Comparative Analysis of Differential-Mode Impedance in Single-Phase Induction Motors

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Abstract: - This paper presents an experimental study of the high-frequency impedance behavior of four types of single-phase induction motors: Split-Phase Induction Motor (SPIM), Permanent Split Capacitor Induction Motor (PCIM), Capacitor Start Induction Motor (CSIM) and Single Phase Repulsion Motor (RIM). A differential-mode impedance and phase angle over a range of frequencies, including resonance and anti-resonance points, are the focus of the present study. The obtained results show that every type of motor has distinctive impedance characteristics; the RIM always shows higher impedance than other motors, whereas the CSIM exhibits lower impedance in low frequencies. Those differences unveil the influence of the motor design on Electromagnetic Compatibility (EMC) performance, since high-impedance motors, such as the RIM, present lower Electromagnetic Interference (EMI) emissions and lower susceptibility to external electromagnetic interference, therefore better general EMC performance. Also, the frequencies of resonance and anti-resonance vary between the motors, which is also reflected in their different electrical and structural designs. The study provides helpful insights into the optimization of motor designs to achieve better EMC compliance and operational stability in various applications.

Key-Words: - Differential-Mode Impedance, Single-Phase Induction Motors, Electromagnetic Interference (EMI), Impedance Measurement, EMC Standards, Resonance.

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1 Introduction

Electromagnetic interference, or EMI, is one of the important concerns in modern electrical engineering, especially due to the expansion use of Adjustable Speed Drives and electric motors in a wide range of industrial applications, as shown in [1], [2], [3], [4]. As those technologies have continued to increase in their complexities and deployment, the challenge of how to control EMI has intensified.

This study focuses on an important part of the problem: Differential Mode (DM) behavior in motor systems. The presence of DM currents and voltages not only deteriorates system performance but also threatens the nearby electromagnetic environment, needing special measures to mitigate such interference, [5]. Since the international EMC standards are getting very severe today, [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], it becomes necessary to understand the mechanisms of the EMI process, especially in motor applications. It is also important to address the DM interference not just for satisfying the requirements of the EMC, but also to ensure the reliability and safety of the electrical system operation. A detailed investigation of DM interference establishes the baseline for the development of efficient EMI mitigation strategies. Such solutions have also been found to be critical for ensuring long-term integrity and performance in electrical systems from various industrial settings, [17], [18], [19]. EMI management in motor systems effectively goes beyond simple compliance to ensure the general stability and efficiency of the electrical infrastructure, [20], [21], [22].

The significance of minimizing Electromagnetic Interference (EMI) in motor systems is repeated in numerous recent studies that have focused on energy efficiency and high-performance systems. For example, [23] discusses how low-power embedded systems necessitate special design standards to assure not only energy savings but also robust electromagnetic performance. Besides, a detailed performance analysis of the multilayer drivers in case of EMI issues is carried out by [24] in high voltage applications.

Furthermore, [25] prove that EMI control is critical to ensuring the continuity of smart production systems. The results of this work can be directly applied to single-phase induction motors, which are increasingly used in various industrial applications where EMI management is essential to maintaining performance and reliability.

Thus, EMI management is critical not only in low-power and medium-voltage systems but also in modern industrial and motor-driven applications, [26], [27], [28], [29]. This underlines the need for a comprehensive EMI control methodology, with an emphasis on taking into account a wide range of applications and ensuring that electrical systems meet severe electromagnetic compatibility requirements. Engineers can build systems that can deal with current and future EMC issues, protect industrial processes, and ensure long-term performance in a range of applications by increasing their knowledge of DM EMI dynamics.

Single-phase induction motors find their applications in a wide range of applications, including household appliances such as refrigerators, washing machines, and air conditioners, as well as power tools such as drills and saws and industrial machinery. Such motors are highest demand, especially for good reliability and usability efficiency. However, they might suffer great hurdles in terms of electromagnetic compatibility (EMC), where the electromagnetic environment hurts their performance and reliability, [30], [31].

One important type of EMC is differential mode electromagnetic interference (EMI), which occurs when noise is conducted through the phase and neutral conductors of an electrical system. Differential-mode EMI propagates along the power conductors rather than through the grounding conductor and has a major influence on the performance of electrical and electronic devices. As a consequence of this type of EMI, motor current and voltage waveforms may become distorted and lead to loss of efficiency, excess heat, and possibly winding damage. It can also cause electrical noise, increased vibration, and audible noise, which can cause mechanical wear and premature component failure, [32], [33]. Furthermore, EMI can interfere with motor control circuits, resulting in irregular operation and disturbing speed and start/stop functions, [34]. EMI also introduces harmonics into the power supply, which reduces motor performance while increasing energy consumption and running costs, [35].

A motor’s impedance, or resistance to current flow is essential in determining Differential Mode (DM) behavior in motor systems, directly impacting the motor's electromagnetic compatibility (EMC) performance. Motors with higher impedance often have lower EMI emissions, and vice versa, [36], [37].

