

TUTORIAL

Induction Motor and PMSM Models with High-Frequency Effect

May 2020

1. Overview

Inverters designed with modern technology use devices (IGBT, SiC-IGBT, MOSFET, and other semiconductors) operating with high dv/dt and di/dt that cause electromagnetic interference (EMI) in a motor drive system.

Consequently, undesirable current components circulate in both differential mode (DM) and common mode (CM). The CM leakage current leads to electromagnetic emission problems, and the DM current impacts the system operation causing surges in the voltage waveform and cable or motor failures.

This document describes how to use induction motor and PMSM models in studies that take into account the high-frequency effect. Together with other models such as the ac cable and the inverter with added parasitic components, the models make it possible to observe the EMI components and the overvoltage at the motor terminals caused by the reflection effect produced by the long cable between the inverter and the motor. Additionally, the model includes the electrical model of the bearing, which allows the evaluation of the current circulating through the mechanical element caused by the high-frequency noise.

Examples are provided to show how to use the models to analyze the EMI effect on the common mode current, as well as noise attenuation when filter stages are added. Different options to decrease the EMI effect are presented: LSIN (line stabilization impedance network), and inverter output filter.

Finally, the appendix briefly describes the experimental steps to obtain the high-frequency parameters of the motors.

2. EMI Analysis of Motor Drive Systems

Fig.1 is a general scheme of an adjustable speed drive that shows current circulating paths due to high-frequency emissions considering all sections: power transformer connection, grid converter, intermediate DC-bus, power inverter, AC cable, and ac motor (induction motor or PMSM). A special configuration of a long-cable-fed induction motor drive system is considered to evaluate EMI emissions.

A power inverter generates common mode EMI on the three-phase output lines by hard switching with very high dv/dt that depend on the rising time of IGBTs and system voltage. As a result, Electromagnetic Compatibility (EMC) troubles are evident due to the parasitic components and operation considerations.

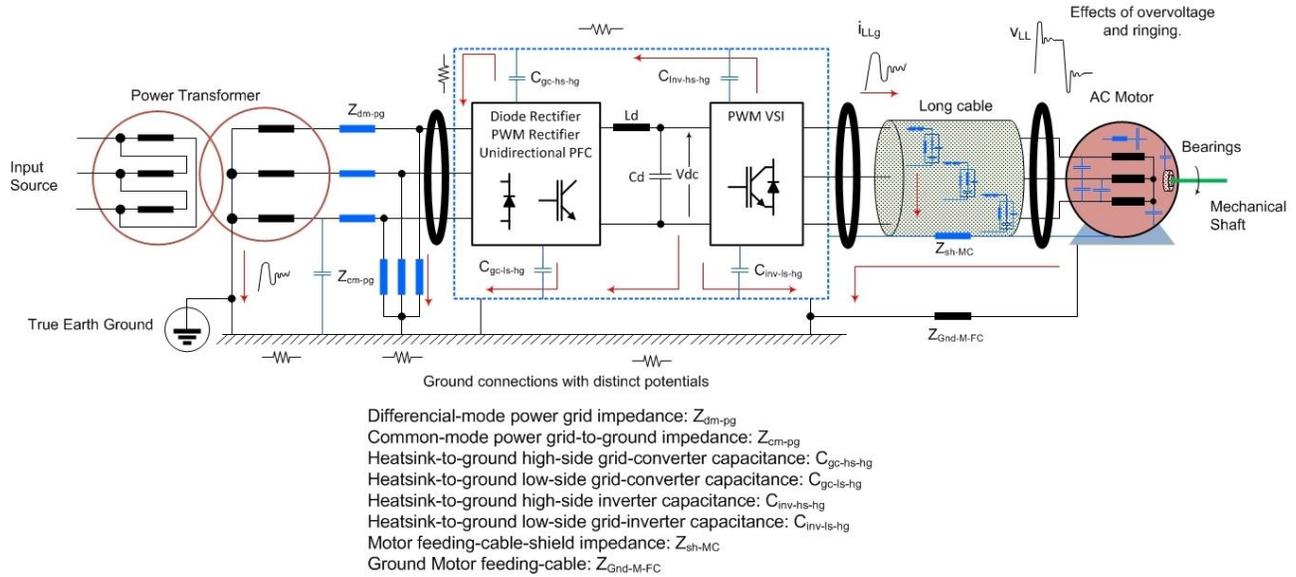


Fig. 1: EMI emissions in an adjustable speed drive

3. High-Frequency Induction Machine Model

Fig. 2 is the image of the high-frequency induction machine model in PSIM. The stator windings are connected in Y with the neutral node accessible. The common node *comm* is used for the external earth connection.

