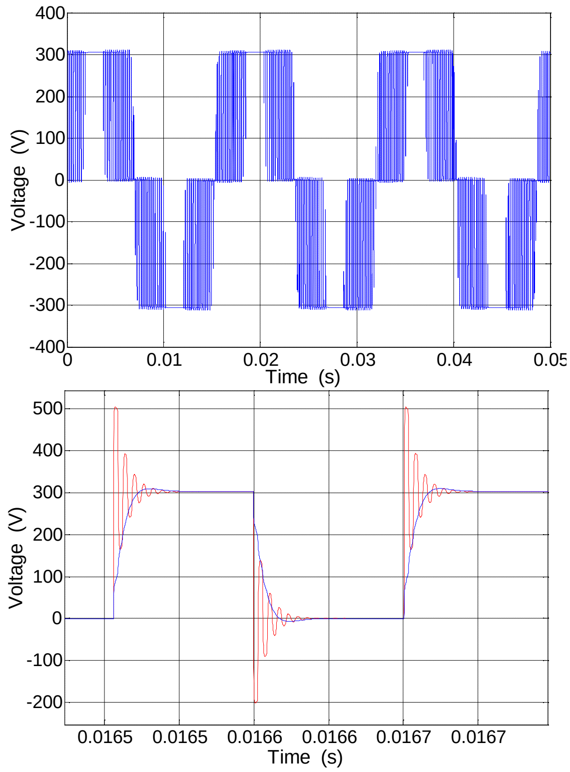


Fig. 7. Output Voltage for the System – Impedance Matching (Red = without Z_{RC}; Blue = with Z_{RC}).

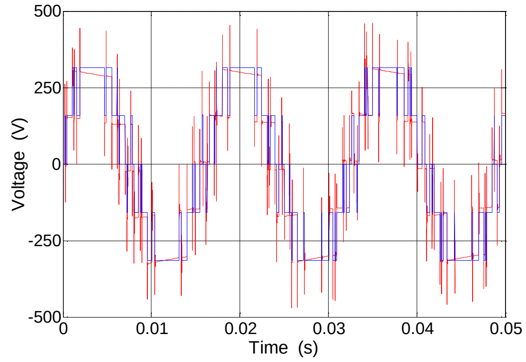


Fig. 8. Input and output voltage for the system with multi-level converter (Blue = inverter output; Red = cable output).

D. Optimum Switching Frequency

Since the converter output voltage can excite resonance throughout the cable, it is also possible to control the converter above such resonance and therefore reduce motor terminal overvoltage. This type of solution involves also frequency domain analyses to determinate which switching frequency the converter should operate. It also involves an increase in the cost since not all switches can operate at such high frequencies. This type of analysis has been presented in [8], [9] and can be summarized in the following way:

- analysis of the harmonic content in the current and voltage;
- identify which harmonic is responsible for the overvoltage;
- modify the switching pattern in a way that this harmonic is not produced.

IV. Experimental Results

Fig. 9 and 10 show in more detail the input and output voltage for the prototype system with a 200m cable and a 1HP motor. The overvoltage is 83%.

The best experimental result to minimize this overvoltage was obtained with a RC matching impedance in parallel with the motor terminals. This result is presented in fig.11.

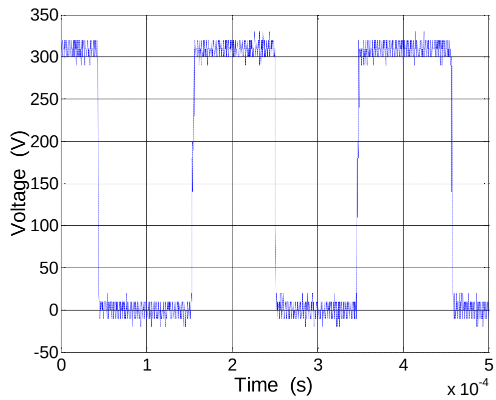


Fig. 9. Inverter Output Voltage

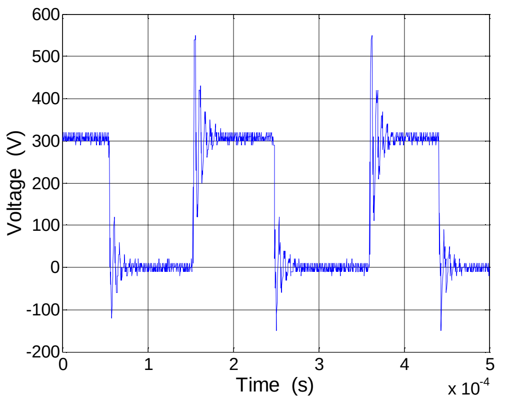
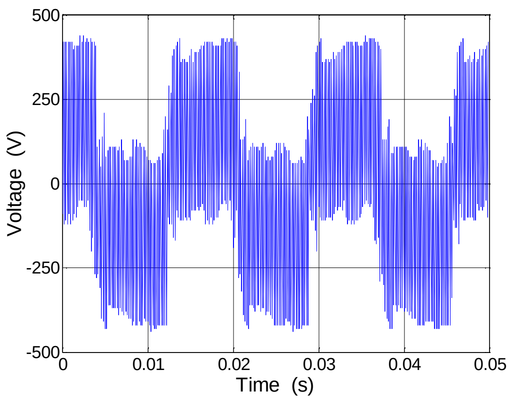


Fig. 10. Motor Input Voltage

(a)



(b)

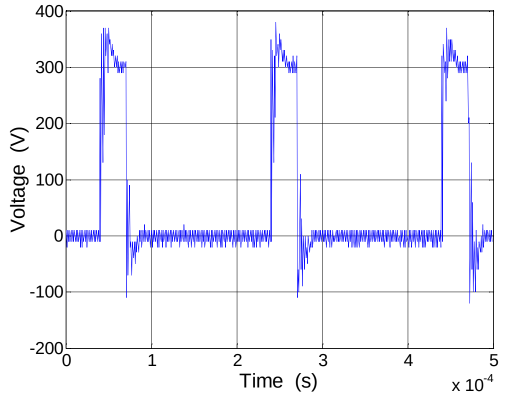


Fig. 11. (a) Motor Voltage (with RC); (b) Voltage Details

V. Conclusion

This paper deals with the analysis and comparison of different techniques to minimize the overvoltage in ASD system with a long cable connecting motor and converter.

For most industrial application, the cable length is under 1km and low costs solutions, such as passive filters, can be implemented. On the other hand, this solution is not so effective in cases where the cable length is greater than 1km, where an optimum switching frequency technique can be applied. The multi-level inverters produce the most efficient output but it is still very expensive representing an option only when high power application is concerned.

VI. Acknowledgment

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