About the High-Frequency Interferences produced in Systems including PWM and AC Motors

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Abstract: - This work analyses the operation of inverter-fed asynchronous motor drives accompanied by high-frequency interferences caused by parasitic currents of the common and differential modes. These emissions propagated by conduction and radiation may unfavorably affect the operation of nearby telecommunication and signal cables and various low-current devices. The study of these phenomena is based on theoretical considerations and numerical analysis.

Key-Words: - AC Motor, High-frequency Interferences, Parasitic Phenomena, Common Mode Currents, Differential Mode Currents, PWM, EMI.

1 Introduction
Application of advanced semiconductor elements in the modern voltage inverters allows substantial raise of their switching frequency. Consequently, the voltage pulses reach considerably high values of $du/dt$ (often more than 10 kV/µs). The situation in a system consisting of the pulse width modulation (PWM) inverter, feeding cable and AC motor is then strongly influenced by its leakage capacitances and characterized by circulation of the high-frequency parasitic common and differential mode currents.

These currents may produce, beside various overvoltages and growth of additional losses in the motor and inverter, electromagnetic interferences (EMI) propagated into the surroundings as conducted and radiated emissions. These interferences signals are divided into two groups: those produced by harmonics up to 9 kHz and those generated by very fast changes of voltage in the semiconductor devices (in the intervals 9÷150 kHz and 150 kHz ÷ 30 MHz) [1], [2].

The electromagnetic interferences can unfavorably affect operation of the telecommunication or signal cables parallel with the supplying power cable and also other near low-current devices. Analysis of the indicated phenomena is extremely difficult and requires correct mathematical models of all parts of the system. This includes good distributed parameter representations of both AC motor and feeding cable and a sufficiently sophisticated model of the inverter. At present, several separate high-quality models exist enabling the modeling of the different elements of the system (cable, AC motor) [1], [4]. The inverter influence itself and the behavior of the whole system have not systematically been studied yet.

2 Problem Formulation
In PWM voltage source inverters, the common and differential mode currents occur simultaneously in their standard mode of operation. Their paths are shown in Figure 1.

2.1 Common and Differential Mode Mechanism
The common mode currents are generated by the output voltage pulses of the inverter. The wave forms of the pulses are trapezoidal, with very high values of $du/dt$ following from the switch-on and switch-off times of the power semiconductor elements [3], [5].

The changes of voltages on different parasitic capacitances produce the common mode currents passing through earth, in the power and/or other elements back to their source as shown by Figure 2.

The figure contains a simplified equivalent diagram of one phase of the inverter for the common mode.
If the LISN (Line Impedance Stabilization Network) isolating the stage of the drive, is used as a fixed artificial network and measurement point, these currents are observed as the common mode noise. The differential mode currents are excited by semiconductor current pulses characterized by steep peaks of reverse recovery currents of free wheeling diodes. These currents (flow via phases of the AC motor and/or through the DC link of the inverter) generate the differential mode noise at the LISN, shown in Figure 3.

In order to generate the common mode currents, a specific control strategy is used. The strategy imposes that all three inverter output terminals are connected simultaneously to either plus or minus bus bar of the DC link. The voltage changes of $U_d$ occur on the parasitic capacitance between the AC motor and ground producing the common mode interferences. The Figure 4 shows an interesting trapezoidal voltage pulse of the inverter.

Both described strategies can be used for excitation of the common and differential modes separately. The PWM strategies for AC motor drives, however, are produced simultaneously within the fundamental period. Thus, the special measuring circuits or techniques are employed for separation of these modes.

3 Problem Solution

3.1 Analytical and numerical models

The high-frequency lumped-parameter model of the AC motor [2] consists of two parts similar in their structures but generally different in parameter values. Starting from that model, the equivalent circuits for both modes (for frequency range up to about 1 MHz) were suggested, in common with their transfer functions [4], [6].

This AC motor model can be generalized by assuming similar blocks connected in series. Such a model may better simulate operation of the AC motor within a substantially wider range of frequencies. Firstly, it is necessary to determine appropriate values of the parameters of the model for $n$ greater than 3. This represents a difficult problem even with the knowledge of the measured AC motor data; the feeding cables may be analyzed using models with distributed parameters and respecting their dependence on frequency. However, the complexity of the system models comprising the cable and AC motor becomes substantially higher. The
Inverter may be represented in the respective frequency range either by its circuit model [3] or by a transfer function in the frequency domain [4]. An appropriate circuit model must include elements representing all relevant parasitic links manifesting themselves in the high frequency range.

With respect to difficulties associated with the finding of the circuit elements values; the second approach seems to be more convenient. Figure 6 shows the transfer characteristics between points A and B (Figure 2) for the common mode, measured at the inverter. This figure shows the amplitude of the output signal for injected AC input signal with the amplitude of 100 mV. The curve may be viewed as a frequency transfer characteristic with the amplitude lower than 1. The transfer function may be used for the prediction of the interference spectra produced by different parts of the drive.