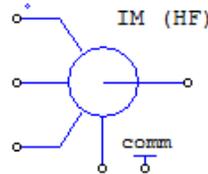


Fig. 2: PSIM symbol of the high-frequency induction machine model

The required attributes of the high-frequency model of the induction motor are:

| Table I. High-frequency induction machine model parameters | | |
|--|-------------------------------|---------------|
| Parameter | Description | Default Value |
| R_s (stator) | Stator resistance | 0.294Ω |
| L_s (stator) | Stator leakage inductance | 1.39mH |
| R_r (rotor) | Rotor resistance | 0.156Ω |
| L_r (rotor) | Rotor leakage inductance | 0.74mH |
| L_m (magnetizing) | Magnetizing inductance | 41mH |
| No. of Poles P | Number of poles | 6 |
| Moment of Inertia | Moment of inertia | 0.4 |
| Master/Slave Flag | Master-slave flag | 1 |
| C_g (winding-ground) | Winding-to-ground capacitance | 190pF |
| R_g (winding-ground) | Winding-to-ground resistance | 1000KΩ |

| | | |
|----------------------|---|-----------------|
| R_e (eddy current) | Resistance representing eddy current loss | 17.49k Ω |
| R_t (skin effect) | Resistance representing skin effect | 0.324k |
| L_t (skin effect) | Inductance representing skin effect | 0.27mH |
| C_t (skin effect) | Capacitance representing skin effect | 29pF |

Experiments can be conducted to obtain the model parameters. The procedure is briefly described in the Appendix.

In the model parameters, R_e is associated with the iron losses caused to eddy currents inside the magnetic core. The composite circuit containing R_t , L_t , and C_t captures the second resonance in the frequency response, which may be caused by the skin effect and capacitance of the stator winding. Meanwhile, R_g (dissipative effect) and C_g (winding-to-ground capacitance) networks represent the measured parasitic components of each phase and of the stator neutral with respect to the motor frame (common point).

Table II provides the high-frequency parameters of typical induction motors under different power ratings.

| Ratings [HP] | R_e [K Ω] | R_t [K Ω] | L_t [mH] | C_t [pF] | R_g [Ω] | C_g [pF] |
|--------------|---------------------|---------------------|------------|------------|--------------------|------------|
| 2 | 3.9 | 0.324 | 0.27 | 29 | 15.3 | 290 |
| 3 | 5.6 | 1.15 | 2.7 | 31.4 | 35.5 | 314 |
| 7.5 | 3.3 | 0.94 | 0.21 | 70 | 36.2 | 700 |
| 10 | 1.4 | 0.086 | 0.09 | 70.4 | 23.2 | 704 |
| 40 | 2.5 | 0.1 | 0.48 | 26.1 | 12 | 260 |

4. High-Frequency PMSM Model

Fig. 3 is the image of the high-frequency PMSM model with the bearing model included. The stator windings are connected in Y with the neutral point accessible. The common terminal *comm* is used for the external earth connection.

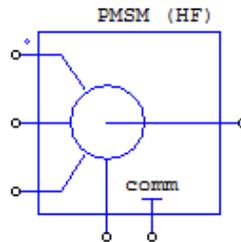


Fig. 3: Image of the high-frequency PMSM model

The parameters of the model are listed below.

Table III. High-frequency PMSM model parameters

| Parameter | Description | Default Value |
|---------------------|--------------------------------------|---------------|
| Rs | Stator resistance | 0.636Ω |
| Ld | d-axis inductance | 2.6mH |
| Lq | q-axis inductance | 3.2mH |
| Vpk/krpm | Peak line-to-line back EMF constant | 45.3 |
| No. of Poles P | Number of poles | 4 |
| Moment of Inertia | Moment of inertia | 2e-4 |
| Shaft Time Constant | Shaft time constant | 5 |
| Initial Rotor Angle | Initial Rotor Angle | 0 |
| Master/Slave Flag | Master-slave flag | 1 |
| Csd | d-axis differential mode capacitance | 2.1nF |
| Csq | q-axis differential mode capacitance | 1.7nF |
| Cs | Phase winding stray capacitance | 1.1nF |
| Rcomm | Common mode resistance | 0.24 Ω |
| Lcomm | Common mode inductance | 0.95mH |
| Ccomm | Common mode capacitance | 7.3nF |
| Rb | Bearing resistance | 10 Ω |
| Cb | Bearing capacitance | 185pF |
| Zb | Bearing impedance | 2.25M Ω |

Unlike the high frequency induction motor model, the PMSM model (HF-PMSM) contains the electric model of the bearing.

Similarly, experiments can be conducted to obtain the model parameters. Refer to the Appendix for more information.

The capacitances Csd and Csq reflect the differential mode effect in the d and q axes.

The common mode parameters are determined by measuring the input impedance between the motor three-phase windings connected together and the motor frame. Rcomm is the leakage resistance.

The capacitance Cs is the stray capacitance in the phase winding. Ccomm is defined as the common mode stray capacitance between the windings and motor frame, and Lcomm can be determined using the relationship $(1/6)*(Ld+Lq)$.

The electrical model of the bearing consists of the resistor Rb in series with Cb and Zb in parallel.

5. AC Cable Model

There are two ac cable models in PSIM library represented: **3-ph AC Cable** and **3-ph AC Cable (1)**. The image is shown below.



Fig. 4: Image of the cable model in PSIM

In the image, the bottom node *N* or *n* on each side of the cable is the cable screen. It is generally connected to the ground on the side of the cable.

