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Transfer Function Method for EMC High-Frequency Modeling of Electrical Machines

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Abstract: Any electrical machine can be exposed to electromagnetic interference, or even be the source of it. Researchers are increasingly taking EMC problems in electrical machines seriously, because of the consequences they can have in terms of operation, efficiency and service life. High-frequency modelling of the winding impedance of electrical machines is becoming increasingly important in this context, as it can be a practical asset for engineers in predicting the EMC behaviour of any machine. Several models have been developed for different electrical machines. In this paper a method based on the principle of transfer functions has been used to model several electric motors for the two propagation modes: differential and common modes. The results obtained show the effectiveness of the proposed model in predicting the impedance of the windings of any motor for frequencies up to 10MHz.

Keywords: EMC, High frequency, Electrical machines, Differential mode, Commun mode.

Introduction

Nowadays, the use of electrical machines has become indispensable to human daily life. These machines cover the majority of mechanical and electrical energy needs in the industrial, commercial and residential sectors (Kudelina et al., 2021). However, these machines are often disruptive to the electromagnetic environment in which they are used (Moreno et al., 2024). This has prompted researchers to take an early interest in the electromagnetic compatibility (EMC) performance of these devices. Several studies have already revealed that most machines are either disruptors or victims of electromagnetic interference, whether conducted or radiated (Das Himadri Sekhar et al., 2024). It was therefore necessary to take EMC aspects into consideration right from the design stage of electrical machines, in order to guarantee higher performance, longer life and a healthier EMC environment (Mariscotti, & Sandrolini, 2021).

Since then, a number of studies have focused on the prediction of conducted electromagnetic disturbances generated by different types of machines, and in particular on the modeling of these disturbances to identify and minimize the sources of electromagnetic emissions likely to disturb neighboring equipment, in order to

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guarantee harmonious operation in sensitive environments. A HF modeling technique for induction motors based on neural networks was described by Xianzhe et al. (2024). An improved permanent magnet synchronous motor lumped parameter model was developed by Rahimi and Kanzi (2020) and Ruiz-Sarrió et al. (2021), used finite element approach to predicting the high-frequency behavior of rotating electrical machines. For developing a high-frequency model of the induction machine, an automated fitting process is suggested by Bruno and Monopoli (2022).

Using transfer functions to model electrical motors is an established technique in EMC analysis because it enables you to examine how the motor reacts to different inputs and disturbances, including electromagnetic interference (EMI). Several recent papers have already used this technique to establish predictive models of conducted disturbances generated by electrical machines for the study of CM and DM path currents, (Miloudi et al, 2022). Proposed an identification method in high frequency for induction motor has been proposed based on the transfer function and the same approach was then used by Bermaki et al. (2023). To propose a predictive model of the DM impedance of the universal motor (Mioudi et al., 2024). Propose and develop a new model based on transfer function for obtaining the High Frequency (HF) characteristics of a single-phase induction motor with capacitance-Start. In this paper, we have applied the transfer function modeling method to the asynchronous machine in order to analyze its effectiveness for EMC studies in CM and DM for frequencies up to 10 MHz.

Materials and Methods

Impedance Measurement of Electrical Machines in CM and DM

Impedance analysis of CM and DM electrical machines is essential for understanding their behavior in the face of electromagnetic disturbances, often in the context of EMC. This measurement is commonly performed using an impedance analyzer, a precise instrument for characterizing impedances in different configurations. In our case, before we can proceed with modeling any electrical machine, it's essential to measure its impedance as a function of frequency. This is done by connecting the machine directly to the impedance analyzer, as shown in Figure 1.