In order to analyze the whole drive in the frequency domain, all its principal parts (inverter, cable, AC motor) have to be represented there together with their mutual interactions. So, the cable frequency characteristics themselves and the AC motor in a wide frequency range, influence the principal parts of the drive along the total frequency domain. The interference fields themselves are regularly 3D and non-stationary. Their distribution is mostly described by non-linear second-order partial differential equations of the (depending on the frequency of the field quantities) elliptical, parabolic or hyperbolic types. The present methods for solution of such tasks are based, therefore, on certain simplifying assumptions: 1) any back influences of the disturbed parts are neglected, 2) the sources of EMI as well as all surrounding media have linear properties (their values are independent of the frequency and field quantities), 3) solved are only the steady states; for example, the inverter is supposed to deliver a series of voltage pulses having the character of a perfectly periodical function. The series of voltage pulses is first decomposed into individual harmonics for which the corresponding common and differential current responses have to be found. The following step is to find the time dependencies of the common and differential mode currents. This is, particularly in case of the distributed parameter representation of the system, often possible only by means of suitable numerical methods (the finite element method, FEM, or special procedures for the back Laplace transform).

The high frequency field computation starts from the Maxwell equations:

$$\begin{align}
\text{rot}\left(\frac{1}{\mu} B\right) &= J + \varepsilon \frac{\partial E}{\partial t}, \\
\text{rot} E &= \frac{\partial B}{\partial t}.
\end{align}$$

(1)

These equations are generally non-linear and time-dependent. Because of the eddy currents induced in the shielding sheaths or grounded metal constructions, the field has to be described by magnetic vector potential A. Due to high frequencies, the displacement currents should also be respected in the first Maxwell equation. The equation describing the vector potential distribution (derived from the system of equations (1)) produced by respective current harmonics then reads:

$$\nabla \times \frac{1}{\mu} \nabla \times A + j \omega \gamma A - \varepsilon \omega^2 A = J,$$

(2)

where: $\varepsilon$, $\gamma$ and $\mu$ denote the permittivity, electrical conductivity and permeability of the medium, respectively, and J denotes the amplitude of the field current density of the given harmonic in the power cable.

Uniqueness of solution of the equation (1) is assured by imposing the correct boundary conditions. The described electromagnetic field generally shows 3D features and must be determined for a wide spectrum of important harmonics. That is why a simplified way of computation is often used consisting in the solution of a series of 2D fields in selected sufficiently large planes perpendicular to the direction of the cables. The discretisation of these planes is much easier and due to constant parameters of all media, the calculations run at a substantially higher rate. The field distribution between any two neighbor planes may be determined by suitable interpolation.

### 3.2 Results

For the EMI determination on used the scheme from the Figure 7. The AC motor is connected to the inverter through a cable (of varying lengths). The inverter was fed from a bridge rectifier via a DC link.

The controller provides the possibility to control each of the inverter elements independently in accordance with the strategy selected.
The inverter can work not only with the PWM strategy, but also generates either only common or only differential mode disturbances. The Figures 8 and 9 show the common mode interference spectra detected at the measurement point in the LISN for two different lengths of the feeding cables (l_c = 2 m and 30 m) with: (a) the inverter in operation; (b) the inverter with the feeding cable and (c) the inverter feeding the AC motor through the cable.

Two main peaks (around 350 kHz and 6.5 MHz) may be recognized at the frequency spectrum for the inverter working alone, without any load. From these figures one can see that the longer is the cable, the higher is the level of the common mode interference and while for the longest cable the spectra is measured without and with the AC motor.

With growing lengths of the cable the current flowing via the stray capacitances of the cable to ground, increases too. For a certain length of the cable the contribution of the AC motor leakage current to the total current is almost negligible, except for the range of lower frequencies (below a few hundreds of kHz).

The character of the spectra between 70 and 300 kHz is practically the same with non dependency of the cables lengths feeding the AC motor. The second dominating part of the characteristics (around 5.5, 2.5 and 1.5 MHz) depends on the cable length (2 and 30 m, respectively). The lower frequency at about 70 kHz of transients does not depend on the cable length, the higher frequency changes in dependence on the cable length and in accordance with the spectra is shown in Figures 8 and 9 (5.5 and 2.5 MHz).

The Figure 10 compares the amplitude frequency spectra measured at point A (see Figure 2) for the common and PWM modes. For the cable length l_c = 10 m, one may observe that the complete noise spectrum for the applied PWM strategy is similar to that for the common mode.

Although the differential mode is also contained in the PWM mode, the PWM emission level is below that for the common mode. The reason is that the real waveforms of the PWM switch cycles have not a constant repeat frequency and the voltage change of U_d between the AC motor case and ground, occurring regularly in the common mode, is only occasional here; mostly only the change of U_d/3 is generated in the PWM
mode. The contribution of the differential mode conducted emissions included in the total interference of the PWM mode is lower than that of the common mode.

4 Conclusion
This work indicates the methodology of the interferences evaluation and discusses the advantages and the drawbacks of various models. The mechanisms of both common and differential current modes have been explained and a way of producing these modes independently by means of a suitable inverter control strategy is introduced.

The work target was a possibility to evaluate the levels of the interference spectra of both modes and to compare the contributions of the different parts of the drive to the total emission level.

The main result is that the AC Motor influences the emission level particularly up to (0.5 ÷1) MHz, while the feeding cable is decisive for the waveforms of the amplitude frequency spectra.

References: