Modeling of Differential-Mode and Common-Mode Characteristics for EMI/EMC Analysis Applied to a High-Frequency Induction Motor

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Abstract: Power semiconductor commutations often become sources of conducted Electromagnetic Interference (EMI) in adjustable speed drivers (ASD). Every switching operation of power devices in the inverter imposes high values of dV/dt for power cables and induction motors. Such voltage variation causes high frequency currents to flow between the motor phases (Differential Mode currents) and also between motor windings and the ground through stray capacitive links (Common Mode currents).

In this paper, equivalents circuits of the three phase induction motor high frequency are presented; the proposed model detailed separately the common Mode and differential mode characteristics AC electrical motor. The high-frequency model has been obtained by means of a frequency domain analysis using MATLAB program.

Index Terms - Common mode, differential mode, electromagnetic compatibility, High frequency, Induction motor

1. INTRODUCTION

Because of rapid changes in voltages and currents within a switching converter, power electronic equipment is a source of Electromagnetic Interference (EMI). The conducted EMI noise in a PWM inverter can be viewed as consisting of two parts, differential mode (DM) noise and common mode (CM) noise, which are illustrated in Fig. 1. The dV/dt at the midpoints of the three legs of the inverter is normally identified as CM noise source. The dV/dt caused by the switch turn on /turn off, coupled through the parasitic capacitance between the IGBT collector and the module base-plate that is normally grounded through the heat-sink, generate CM noise current.

The CM noise current flows into the ground and through the stray capacitance inside the motor to the motor frame and back to the source via the power mains. The CM noise current also flows into the ground and through the stray capacitance inside.

The power supply and back to the noise source. The dI/dt in the DC bus is normally identified as DM noise source. This change of current is also caused by the switching operation of the inverter. The DM noise current flows into power supply and back to the inverter. The DM current also flows through the motor phase windings, and through the stray capacitance inside the motor,
and then back to the power mains via the DC bus and the rectifier.

For the analysis of conducted EMI it is necessary to use the precise models of the different left from the adjustable speed driver (ASD). One of the mains propagation paths is constituted by the AC motor.

In the paper a high frequency model of induction motor is presented, in the first time the authors are presented a simple model based on classical high frequency models [3] is mainly defined for common and differential mode path. Nevertheless, this approach allows defining the impedances of the motor windings.

In the second time a particular discussion is required about the value of the inductance L (Skin effect in windings) to presented complete model of induction motor, the identified HF motor parameters provided by this work can be considered as a useful reference database for the drive designers interested on conducted EMI problems in inverted-fed AC motor systems. The results has been obtained using MATLAB program.

2. COMPONENTS MODELS

In this section the RF models for inductors are investigated. Finally the general selection guide of the components used in radio frequencies is given.

The impedance of an ideal inductor is given in the following equation:

\[ Z = j \cdot \omega \cdot L \]  

(1)

The frequency response of impedance Z as shown in Fig. 2.

The impedance magnitude of the inductor increases linearly with frequency at a rate of +20 dB/decade and the phase angle is +90° for all frequencies.

Generally inductors are more problematic than capacitors. For simplicity, an equivalent circuit model for a real inductor is given in Fig. 3. We can see that at low frequencies the resistance dominates and then the impedance is replaced by \( R_{par} \).

As the frequency increases, the inductance begins to dominate at

\[ f_1 = \frac{R_{par}}{2 \cdot \pi \cdot L} \]  

(2)

and the impedance increases at 20 dB/decade while the angle is +90° (Fig. 4). As frequency is further increased, the impedance of the parasitic capacitance decreases until its magnitude equals that of the inductor. This occurs at the self-resonant frequency of the inductor:

\[ f_2 = \frac{1}{2 \cdot \pi \cdot \sqrt{LC_{par}}} \]  

(3)

The impedance of inductor is given in the following equation:

\[ Z(p) = \frac{L \cdot p + R_{par}}{LC_{par} \cdot p^2 + R_{par} C_{par} \cdot p + 1} \]  

(4)
3. AC MOTOR MODEL

Classical frequency models for the induction motor are used in [4]. It is proposed below to develop an AC motor model adapted to a wide range of frequency. This will be developed by taking into account all phenomenon described above; in order to obtain a coherent behavioral model in a representative frequency range of conducted EMI [5].

The model used in this first part is defined from an equivalent diagram by phases in which the \( L_d \) inductance doesn't correspond precisely to the value of the clean inductance of coil. Indeed, to determine this parameter, the three phases of a machine are connected in parallel. In this part the various electrostatic couplings which intervene in the motor are to be exposed.

There are capacitive couplings between:
- windings,
- windings and the iron core,
- stator and rotor [8].

We can also mention the other parasitic couplings in the motor:
- Magnetic coupling between windings, and their evolution according to frequency,
- distributed capacitive effects,
- skin effects in windings,
- bearing currents.

With the descriptions of these main stages the motor impedance characteristics can be represented.

4. ANALYSIS OF THE MOTOR IMPEDANCE

The conducted electromagnetic interference (EMI) is classified into two types of differential-mode (DM) and common-mode (CM).

