A Multi Conductor Transmission Line Model for the Evaluation of the Rotor Shaft Voltages in Adjustable Speed Drive Motors

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Abstract—The use of switching devices, such as IGBTs, characterised by high switching frequencies and very low switching times in new generation pulse width modulation (PWM) inverters has increased the efficiency and performances of Adjustable Speed Drives (ASDs) for industrial and traction applications. However, such systems may be affected by disadvantages like over voltages at the motor terminals, when long cables are used between the drive, and the generation of rotor shaft voltage, due to the capacitive couplings in the motor (between the windings and the rotor and between the rotor and the stator). The shaft voltage may cause the breakdown of the lubricating film in the bearings. The resulting impulsive currents, by damaging the bearing elements shorten the component life, which in turn seriously affects the ASD reliability. For this reason, it is of great importance to develop numerical models able to predict the shaft voltage so as to estimate the currents flowing through the bearings. Several works, based on either concentrated or distributed circuit models, have been proposed for the evaluation of the shaft voltage magnitudes for several motors sizes. However, the results obtained by such approaches suffer from approximations and simplifications in the considered circuit model. Therefore, in the present paper, a numerical model able to accurately predict the shaft voltage in high power induction motor for traction applications fed by a PWM inverter is presented. The windings of the motor are modelled by a multi conductor transmission line (MTL), whereas the cables between the source and the motor are described by a single transmission line. The effect of wave propagation and reflection and of the frequency-dependent distributed losses is considered by using a time-domain equivalent circuit to represent the MTL. A semi-analytical method, based on the perturbation theory of the spectrum of symmetric matrices, is adopted. The parameters of the MTL are obtained either analytically or numerically by using a commercial software (Maxwell® by Ansoft). The effects of the rise time of the input voltage together with the length of the cables are considered.

1. Introduction

A drive system composed of a traditional induction motor matched to a pulse-width modulated (PWM) inverter can overcome the limitations of induction motors operating directly on line voltage, consisting essentially in a nearly constant, unadjustable output speed and in a small starting torque, drawing a large starting current. By feeding the motor with a variable ac voltage and a variable ac frequency, thus obtaining an adjustable-speed drive (ASD), most requirements of modern drives can be satisfied. More recently, such systems have reached a great diffusion, which can be mostly associated to the rapid development of new switching devices, such as the insulated gate bipolar transistor (IGBT), which have led to increased efficiency, performance and controllability in medium voltage, medium power induction motor applications, such as traction, cranes for port operation, etc.

Unfortunately, the output voltage from the inverter is not purely sinusoidal and, in particular, steep front pulses can be generated in correspondence to the commutations of the switching devices. Slew rates (dV/dt) of about $2500\,\mathrm{V}/\mu\mathrm{s}$ can be produced, resulting in overvoltages at the motor terminals and in critical stresses of the motor electrical insulation which can lead to a sensible reduction of the life-time of the machine [1].

Furthermore, it should be considered that such pulses can excite the capacitive coupling between the stator and the rotor, resulting in shaft voltages, even 20 times larger than those observed when feeding the motor with a pure sinusoidal waveform. The shaft voltages may cause the breakdown of the lubricating film in the bearings. The resulting impulsive currents, by damaging the bearing elements can shorten the component life, which in turn seriously affects the ASD reliability.

For design purposes, it seems, therefore, of great importance to provide the electrical engineers with a model able to predict the voltage distribution in the motor windings and evaluate the electrical stresses on the rotor shafts as a function of many geometrical and electrical parameters, such as the stator insulation dimension, the length of feeding cable, shape of the applied voltage, insulating material permittivity etc.

The model developed by Melfi et al., [2] is based on a representation of the motor winding as a lumped network; in order to preserve its physically distributed nature, the parasitic coupling between the stator and the rotor has been modelled over a range of frequencies. Also Lipo et al., [3] have used an equivalent lumped parameter π-network to describe the parasitic coupling phenomenon. They remark that the parasitic coupling circuits are the same as transmission line circuits, but a distributed parameter circuit is not suitable for a simplified analysis of the bearing currents.

The present paper is dedicated to the illustration of a machine model based on the representation of the motor winding as a connection of multiconductor transmission lines. The model is able to predict the voltages across the rotor shaft, taking into account the main phenomena occurring along the lines, such as the propagation and the reflection, together with the time dispersion introduced by the losses, eventually dependent on the frequency. The solution technique is accurately described in many papers [4]; it consists of a semi-analytical method based on the perturbation theory of the spectrum of symmetric matrices. The MTL lines are described by their characteristic $\mathbf{R}$, $\mathbf{L}$, $\mathbf{C}$, and $\mathbf{G}$ per unit length matrices, that is, in the Laplace domain by the longitudinal impedance $\mathbf{Z}(s) = \mathbf{R} + s\mathbf{L}$ and transverse admittance $\mathbf{Y}(s) = \mathbf{G} + s\mathbf{C}$.