The parameters for the model **3-ph AC Cable** are described below.

| Table IV. Parameter of the model 3-ph AC Cable | |
|--|---|
| Parameter | Description |
| Cable Length | Length of the cable, in m |
| Operating Frequency | Operating frequency of the cable, in Hz |
| Resistance Rd | Positive sequence resistance Rd of the cable, in Ohm/km |
| Reactance Xd | Positive sequence reactance Xd of the cable, in Ohm/km |
| Capacitance Cd | Positive sequence capacitance Cd of the cable, in F/km |
| Resistance Ro | Zero sequence resistance Ro of the cable, in Ohm/km |
| Reactance Xo | Zero sequence reactance Xo of the cable, in Ohm/km |
| Capacitance Co | Zero sequence capacitance Co of the cable, in F/km |

The cable parameters should be available from manufacturer’s datasheet. When they are not available, assuming that each phase of the cable has a resistance of *R*, self-inductance of *L*, and mutual inductance of *M*, the positive sequence and zero sequence parameters can be calculated as follows:

$$R_d = R$$

$$X_d = \omega \cdot (L - M)$$

$$R_o = R$$

$$X_o = \omega \cdot (L + 2M)$$

where $\omega=2\pi f$ and *f* is the operating frequency in Hz.

The parameters for the model **3-ph AC Cable (1)** are described below.

| Table V. Parameters of the model 3-ph AC Cable (1) | |
|--|--|
| Parameters | Description |
| Number of Sections | Number of sections. Parameters below are for each section. |
| Cable Length | Length of the cable per section, in ft or in m |
| DC resistance | DC resistance per unit length (Rs), in Ohm |

| | |
|----------------------------|---|
| Inductance | Inductance per unit length (L_s), in H |
| Phase-to-phase Capacitance | Phase-to-phase capacitance per unit length (C_{ph}), in F |
| Ground Capacitance | Phase-to-ground capacitance per unit length (C_{gnd}), in F |
| Shield DC Resistance | Shield resistance per unit length (R_{shield}), in Ohm |

The models of the AC cable allow to represent a lumped or distributed connection according to the assigned parameters.

The circuit schematic in the Fig.4 shows the equivalent circuit for each section.

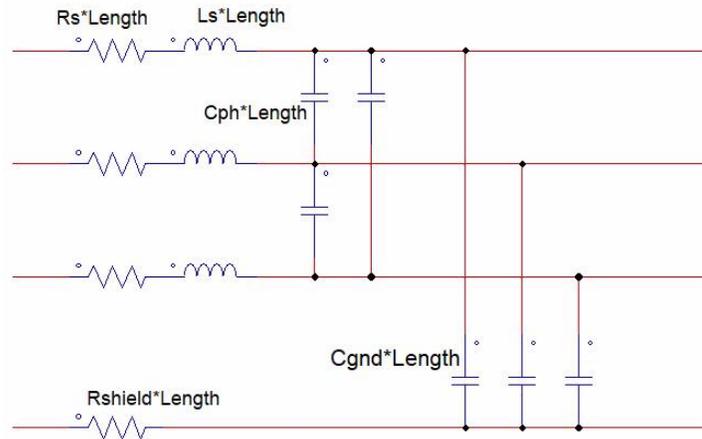


Fig. 5: Equivalent circuit for each section of the 3-ph AC Cable (1)

6. Parasitic Components of the Inverter

Inverter EMC components are considered as shown in Fig. 6. In the figure, L_e is the parasitic inductance of the emitter and C_{ch} is the stray capacitance between collector terminal and grounded heatsink of the each IGBT. Values used in the examples in this tutorial are: $L_e = 7.5nH$, and $C_{c_h} = 0.1nF$.

To model the switching transient of the inverter power devices, the IGBT Level-2 model is used. The serial component of the DC bus filter capacitor is taken into account.

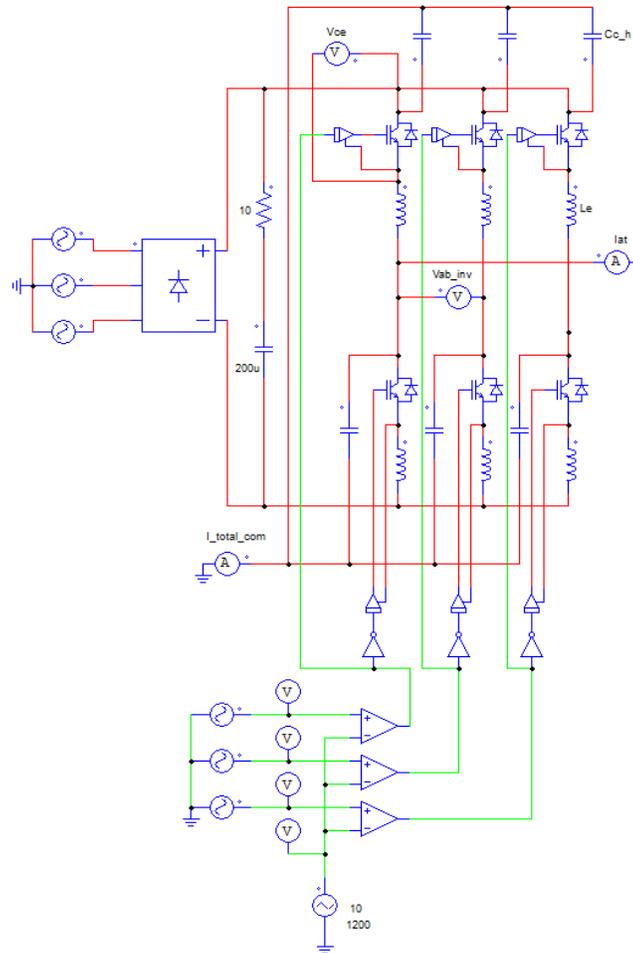


Fig. 6: Inverter model for EMI analysis

7. Simulation Examples

Files of the examples below are available in the **examples >> Motor Drive** folder.