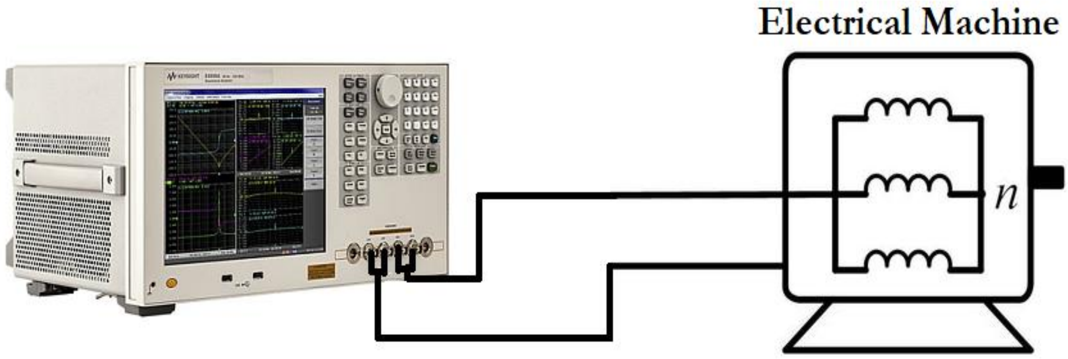

Figure 1. Impedance measurement of electrical machines

In CM, the current flows in both conductors in the same direction relative to machine ground. This type of measurement can be used to assess disturbances between the system and ground. both analyzer terminals are connected to the same point (e.g. phases) in relation to the machine frame. The current moves in opposing directions between the two conductors when in DM. This enables the analysis of disturbances between two specific points, as well as between phases or, in the case of a three-phase system, between phase and neutral. The two terminals of the impedance analyzer must therefore be connected between two points of interest on the electrical machine, e.g. between two phases or between phase and neutral.

Transfer Function Modeling Method

In situations where electromagnetic interference (EMI) might affect performance, modeling electrical machines for EMC and high-frequency behavior is essential. A strong framework for this analysis is provided by the transfer function approach in combination with impedance measurements and asymptotic Bode graphs. Using impedance measurements, the asymptotic Bode method offers an organized way to simulate the dynamic behavior of an electric motor. This procedure makes it possible to identify important dynamic features and create a prediction model that can be applied to simulation and control.

- From the plot of the impedance as a function of frequency of the electrical machine obtained with the impedance analyzer, the first thing to do is to identify the breakpoints representing the frequencies at which there is a significant variation in the slope of the impedance curve.
- The second step consists in extracting the initial gain as well as the poles and zeros. The initial gain is the impedance value at low frequency, before the first breakpoint. This gain can be noted K. Poles correspond to frequencies where impedance increases rapidly in response to an increasing frequency and zeros represents to frequencies where impedance decreases. For each breakpoint at frequency fc, If the slope increases: this is probably a zero. If the slope decreases: this is probably a pole.
- Using the gain K, poles and zeros, we can write the transfer function. If we have n zeros and m poles, the transfer function takes the following form:

$$Z\,(s) = K\,.\frac{(s - z_1)\,(s - z_2)\,\ldots\,(s - z_3)}{(s - p_1)\,(s - p_2)\,\ldots\,(s - p_3)}$$

where :

zi are zero frequencies,
pi are pole frequencies,
K is the initial gain.

- Finally, once the transfer function has been obtained, we can plot the curve of the predictive model of the electrical machine's impedance, and compare it with experimental measurements to assess its reliability. This can be done using analysis software such as MATLAB.

Results and Discussion

The transfer function modeling method described above was used to model the frequency behavior of the induction motor windings in CM. The motor used in this work has two windings, a main winding and an auxiliary winding, plus a starting capacitor. In the following, the results of impedance measurements for each winding and the proposed model will be presented.

