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Research Article

Conducted Electromagnetic Interactions in the Inverter-Cable-Machine System: A Focus on Common Mode Phenomena

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Abstract –Today's power electronics systems increasingly rely on faster switches capable of handling higher power levels. However, the integration of these advanced components presents significant challenges in terms of electromagnetic compatibility (EMC), including environmental interference and self-disturbance. In inverter-cable-machine systems, high di/dt and dv/dt rates are common. The steep current and voltage waveforms generated by these systems tend to produce conducted and/or radiated electromagnetic disturbances, which can be both disruptive and potentially destructive. To analyze the propagation paths of these currents and the levels of conducted disturbances generated by the system, precise modeling of the various components of the variable-speed drive is essential. In this study, we developed a parameter identification method for a load consisting of an asynchronous machine and its power cable. The resulting models, validated in the frequency domain, enable the identification of propagation paths for common-mode and differential-mode currents. Furthermore, these models allow for the prediction of overvoltages caused by semiconductor power switches.

Keywords –EMI, EMC, Asynchronous Machine, Common Mode, High Frequency, Cable.

I. INTRODUCTION

Electromagnetic Interference (EMI) has emerged as a significant concern in modern electrical engineering [1]–[8], particularly with the widespread deployment of Adjustable Speed Drives (ASDs) and electric motors in diverse industrial sectors [9]–[14]. As these technologies advance in complexity and application, mitigating EMI has become increasingly critical to ensure system reliability and compliance with electromagnetic compatibility (EMC) standards.

This paper focuses on a crucial aspect of EMI: Common Mode (CM) behavior in motor systems. CM currents and voltages can severely impact system performance and compromise the electromagnetic environment, necessitating robust mitigation measures [15]. With global EMC regulations growing increasingly stringent [16]–[18], understanding the mechanisms behind CM interference is essential not only for compliance but also for ensuring the reliability, stability, and safety of electrical systems. Thorough analysis of CM interference serves as the foundation for developing effective EMI mitigation strategies, which are indispensable for maintaining the long-term performance and integrity of industrial electrical systems [19]–[21].

Effective EMI management in motor systems transcends regulatory compliance by enhancing the overall efficiency and stability of electrical infrastructure [22]–[24]. Recent studies emphasize the critical importance of EMI control in energy-efficient and high-performance systems. For example, Swami [25] highlights the need for specialized design standards in low-power embedded systems to achieve energy savings while maintaining robust electromagnetic performance. Similarly, [26] investigates the impact of multilayer driver configurations on EMI in high-voltage applications, and [27,28] underscores the role of EMI control in supporting the reliability of smart production systems.

These insights are particularly relevant to single-phase induction motors, which are increasingly deployed in industrial environments where controlling EMI is vital for maintaining dependable performance. By addressing CM interference and its implications, this paper aims to contribute to the development of advanced EMI mitigation techniques, ensuring the sustained reliability and efficiency of motor-driven systems in demanding industrial applications.

The operation of a static converter, based on switching, generates abrupt changes in voltage and current. These variations give rise to electromagnetic disturbances, often referred to as EMI (Electromagnetic Interference), which unintentionally propagate within the circuit and/or to its surroundings. These disturbances superimpose onto useful signals, disrupting the normal operation of the circuit and neighboring devices. Consequently, every system can act as both an emitter and a receiver of such disturbances, leading to the concepts of emission and susceptibility [3]. Two types of disturbances are categorized based on their propagation nature:

- Conducted disturbances: Propagate through electrical conduction (e.g., ground planes, cabling, etc.);
- Radiated disturbances: Spread via electromagnetic fields.

In this study, we focus exclusively on conducted disturbances, which can propagate in two distinct modes:

1. Common mode: When parasitic currents flow in the same direction through connected paths and return via an equipotential plane [4, 13].
2. Differential mode: When parasitic currents flow in opposite directions through the connected paths.

The rapid voltage (dv/dt) and current (di/dt) changes at the inverter output are the primary causes of common-mode and differential-mode currents.