7.1 High-Frequency Induction Motor Drive

Evaluating the EMI Effect:

This example is to evaluate the EMI effect of an induction motor drive. The example file is: “Induction motor drive with cable and high-freq motor model.psimtech”.

The system diagram is shown in Fig. 7. The case allows the evaluation of the EMI effect using the high-frequency models of the inverter, the ac cable, and the induction motor.

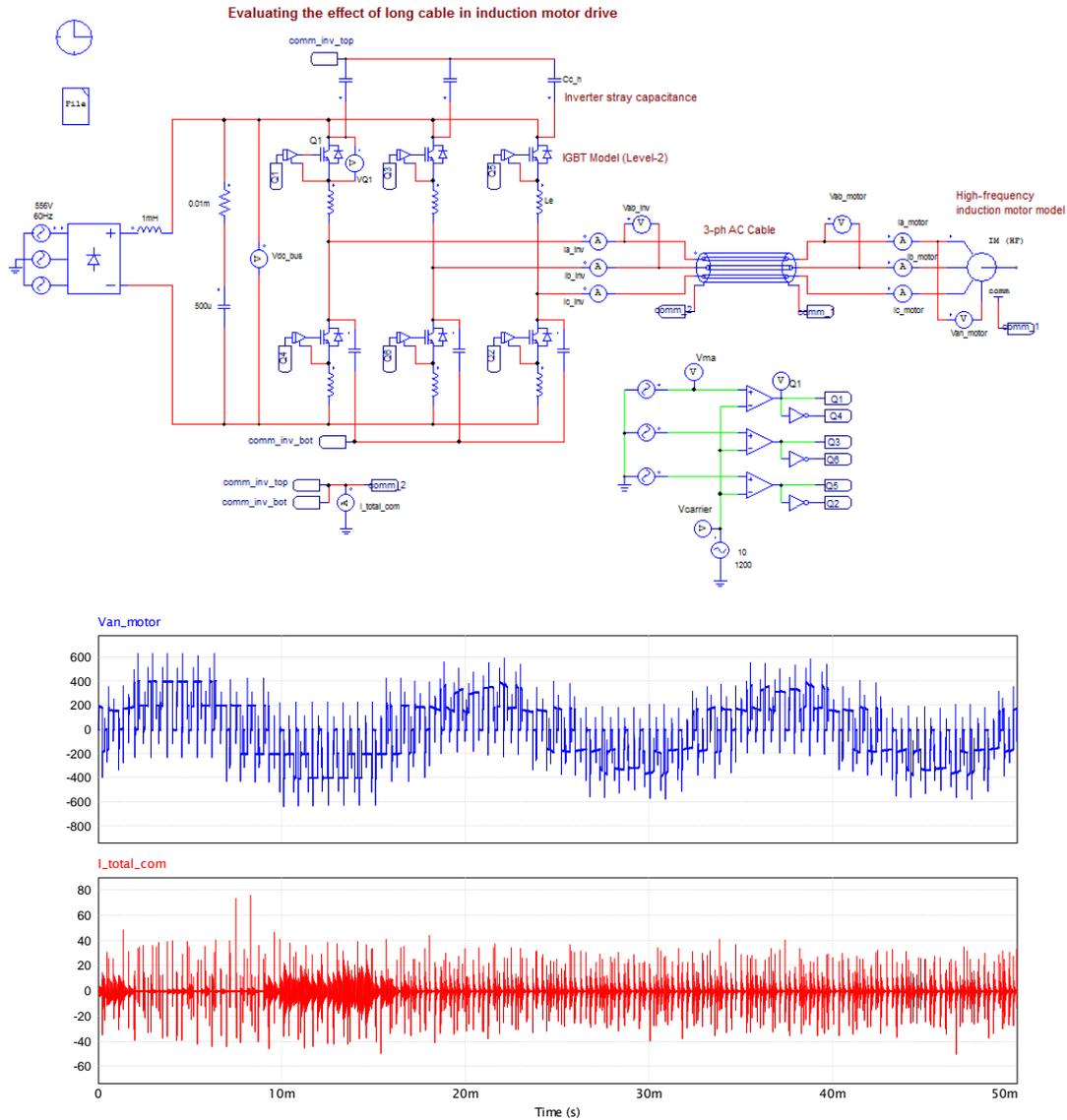


Fig. 7: Top: Induction machine motor drive with high-frequency models; Bottom: Motor terminal voltage and common-mode current

The results show the presence of the high-frequency components in the common mode current from the inverter and induction motor cable array interference components as well as the overvoltage effect on the motor terminals.