Common-Mode (CM) noise flows via two supply lines in the same direction and returns via the ground wire. Common-mode propagation in the induction motor take place between the three phase terminals connected together and the ground terminal, with floating motor neutral.
Differential-Mode (DM) noise flows in via two supplies in opposite directions, Differential-Mode propagation in the induction motor take place between the three phase terminals connected together and the motor neutral, with floating ground terminal.

The high frequency model of the induction motor consists of 3 differential mode impedances \( Z_{DM} \) and 3 common mode impedances \( Z_{CM} \) with connection to the earth.

### 4.1. Differential Mode Characteristic

The model of the impedances \( Z_{CM} \) is obtained by observation of the variations of the impedance \( Z_{AG} \) with the frequency when the windings of phases A and B are short-circuited and when the phase C is not connected (Fig. 6) [1].

According to such an equivalent circuit Differential mode current and voltage are linked by the following expression in the Laplace domain:

\[
Z = \frac{V_{DM}(p)}{I_{DM}(p)}
\]

\[
Z_{pp} = \frac{1}{3} \frac{L \cdot p}{L(C_p + \frac{C_{g1}C_{g2}}{C_{g1} + C_{g2}}) p^2 + \frac{L}{R_p} p + 1}
\]

The differential mode impedance has a zero in the origin and a pair of complex conjugate poles with natural frequency:

\[
F_{N(PG)} = \frac{1}{2\pi \sqrt{L(C_p + \frac{C_{g1}C_{g2}}{C_{g1} + C_{g2}})}}
\]

The evolution of the differential mode impedances of the motor as a function of the frequency is represented in Fig. 7.

Figure 7 shows model data of the impedance of induction motor, the impedance peak (resonance) is at 500 kHz, impedance values from 10 kHz up to 100 kHz correspond to inductance values decreasing from 250 mH down to 2.5 mH by simply equation:

\[
L = \frac{Z}{\omega}
\]

For frequencies higher than 500 kHz the impedance is determined by capacitive coupling among the phases.

### 4.2. Common Mode Characteristic

The variations of the impedance \( Z_{AB} \), when phases A and B are series-connected and without connection to the earth (fig. 8), allows building a model of \( (2Z_{DM} \parallel 2Z_{CM}) \).

The impedances \( Z_{CM} \) of the motor in
common mode configuration shown in Fig.8 can be expressed by equation:

$$Z = \frac{V_{CM}(p)}{I_{CM}(p)}$$  \hspace{1cm} (9)

$$Z_{pg} = \frac{L(C_p + C_{g1})p^2 + \frac{L}{R_p}p + 1}{6C_{g2}p(L(C_p + \frac{C_{g1}C_{g2}}{C_{g1} + C_{g2}})p^2 + \frac{L}{R_p}p + 1)}$$  \hspace{1cm} (10)

Two characteristic frequencies are extracted from the phase-ground impedance. The first one \(F_{N(PG)}\) represents the natural frequency of the \(Z_{pg}\) numerator that minimizes the impedance (Resonances of the common mode impedance). A similar frequency \(F_{D(PG)}\) is obtained from the denominator and defines the impedance resonance (Resonances of the differential mode impedance).

$$F_{N(PG)} = \frac{1}{2\pi \sqrt{L(C_p + C_{g2})}}$$  \hspace{1cm} (11)

$$F_{D(PG)} = \frac{1}{2\pi \sqrt{L(C_p + \frac{C_{g1}C_{g2}}{C_{g1} + C_{g2}})}}$$  \hspace{1cm} (12)

The simulation results shown in Fig.9 confirm the frequency response of the impedance \(Z_{pp}\).

As can be observed in Fig. 9 the common mode impedance decreases as the switching frequency decrease. This is the reason why common mode currents became a serious problem in high switching frequency drives [3].

The impedance values at low frequencies provide \(C_e = 4.4 \, nF\) by equation:

$$C = \frac{1}{\omega Z}$$  \hspace{1cm} (13)

with \(C = (\frac{C_p + C_{g1}}{C_{g1} + C_{g2}})\).

The common-mode inductance \(L_e\) is determined from the resonance frequency at 66 kHz:

$$L_e = \frac{1}{\omega^2 C} = 2.1 \, mH$$

5. CONCLUSION

In the analysis of conducted electromagnetic interference, the impedances and the transfer behaviour of all parts of common mode and differential mode coupling paths between source and target of EMI must be known. The goal of this work was developed a behavioural model of the motor using the high frequency model. Certain elements were added to take into account the motor parasitic elements (essentially capacitive and due to skin effects). The CM currents became a serious problem in high switching frequency drives.

So as to predict and imagine EMI reduction solutions it is necessary to modelling the complete system: inverter-fed AC motor, on a range of frequency going up to 10 MHz. The next application of this work is to modelling energy cables, shielded or unshielded.

If it is easy to find models allowing simulating the High Frequency behaviour of cables shielded or unshielded intended to transmit information.

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