II. MATERIALS AND METHOD

Electromagnetic Compatibility (EMC) is a specialized field of electrical engineering that focuses on studying and characterizing the interactions between electrical equipment, their environment (such as networks, loads, and control devices), and natural electrical phenomena to ensure the functional integrity of all systems involved. The concept of EMC emerged in the 1920s with the rise of radio communications, when the increasing proliferation of electrical devices was found to cause significant interference with signal reception. The first EMC standards were established during this period [29].

Today, EMC has become a critical area of focus due to the growing number, complexity, and strategic importance of electrical and electronic systems, such as avionics systems in aircraft, which are highly susceptible to electromagnetic pollution. This vulnerability can lead to severe consequences if not properly managed.

The analysis of an electromagnetic disturbance reveals that the issue involves three key elements:

1. A source of disturbance that emits electromagnetic energy.
2. A coupling channel through which the disturbance energy propagates.
3. A receiver that captures this energy, processes it, and inadvertently adds it to its normal operating functions (Figure 1).

This triad highlights the need for robust EMC strategies to mitigate interference, protect sensitive systems, and maintain the reliability of increasingly interconnected and technologically advanced devices.

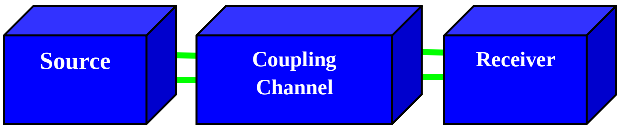

Fig. 1. Transmission of Disturbances

A clear understanding of Electromagnetic Compatibility (EMC) phenomena requires careful attention to the propagation channel, as it plays a crucial role in the behavior and impact of electromagnetic disturbances.

Common mode is rarely used for transmitting useful signals and is often associated with parasitic phenomena. It is also referred to as parallel mode, longitudinal mode, or asymmetric mode [1,30]. Common-mode voltages develop between the connecting wires and the reference potential, such as the grounding of devices or the equipotential protective conductor (PE). The common-mode voltage is defined as the average value of the potential differences between the various wires and the grounding (Fig. 2). The common-mode current corresponds to the current flowing toward the ground. This current is distributed across the different connecting wires, flowing in the same direction through each wire.

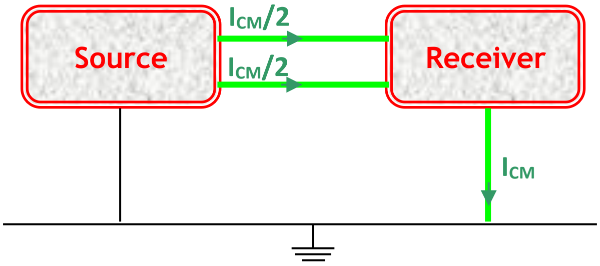

Fig.2. Common mode

Common-mode voltages arise between the connecting wires and the reference potential, such as the equipment ground or the equipotential protective conductor (PE). The common-mode voltage is defined as the average value of the potential differences between the various wires and the ground (Fig.2). The common-mode current is the current flowing toward the ground. This current is distributed among the connecting wires, flowing in the same direction through each wire. It can be measured using a current probe that detects the flow through all wires in the same direction (Fig.3) [1, 31].

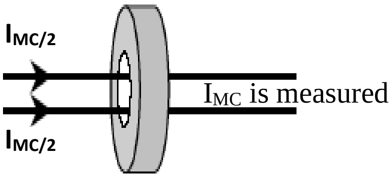

Fig. 3. Measurement of Common-Mode Current

In previous work [1], we highlighted the importance of accurately representing propagation paths, particularly those of common-mode currents, in electromagnetic compatibility (EMC) studies of variable speed drives. The asynchronous machine (ASM) acts as a primary propagation path for conducted disturbances. Most models developed for similar studies are generally applicable to low and medium frequencies (< 1 MHz). This frequency limitation is overly restrictive for a comprehensive analysis of conducted disturbances. Furthermore, the models presented in this chapter, as well as those found in the literature, rely heavily on the assumption of machine linearity. This assumes that the machine is never subject to magnetic circuit saturation, meaning the elements depend solely on frequency, allowing the use of impedance-based analysis.

High-frequency modeling of an asynchronous motor can be achieved using numerical models, but these quickly become impractical as the number of model parameters increases. In such cases, the model resembles that of a coil wound on a magnetic circuit, with parasitic couplings to the chassis superimposed [32,33].