Reducing the EMI effect and Motor Terminal Overvoltage with a filter:

This example shows how a filter can be used to reduce the EMI effect and the motor overvoltage. The example file is “Induction motor drive with cable and high-freq motor model (filter).psimsch”.

The scheme and the results of the simulation are shown in Fig. 8. Unlike the previous circuit, the filtering stage is added at the inverter output, designed to remove the overvoltage at the terminals of the motor. Although the high-frequency components still exist, the reduction in the peak values of the common mode current can be observed.

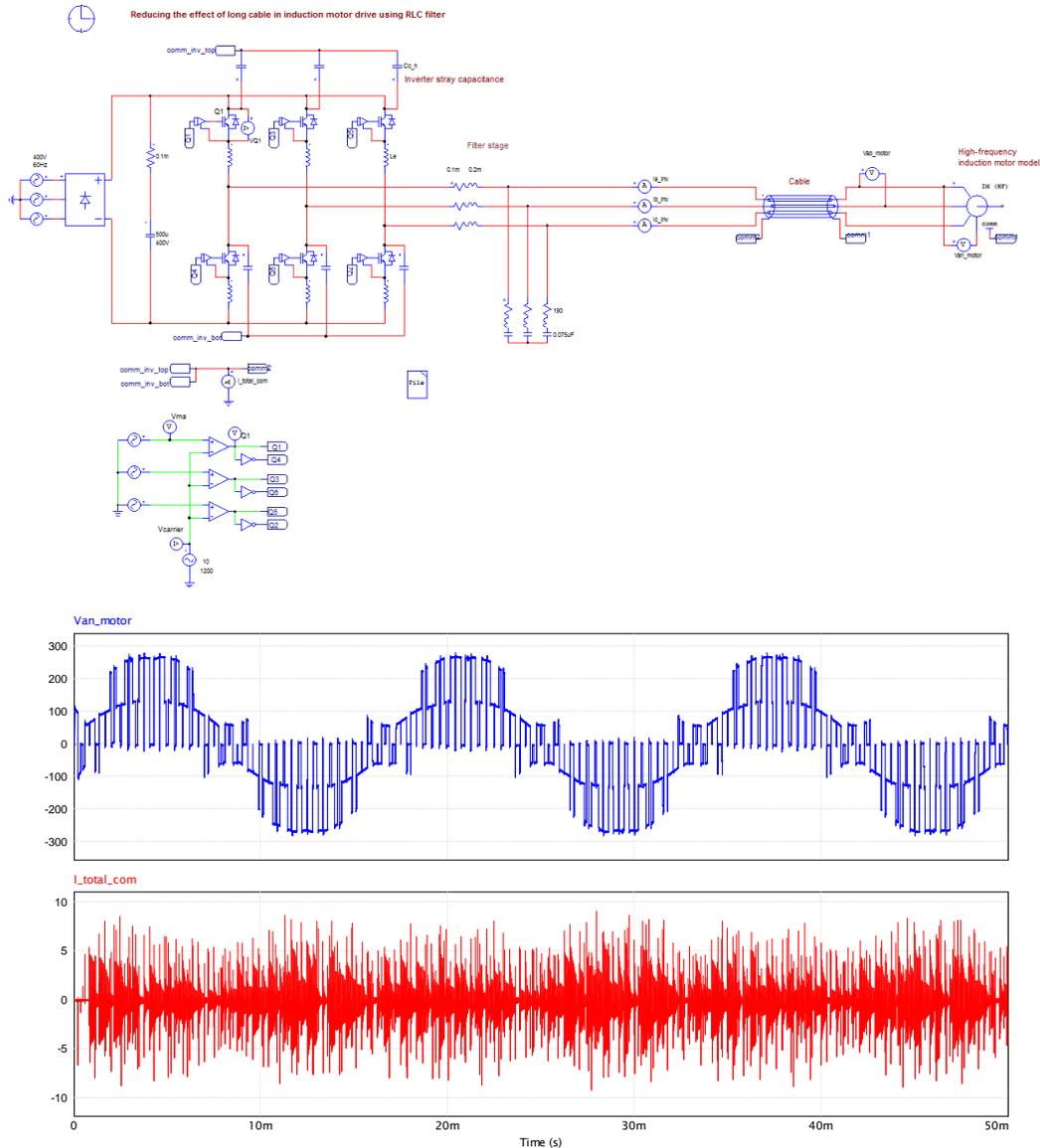


Fig. 8: Top: Motor drive system with the output filter; bottom: Motor terminal voltage and common-mode current

7.2 High-Frequency PMSM Drive

Evaluating the EMI Effect:

This example uses the high-frequency PMSM model to evaluate the EMI effect of a PMSM drive. The example file is “PMSM drive with cable and high-freq motor model.psimsch”.

The power stage and the control unit of the motor drive are shown in Fig. 9. Similar to the induction motor, the power stage contains the parasitic components in the inverter, the high-frequency cable, and high-frequency PMSM model. The bearing is included in the PMSM model.