The authors explicitly remark that the paper is dedicated to the illustration of the model and its potentiality but, at present, not to the estimation of the shaft voltages in the motor operating conditions. In fact, as discussed in the following sections, the results of the simulations have been obtained by feeding the machine not with a typical three-phase inverter output voltage, but providing a single-phase ramp voltage with variable slew rate. It is the author's opinion that the findings are still extremely significant since they can describe the effects of slew rate (dV/dt) of the input voltage together with the length of the feeding cable adopted. Simulations in real operating conditions, together with experimental verifications will be the subject of future works.

In the following, section 2 is dedicated to an illustration of the basic model, together with a brief description of the solution technique; in section 3 the results of the numerical simulations are illustrated; the last section contains remarks, comments and proposals for the future activity.

2. The Model

A schematic representation of the model is reported in Fig. 1. An ideal ramp voltage generator is connected through a feeder cable to the motor. The stator winding is represented by a form wound stator coil, composed of conductors of rectangular cross section; it faces the rotor iron laminations; the rotor is connected to a pair of bearings represented in the picture by their equivalent capacitance C_{b1} and C_{b2}.

The system can be studied (Fig. 2) as single transmission line, representing the cable, connected to four multiconductor transmission lines in series placed in the slot and overhang regions of the machine. Further details can be found in [5] by Lupò et al., The MTL are composed of n conductors; the n-th conductor represents the rotor iron.

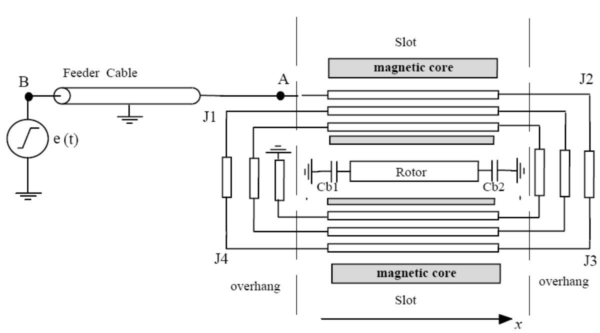

Figure 1: Schematic representation a motor phase.

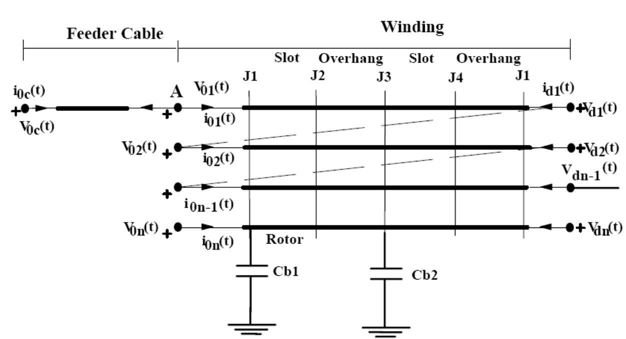

Figure 2: MTL model of the machine.

The multiconductor line can be studied in the time-domain by means of a $2n$-ports representation (Fig. 3) described by Eqs. (1) and (2) [4]:

$$\begin{cases} \mathbf{i}_0(t) = \int_{0^-}^{t^+} \mathbf{Y_c}(t-\tau)\mathbf{v}_0(\tau)d\tau + \mathbf{j}_0(t) \\ \mathbf{i}_d(t) = \int_{0^-}^{t^+} \mathbf{Y_c}(t-\tau)\mathbf{v}_d(\tau)d\tau + \mathbf{j}_d(t) \end{cases} \tag{1}$$

$$\begin{cases} \mathbf{j}_0(t) = \int_{0^-}^{t^+} \mathbf{P}(t-\tau)[-2\mathbf{i}_d(\tau) + \mathbf{j}_d(\tau)]d\tau \\ \mathbf{j}_d(t) = \int_{0^-}^{t^+} \mathbf{P}(t-\tau)[-2\mathbf{i}_0(\tau) + \mathbf{j}_0(\tau)]d\tau \end{cases} \tag{2}$$

The impulse responses $\mathbf{Y_c}(t)$ and $\mathbf{P}(t)$ are defined as:

$$\begin{cases} \mathbf{Y_c}(t) = \mathbf{L}^{-1}[\mathbf{Y_c}(s)] = \mathbf{L}^{-1}\left[\sqrt{\mathbf{Z}^{-1}(s)\mathbf{Y}^{-1}(s)}\mathbf{Y}(s)\right] \\ \mathbf{P}(t) = \mathbf{L}^{-1}[\mathbf{P}(s)] = \mathbf{L}^{-1}\left[\exp\left[-d\sqrt{\mathbf{Y}(s)\mathbf{Z}(s)}\right]\right] \end{cases} \tag{3}$$

where $\mathbf{Y_c}(s)$ is the characteristic admittance and $\mathbf{P}(s)$ is the propagation function.

