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A new mathematical tool to investigate the influence of cable characteristics and IGBT fast switching on voltage transients and differential mode currents for PWM drives

Saïd Amarir*, Kamal Al-Haddad

Canada Research Chair in Energy Conversion and Power Electronics (CRC-ECPE), École de Technologie Supérieure,
1100 Notre-Dame, Montréal, Québec H3C 1K3, Canada

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Abstract

The authors propose a new mathematical tool to investigate the influence of cable characteristics upon pulse voltage transients and their associated differential mode (DM) currents in PWM long cable drives. Even if reflected wave transient voltages have received considerable investigation for IGBT voltage source inverters, the modeling and simulation of these voltage transients still require precise modeling. Moreover, another consequence of the IGBT fast rise time, which is the resulting high frequency DM current, has not been previously examined in detail for these systems.

This paper presents fully developed mathematical formulas for both pulse voltages and their resulting DM currents at any point along the inverter-to-motor cable. Using the developed formulas, an appropriate tool has been built, using SimPowerSystems (SPS) and Simulink of Matlab software, to predict the high frequency over-voltages and their associated DM currents all along the feeding cable. This tool has then been applied to an industrial 5 kV A PWM drive prototype using a 4-wire shielded long cable. Some simulation results and experimental validations are included.

Keywords: Cables; Over-voltage; Insulated gate bipolar transistors; Pulse width modulation; Variable speed drives

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1. Introduction

In many applications, PWM drives require long motor leads. Consequently, motors often undergo over-voltages stress due to the traveling-waves. These over-voltages increase with the length of the feeding cables (up to a critical cable distance) and the *dv*/*dt* generated by the inverter IGBT switches. In addition to torque oscillation and localized heating problems, they can cause the destruction of the motor insulation, in particular in the early turns. They can also cause partial discharges in the drive-to-motor cable thereby reducing its lifespan [15]. Besides, the reflected waves contribute to the common mode (CM) disturbances and the bearing current problems [17]. As it will be shown in this paper, they are also associated with oscillating currents in differential mode (DM) that have not been previously

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* Corresponding author at: Electrical Department, École de Technologie Supérieure, 1100 Notre-Dame, Montréal, Québec H3C 1K3, Canada. Tel.: +1 514 396 8874; fax: +1 514 396 8684.

E-mail addresses: said.amarir.1@ens.etsmtl.ca (S. Amarir), Kamal.Al-Haddad@etsmtl.ca (K. Al-Haddad).

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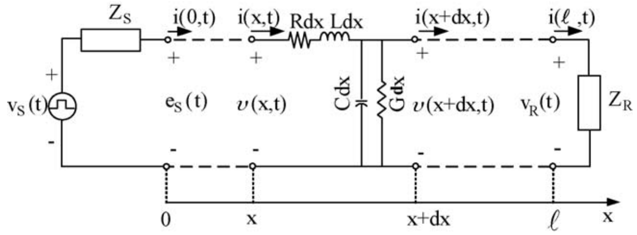

Fig. 1. ASD-motor equivalent single-phase circuit representation.

examined in detail. The frequency range of these parasitic currents can go up to several MHz (depending on the cable length). As a result, electromagnetic interferences in CM and DM, which are common problems in these systems, become more threatening.

Historically, traveling-wave problems have been studied using graphical Bewley diagrams, also known as Lattice diagrams [15]. Since this method was poorly adapted to computer analysis, other methods have started appearing in the literature. In these methods, differential equations of lumped elements L and C of the transmission line were transformed into algebraic difference equations using the trapezoidal rule of integration [5]. But these methods appeared to be poorly adapted so as to represent a distributed parameters line. The Electromagnetic Transient Program (EMTP) software method has long been the best suited for digital computer analysis. Indeed, it does not use reflection coefficients but instead it uses a line model [9]. In the latter method, an exact solution requires that the time propagation τ should be an integer multiple of the calculation step Δt ($\tau = k\Delta t$; k integer). Moreover, it is difficult to use this method to determine the voltage transient at any point x along the cable.

In the last decade, the application of the traveling-wave theory to ASD systems has been addressed by several researchers. Qualitative analysis relating to this phenomenon has been reported in the literature [7,8] as well as the impact of the phenomenon on the motor and/or the cable [4,6,10,19]. Some mitigation techniques, especially to design output filters capable of matching the cable's characteristic impedance [1,13], have also been proposed. Some authors focused on the frequency modeling of the motor and resorted to known traveling-wave methods to analyze over-voltage at the motor terminals [11–14,18–20]. The cable was often represented by multiple π equivalent sections. The cable eigen frequencies will increase with the number of π sections. But, as more sections are added, the step time must be very small to get accurate results. This implies convergence problems, as well as longer time simulations. Recently, the authors have developed a precise modeling technique to evaluate the impact of high frequency over-voltages along the feeding cable in PWM drives [2,3]. Besides, in Ref. [3] an approach to measure the cable, inverter and motor required characteristics has also been presented.

This paper consists mainly in extending the technique presented in Ref. [3] to investigate the influence of cable characteristics, not only upon pulse voltage transients, but also on their associated DM currents. Firstly, it offers new methods of direct and fast calculation of the over-voltages and currents due to the traveling-waves. Secondly, the maximum peak voltage, the oscillation frequency, the critical cable length and the parasitic DM current amplitude have all been determined. Finally, a mathematical tool is built in SimPowerSystems (SPS/Simulink) of Matlab to model voltage and current as well as their derivatives (*dv*/*dt* and *di*/*dt*) at any point along the cable. It takes into account the cable characteristics, the motor and inverter impedances at high frequency, the rise and fall times of the inverter output pulse voltages and also the PWM carrier frequency. The proposed tool has been applied to an industrial 5 kV A prototype, therefore obtaining valuable experimental and simulation results.

2. Frequency domain analysis of traveling voltage waves and its DM associated current

In a typical PWM motor-drive system, at each inverter state variation, the connection between the inverter and the motor can be represented by the equivalent single-phase circuit as shown in Fig. 1. In this figure, $v_S(t)$ is an impulse voltage that represents the inverter output signals. The cable is represented by infinite infinitesimal single-phase portions with a length dx; ℓ being the cable length. Z_S is the inverter impedance and Z_R the motor impedance which can be observed between phases at an operating point. $\upsilon(x,t)$ and $i(x, t)$ represent the voltage and current vs. time t at a given point x units away from the sending end. R and G, respectively are the cable resistance and conductance per unit