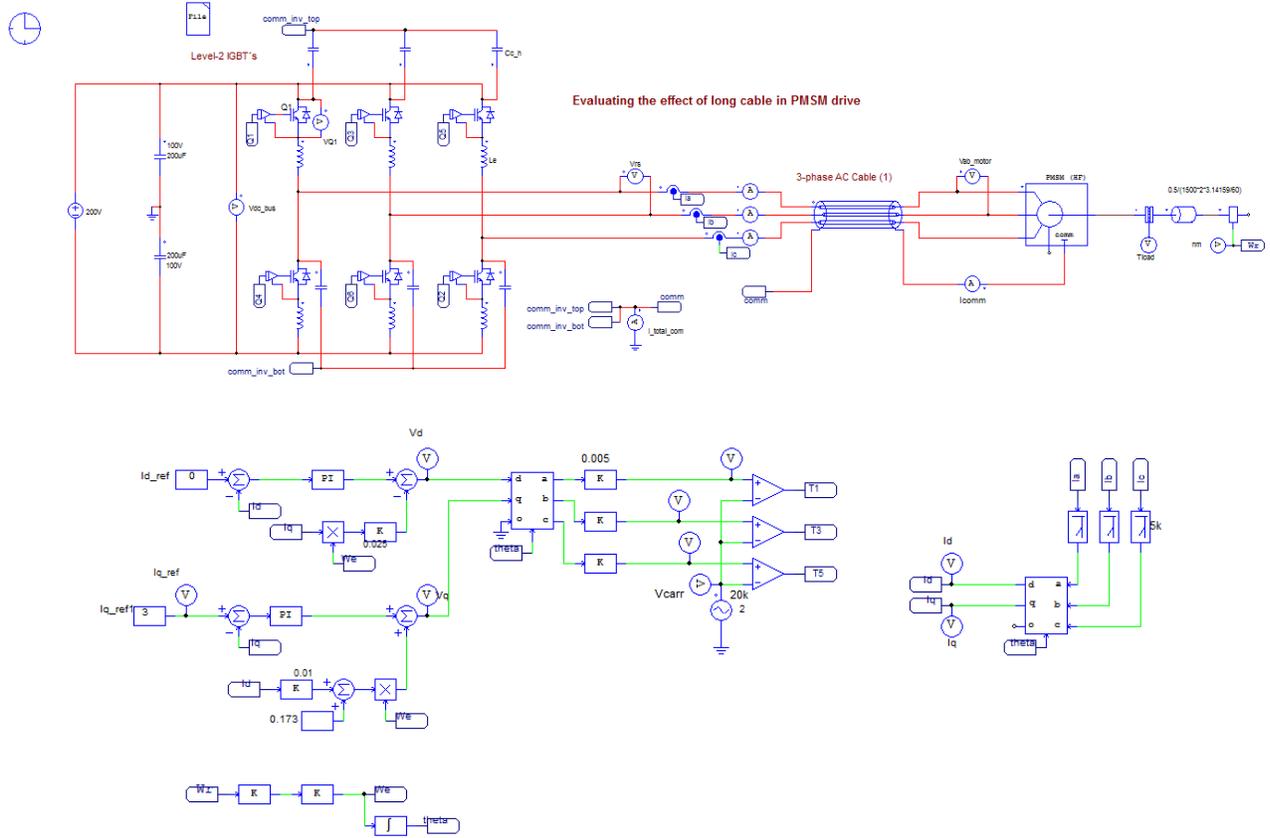


Fig. 9: The PMSM drive with the high frequency models

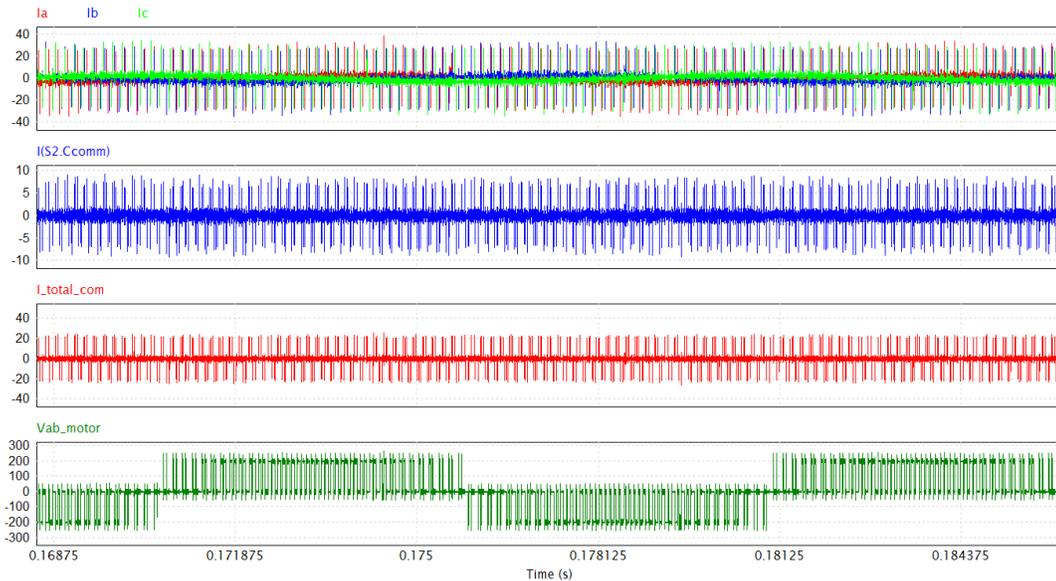


Fig. 10: The currents and voltage in the motor drive system

Reducing the EMI Effect and the Motor Terminal Overvoltage with Filters:

In this example, LISN and inverter output filters are added to see their effect on reducing the EMI components and the overvoltage. The example file is “PMSM drive with cable and high-freq motor model (filter).psimsch”.