$\mathbf{Y_c}(t)$ and $\mathbf{P}(t)$ can be found as a sum of their principal part, i. e., the parts containing terms as Dirac pulses, and a remainder evaluated by performing a numerical inverse transform. The solution can be achieved by means of a recursive approach since at time instant t the state variables $\mathbf{j}_0(t)$ and $\mathbf{j}_d(t)$ are known because they depend on the values assumed at time instant $(t-T)$ by themselves and by the currents, where T is the propagation time delay.

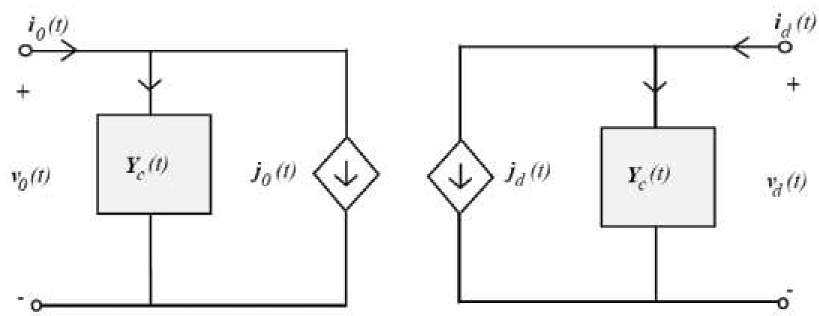

Figure 3: 2n-ports representation of a MTL.

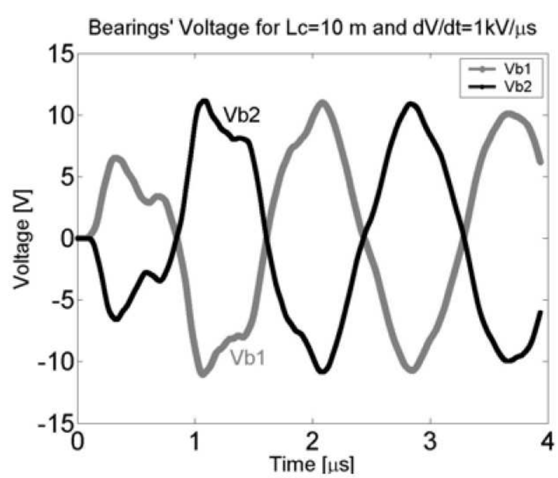

Figure 4: Bearings' voltages $V_{b1}(t)$ and $V_{b2}(t)$.

3. Results of Numerical Simulation

The numerical simulations have been carried out on a traction motor characterised by 9 conductors per slot. The applied voltage has a maximum value Emax= 750 V and a variable slew rate chosen in the interval (0.5÷2.0 kV/μs); the length Lc of the feeder cable varies between 5 m and 15 m. The equivalent capacitances Cb_1 and Cb_2 are chosen equal to 5 nF. Prior to the numerical simulation the p.u. length matrices, **C** and **L** have been evaluated with the software packing Maxwell® by solving, respectively, an electrostatic and a magnetostatic problem.

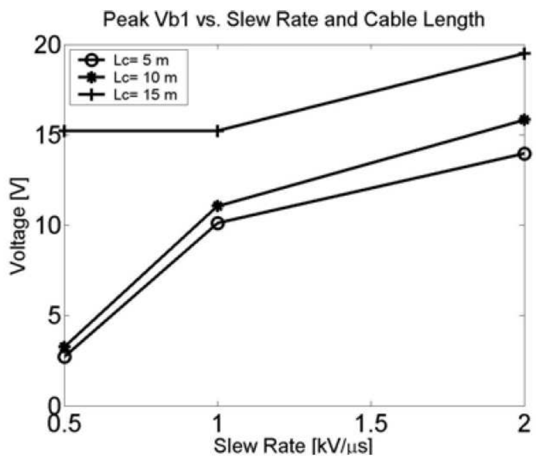

Figure 5: Peak value of Vb1 vs dV/dt and Lc.