Asynchronous Motor Behavior in CM

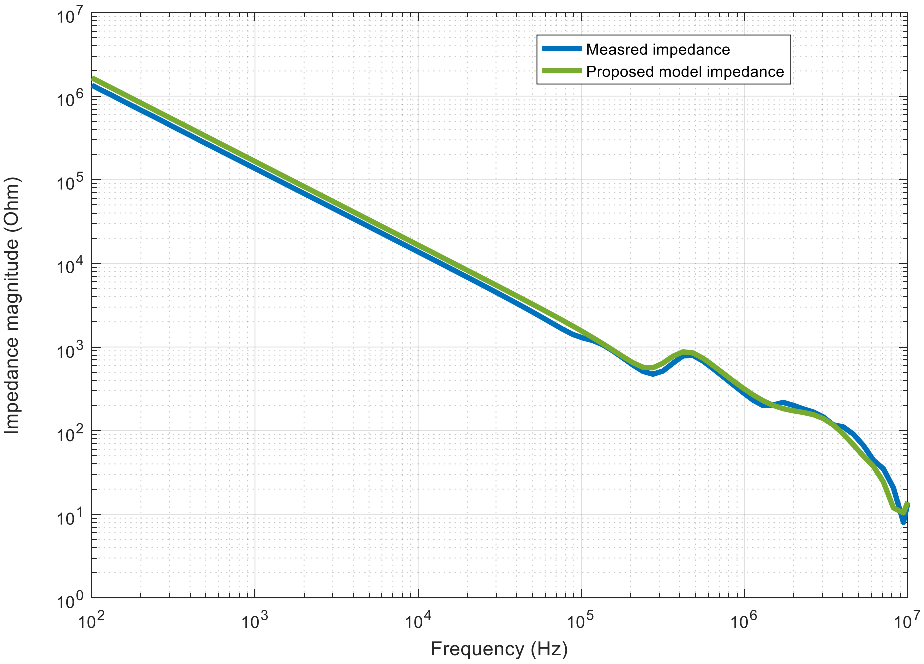

Figure 2. CM impedance measurement and simulation for main asynchronous motor winding

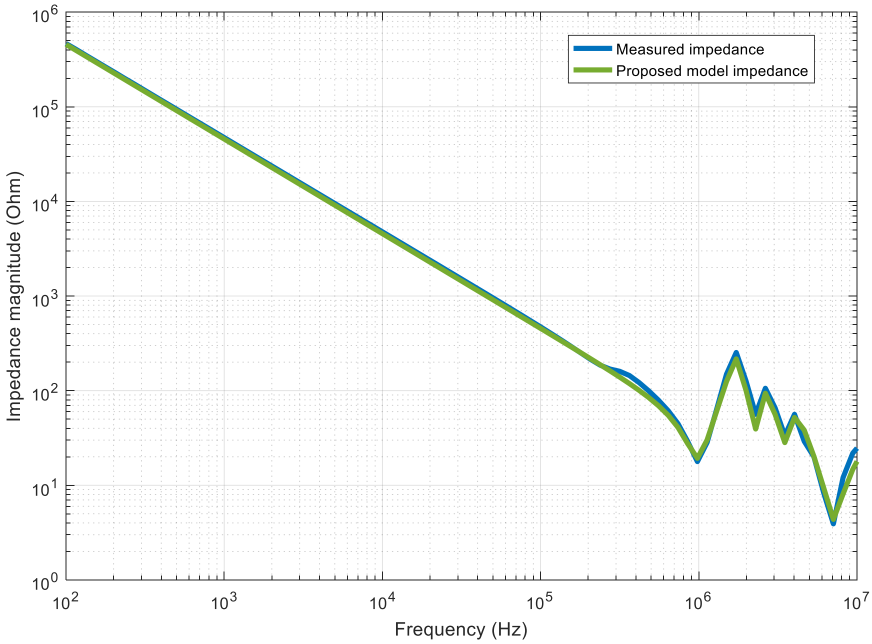

Figure 3. CM impedance measurement and simulation for auxiliary asynchronous motor winding

First, the two motor windings were studied independently. Figure 2 shows the measurement and simulation results obtained. We can clearly see that the CM impedance behaves capacitively over most of the frequency range considered. Figure 03 illustrates the behavior of the auxiliary winding in CM. In this case, capacitive behavior predominates for frequencies up to 1Mhz. Above this value, several resonances are observed.

After studying each winding separately, both were taken into consideration in order to analyze the behavior of the asynchronous motor as a whole in CM. Figure 4 shows the measurement and simulation results obtained from the variation in impedance of the asynchronous motor in CM. It can be seen that the behavior of the induction motor in CM is very similar to that of the auxiliary winding. This shows that the auxiliary winding has a greater influence on the machine's EMC performance.