In the system, a LISN stage is added on the dc side and a filter on the inverter output, as shown below. The control unit remains unchanged from the previous example.

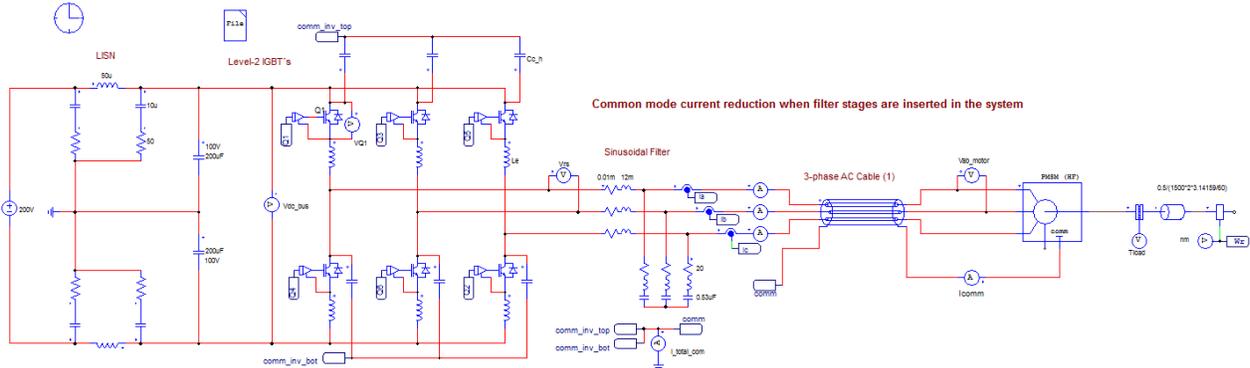


Fig. 11: The PMSM drive with the high-frequency models, LISN, and inverter filter

The results are shown in Fig. 12. The considerable reduction of the peak values in the common mode current can be observed. In addition, the high-frequency components in the current absorbed by the motor are removed, and in the same manner at the PMSM terminals.

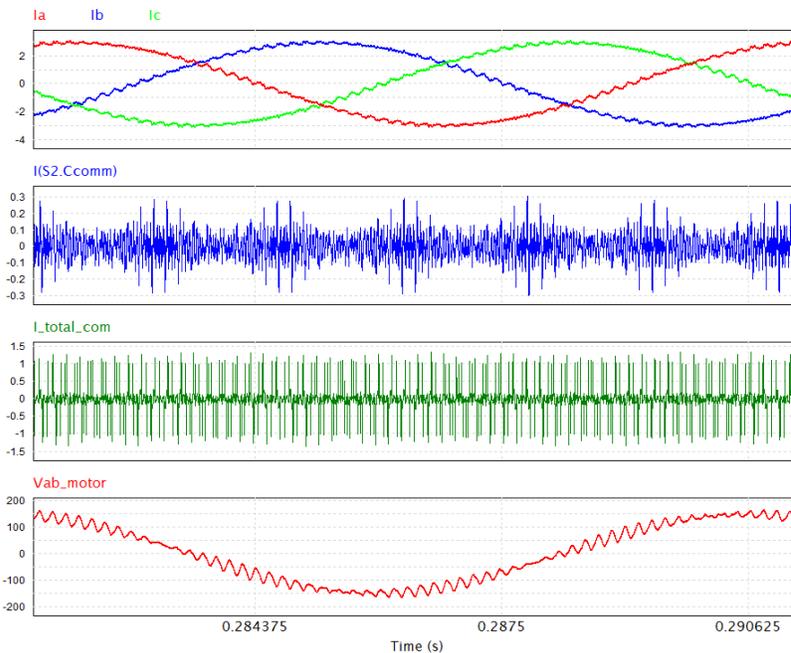


Fig. 12: Reduction of EMI effects on the PMSM drive when filter stages are added

PSIM’s waveform display program SIMVIEW provides the capability to display various EMI standards. With this capability, one can easily check if certain EMI standards can be met. The figure below shows the harmonic spectrum of the common mode current together with EMI

standards FCC Class A, FCC Class B, and CISPR 25 (Class 3) with and without the filters. The waveforms show that these standards are met when filters are added.