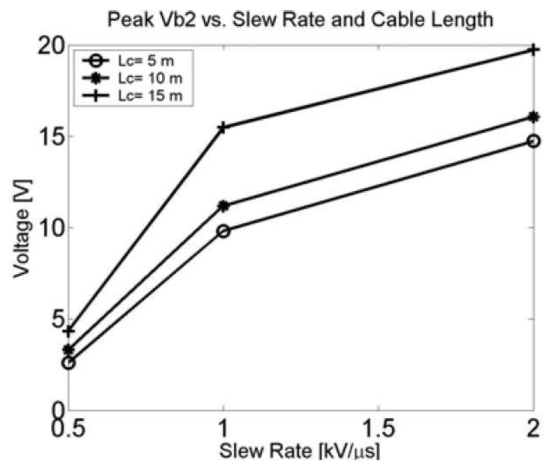

Figure 6: Peak value of Vb2 vs dV/dt and Lc.

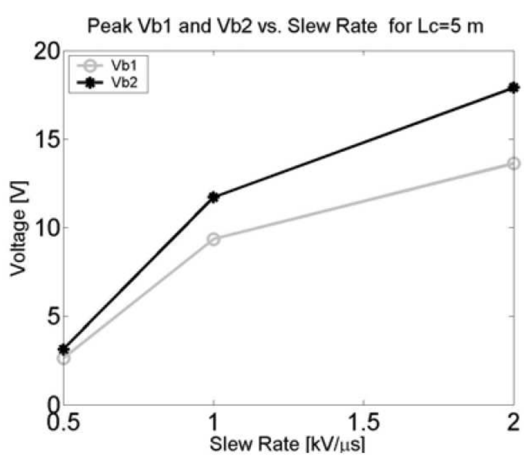

Figure 7: Peak value of Vb1 and Vb2 vs. dV/dt.

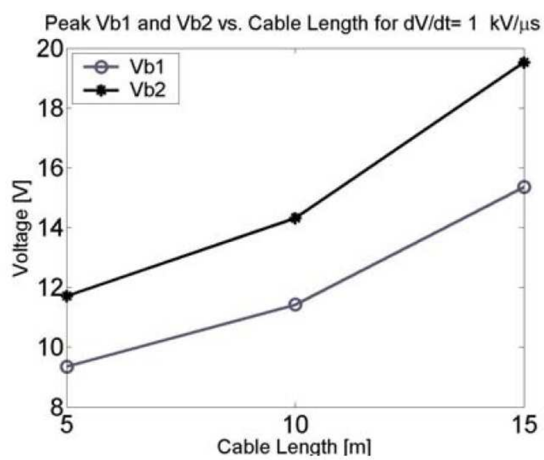

Figure 8: Peak value of Vb1 and Vb2 vs. Lc.

As an example of the results obtained, in Fig. 4 the time evolutions of the voltage $V_{b1}(t)$ and $V_{b2}(t)$ across the two bearings are reported when dV/dt = 1 kV/μs and $Lc = 10$ m. Voltage $V_{b2}(t)$ is slightly delayed with respect to $V_{b1}(t)$, due to a propagation delay of about 40 ns.

Since the main parameter influencing the breakdown phenomena in the lubricating film in the bearings is the maximum amplitude Vm of the voltage, in Figs. 5 and 6 the peak values of V_{b1} and V_{b2} are reported as a function of the slew rate and the cable length.

In particular, it is evident that critical situations can be reached with long cables and high slew rates: the peak voltages can be almost 5 times higher with $Lc = 15\,\text{m} - \text{dv/dt} = 2.0\,\text{kV}/\mu\text{s}$ if compared with $Lc = 5$ m and dv/dt = 0.5 kV/μs. Furthermore, the peak voltages can be different for the two bearings and, as a consequence, the breakdown phenomena can occur only in one bearing.

Such a difference is amplified when the bearings' capacitances are not equal, for instance when bearings of different type are installed (bearings produced by diverse manufacturers, standard or insulated bearings, new or aged bearings, etc.). In fact, when introducing in the simulations two values for such capacitances (Cb1=4 nF;

Cb2=5 nF), the difference in the peak values of Vb1 and Vb2 is strongly evident, as shown in Figs. 7 and 8. In particular, the dissimilarity between peaks of Vb1 and Vb2 grows with the slew rate and the length of the feeding cable.

4. Conclusions

The present paper describes an equivalent MTL model able to predict the shaft voltages in high power induction motor for traction applications fed by a PWM inverter. By feeding the motor with an ideal ramp voltage generator, it is possible to derive significant information on the voltages across the motor bearings; their peak values strongly depend on the slew rate of the applied voltage and on the length of the connecting cable. The effect of different bearings' capacitances has also been evidenced. Further work is in progress in order to introduce a typical three-phase inverter output voltage and to clarify the effect of other parameters like the amplitude of the applied voltage, the electrical characteristics of the cables, the geometrical parameters of the machine.

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