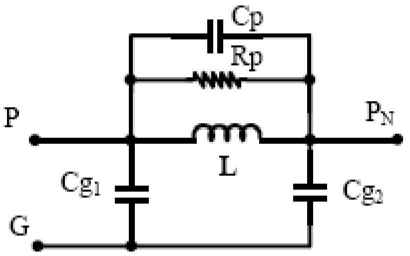

Fig. 4. Simple model of a winding

With:

- R: The resistance of a winding;
- L: The self-inductance of a winding;
- Cp: Parasitic capacitive couplings between turns within the winding;
- Cg_1, Cg_2: Common-mode capacitances between a winding and the motor chassis;
- Rp: The resistance representing iron losses in the machine's stator.

The analysis of the motor's impedance is based on observing the impedance curves as a function of frequency, measured under two configurations: common-mode and differential-mode [34,35]. To determine the motor's common-mode impedance, phases A and B are connected in series and are left floating, without being grounded (Fig. 5).

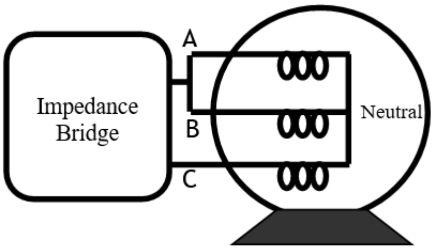

Fig. 5. Common-Mode Configuration of a Motor

In the common-mode configuration, the equivalent circuit of the impedance for a single phase in common-mode (CM) can be represented as shown in Figure 6.

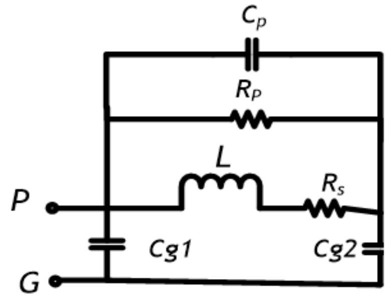

Fig. 6. Equivalent Circuit of a Single-Phase Common-Mode Impedance

The common-mode impedance Z_{CM} of the motor, based on the configuration shown in Figure 6, can be expressed using the following equation:

$$Z = \frac{V_{CM}(p)}{I_{CM}(p)} \qquad (1)$$

$$Z_{pG} = \frac{L(C_P + C_{g2})p^2 + \frac{L}{R_p}p + 1}{6C_{g2}\,p(L(C_p + \frac{C_{g1}C_{g2}}{C_{g1}+C_{g2}})p^2 + \frac{L}{R_p}p + 1)} \qquad (2)$$

Two characteristic frequencies are derived from the common-mode impedance. The first frequency, denoted as F_N(PG), represents the natural frequency of the numerator Z_{PG}, which minimizes the impedance (common-mode impedance resonances). The second frequency, denoted as F_D(PG), is determined from the denominator and defines the impedance resonance (differential-mode impedance resonances) [1, 2].

These two frequencies are calculated using the following equations:

$$F_{N(PG)} = \frac{1}{2\pi\sqrt{L(C_p + C_{g2})}} \qquad (3)$$

$$F_{D(PG)} = \frac{1}{2\pi\sqrt{L(C_p + \frac{C_{g1}C_{g2}}{C_{g1}+C_{g2}})}} \qquad (4)$$

The study of couplings in the wiring networks of systems is a key concern in electromagnetic compatibility (EMC) [1, 4, 5, 6]. In prior work [1], we developed a parameter identification method for a behavioral model of unshielded power cables exposed to high voltage gradients generated by power electronic converters. The cable analyzed in this study is a typical 22 AWG model consisting of three conductors insulated with rubber, commonly used to power the motor. The reference conductor is the ground.