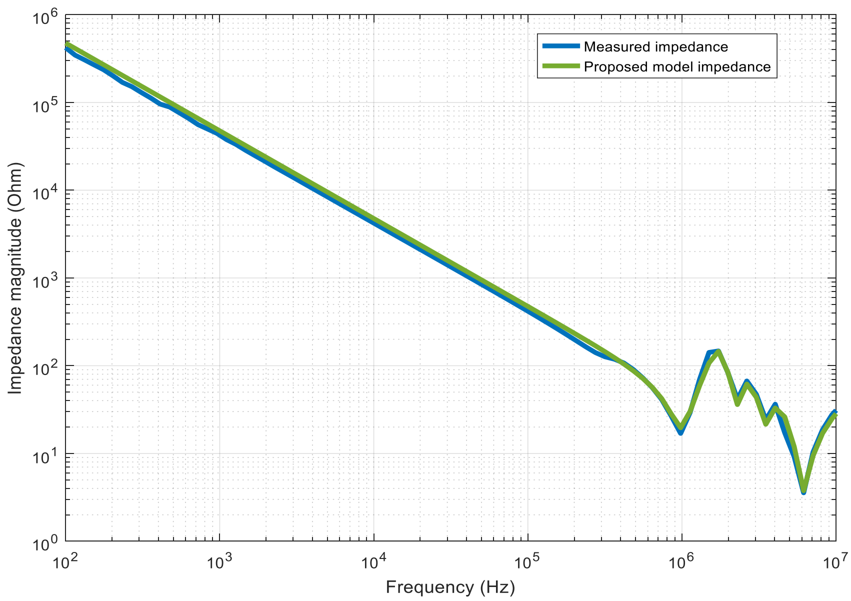

Figure 4. CM impedance measurement and simulation for asynchronous motor

The results obtained in Figures 2, 3 and 4 clearly show total alignment between the measurement curves obtained with the impedance analyzer and the simulation curves obtained with transfer function modeling for the entire frequency band between 100 Hz and 10 MHz. This confirms the reliability of this CM modeling method.

Asynchronous Motor Behavior in DM

Once the transfer function modeling of our electric machine had been validated in CM, we tested the same modeling method for the same machine, the asynchronous motor, but in DM.

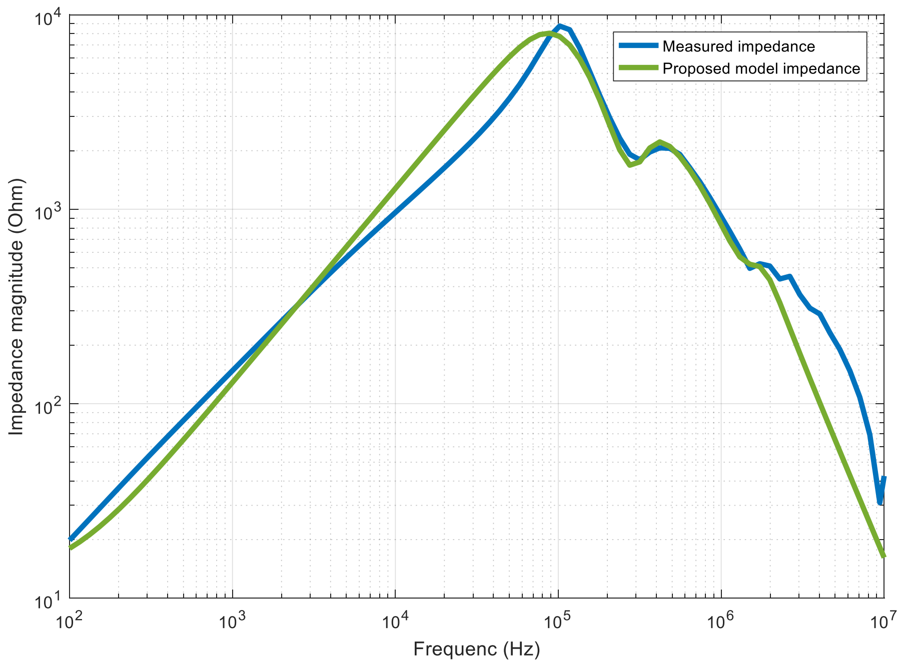

Figure 5. DM impedance measurement and simulation for asynchronous motor

The first observation we can make is that the impedance behavior of the DM machine is divided into two parts: an inductive behavior for frequencies below 100 KHz and a capacitive behavior for frequencies above this value. As for the reliability of the DM model, the measured impedance curve has the same shape as the impedance curve obtained by simulation. However, there are certain frequency ranges where the two curves are not aligned, with a fairly substantial gap between the two. This can be explained by the nature of the impedance of electrical machines, which is stable in CM and quite complex in DM. This calls for greater effort in determining the breakpoints, as the transfer function may be more complex, but will result in a more efficient predictive model.

Conclusion

In this paper, we present a method for modeling electrical machines used for EMC studies. This method is based on the principle of transfer functions and allows the impedance behavior of any electrical machine to be predicted for very high frequency ranges. This method has been applied to the asynchronous machine, and the results obtained have demonstrated the reliability of transfer function modeling, especially for the common mode. Differential mode modeling, however, requires some additional effort to improve the proposed model.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

* This article was presented as an Poster presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Turkey on November 14-17, 2024.

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