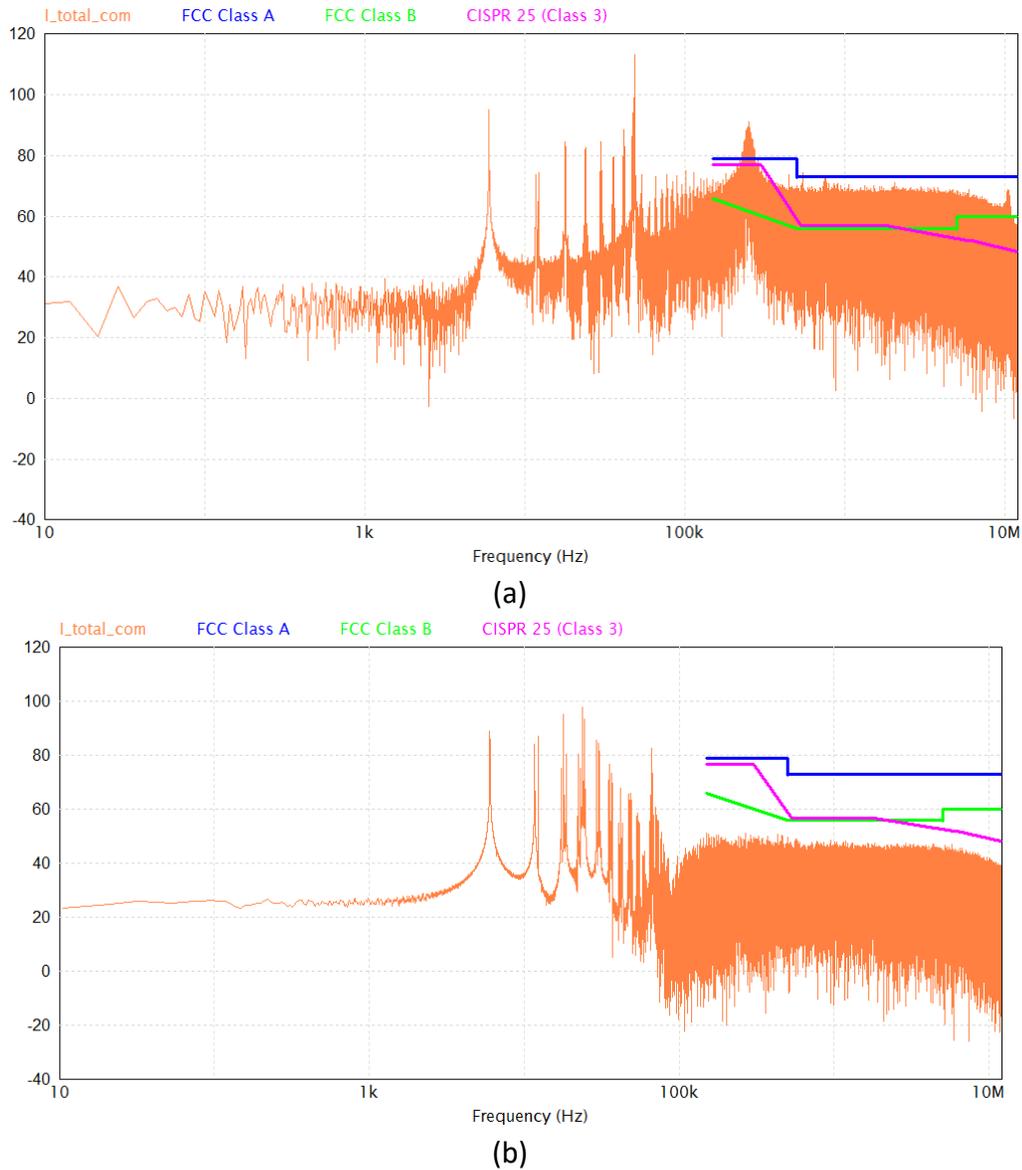


Fig. 13: Common mode current and the EMI standards FCC Class A, FCC Class B, CISPR 25 (Class 3): (a) without filter (b) with LISN and inverter filter

Appendix: Experimental procedure to obtain model parameters

The following is a brief description of the experimental steps to obtain the high-frequency parameters of the AC motors. An impedance analyzer is used to evaluate the impedances in DM (Differential Mode) and CM (Common Mode). A frequency band between 1kHz to 2MHz is recommended, although the high frequency value can be extended to 10MHz. Fig.12 illustrates the circuits for measuring impedances in both modes.

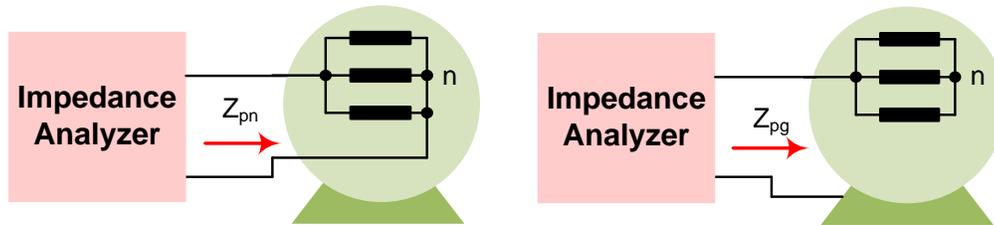


Fig. 14: Connections to determine phase-to-neutral and phase-to-ground impedances