Maxwell formulated the equations of electromagnetism in a vacuum, where at any given point, a charge density and a current density of free charges can exist. These equations are expressed as follows:

$$\nabla \times \vec{D} = \rho \qquad (5)$$

$$\nabla \times \vec{B} = 0 \qquad (6)$$

$$\nabla \times \vec{E} = \frac{-\partial \vec{B}}{\partial t} \qquad (7)$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad (8)$$

Through mathematical derivation, the equations for harmonic waves in conductive materials can be expressed as follows:

$$\nabla^2 \dot{\vec{E}} = j\omega\mu(\sigma + j\omega\varepsilon)\dot{\vec{E}} \qquad (9)$$

$$\nabla^2 \dot{\vec{H}} = j\omega\mu(\sigma + j\omega\varepsilon)\dot{\vec{H}} \qquad (10)$$

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta \qquad (11)$$

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right)} \qquad (12)$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right)} \qquad (13)$$

In this example, let us consider copper with a conductivity value of $\sigma_{Cu} = 5.8 \times 10^7$ S/m and a permittivity of $\varepsilon_{Cu} = \varepsilon_0 = 8.8854 \times 10^{-12}$ F/m. However, given the ratio $\left(\frac{\sigma}{\omega\varepsilon}\right) >> 1$, the constants α and β can be expressed as:

$$\alpha = \beta = \sqrt{\frac{\omega\mu\sigma}{2}} \qquad (14)$$

III. RESULTS

In this section, we present a detailed analysis of the results. The simulation results shown in Figure 7 validate the frequency response of the impedance Zpp.

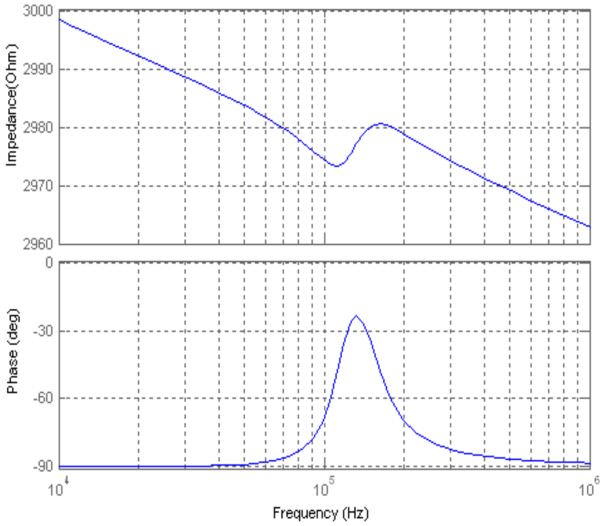

Fig. 7. Simulation of Motor Impedance (Common-Mode Configuration)

The desired accuracy in analyzing the motor's impedance is meaningful only when the power supply cable is also taken into account.

Figures 8 and 9 illustrate the variation of the constants α and β, respectively, as a function of frequency for two materials: copper and aluminum.

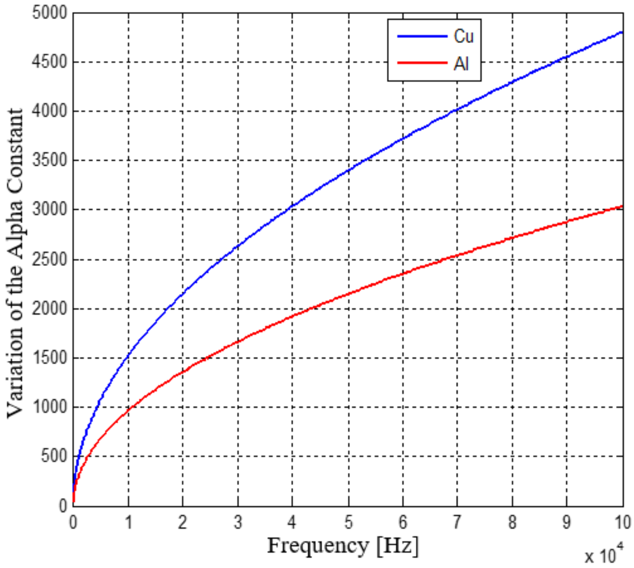

Fig. 8. Variation of the Alpha Constant with Frequency

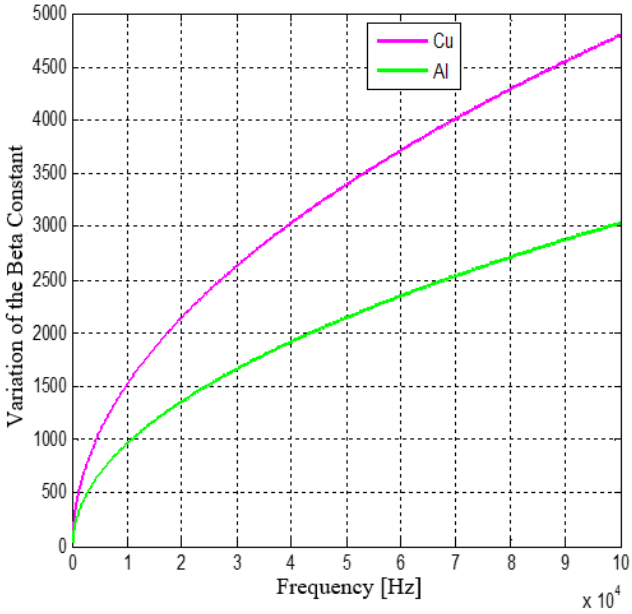

Fig. 9. Variation of the Beta Constant with Frequency

IV. DISCUSSION

The impact of different motor configurations (SPIM, PCIM, CSIM, RIM) on electromagnetic behavior was another key finding. The results suggest that:

- **Higher Impedance and Better EMC**: Motors like the RIM, which exhibited higher differential-mode impedance, also showed lower EMI emissions. This aligns with the understanding that motors with higher impedance tend to offer better EMC performance, as they resist external disturbances more effectively and produce less noise.
- **Mode-Dependent Impedance**: The study revealed a clear distinction between the impedance behavior in common-mode and differential-mode configurations. While the common-mode impedance is influenced by parasitic capacitive couplings between the windings and the motor

chassis, the differential-mode impedance primarily reflects the internal characteristics of the motor windings. The difference in behavior under these modes underscores the importance of analyzing both modes when designing motors for low EMI.

These findings have significant implications for the design and optimization of electrical motors in sensitive applications. The ability to reduce EMI and enhance immunity to electromagnetic disturbances is crucial for:

- **Improved Motor Design**: By understanding the frequency-dependent impedance behavior and the effects of different motor designs and materials, engineers can optimize motor configurations for better EMC performance, leading to reduced interference with other electronic systems and improved operational reliability.
- **Power Electronics and Variable Speed Drives**: In variable speed drive systems, where high-frequency switching is involved, the study's results suggest that choosing the right motor type and material (e.g., copper vs. aluminum) can significantly affect the system's overall electromagnetic behavior.
- **Regulatory Compliance**: For industries where EMC regulations are strict (e.g., aerospace, automotive, medical devices), ensuring that the motor impedance profiles align with required standards is crucial. These findings can inform the development of EMC filters, grounding strategies, and shielding techniques to meet these requirements.

While the study provides valuable insights into the impedance characteristics of various motor types, further research could explore the following areas:

- **Non-Linear Effects**: The assumption of linearity in motor behavior, especially at high frequencies, is a limitation of the study. Future research could consider non-linear effects, such as magnetic saturation, which may affect impedance at higher power levels or frequencies.
- **Extended Frequency Range**: The study focused primarily on low-to-medium frequencies (<1 MHz). Extending the analysis to higher frequencies (e.g., above 10 MHz) could provide deeper insights into the high-frequency behavior of motors, especially in systems involving fast-switching power electronics.
- **Impact of Motor Size and Load Conditions**: The study could be expanded to include motors of different sizes and under varying load conditions. Load-dependent impedance variations may provide additional insights into the practical performance of motors in real-world applications.

V. CONCLUSION

Building on the findings of this study, it is clear that a detailed understanding of the impedance characteristics in both common-mode and differential-mode configurations is critical to optimizing motor designs for enhanced electromagnetic compatibility (EMC). The high-frequency models developed for both the asynchronous motor and shielded power cables will aid in predicting and mitigating EMI, ensuring that these systems comply with regulatory standards and maintain stable operation in environments sensitive to electromagnetic disturbances.

This research underscores the importance of using precise models for system components, as the interaction between the motor, cables, and other system elements significantly influences the overall EMI behavior. As we move toward more complex and integrated systems, particularly in industries such as automotive, aerospace, and telecommunications, understanding these interactions and designing accordingly will be crucial for both operational performance and compliance with electromagnetic standards. Future studies focusing on differential-mode characteristics will further refine these models and contribute to a more comprehensive understanding of motor and cable EMC behavior across a broader range of frequencies.

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