Despite the wide usage of single-phase induction motors, the issue of EMI in these motors has gotten far less attention than three-phase motors. This is most probable because three-phase motors are widely used in industrial applications where EMI is a major concern, [38], [39]. However, single-phase motors are increasingly being employed in locations where electromagnetic interference (EMI) is an issue.

This lack of attention to EMC in single-phase motors has resulted in a gap in the knowledge base. There is a need for more research on the EMC of single-phase motors and methods for reducing EMI in these motors, [40], [41].

This paper conducts a comparative study on the differential-mode impedance of four different types of single-phase induction motors and their correlation with EMI emissions. Variations of the impedance within these motor types are analyzed in order to study how impedance is related to their EMI performance. These results can be useful for motor designers to design motors that exhibit a reduced possibility of EMI problems, [42], [43], [44].

2 General Overview of Single-Phase Induction Motors

Single-phase induction motors work on the principle of electromagnetic induction to produce a rotating magnetic field, [45]. The stator consists of the primary winding and an auxiliary winding and is the stationary part of the motor. When an AC voltage is supplied to the main winding, it generates a magnetic field. The auxiliary winding, which is present in many motors, provides a phase shift to create the rotating magnetic field, [46].

Figure 1 shows the structure of single-phase induction motors. When the stator's rotating magnetic field passes through the squirrel cage bars in the rotor, it induces currents that form a magnetic field. This field interacts with the stator field, resulting in rotational movement, [47].

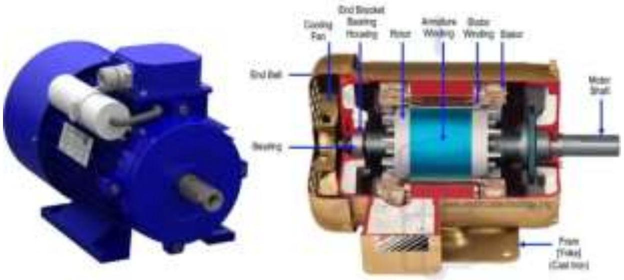

Fig. 1: Single-Phase Induction Motors

In this study, we investigate four specific types of induction motors:

2.1 Split-phase Induction Motor (SPIM)

In the Split-Phase Induction Motor (Figure 2), an additional winding is wound on the same stator core. This creates two windings: the auxiliary winding, which is highly resistive, and the main winding, which is highly inductive, [48]. The auxiliary winding is primarily used for starting, after which it is disconnected.

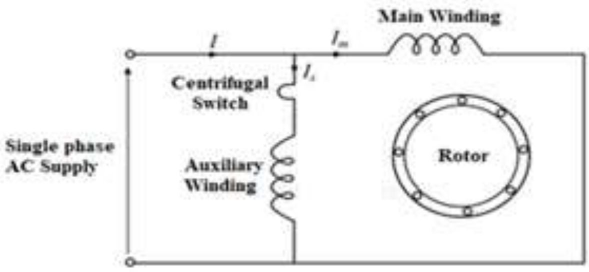

Fig. 2: Split-phase Induction Motor (SPIM)

2.2 Capacitor Start Induction Motor (CSIM)

A Capacitor-Start Induction Motor (Figure 3) is a type of single-phase induction motor with a capacitor primarily used to produce the machine's starting torque. Therefore, the capacitor-start single-phase induction motor has a starting capacitor connected in series with its starting winding or auxiliary winding, [49].

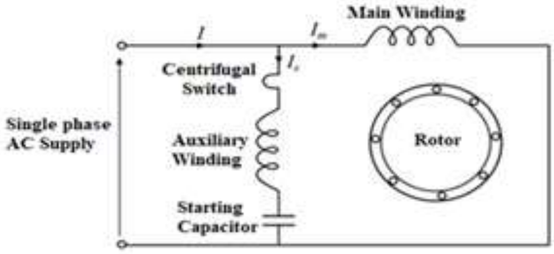

Fig. 3: Capacitor Start Induction Motor (CSIM)

2.3 Permanent Capacitor Induction Motor (PCIM)

In contrast to the Capacitor Start Induction Motor (Figure 4), in the Permanent Capacitor Induction Motor, the capacitor is permanently connected to the circuit, both at start-up and during motor operation, [50].

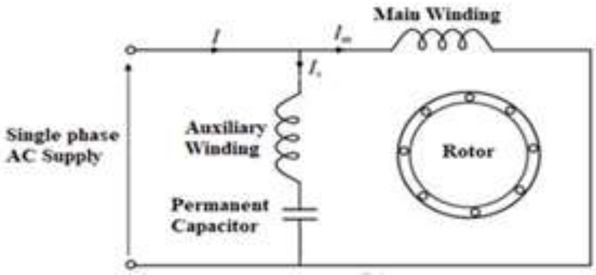

Fig. 4: Permanent Capacitor Induction Motor (PCIM)

2.4 Repulsion Induction Motor (RIM)

The Repulsion Induction Motor (Figure 5) consists of a stator carrying a single-phase exciting winding and a rotor with a closed-type armature winding with a commutator and brushes, [51].

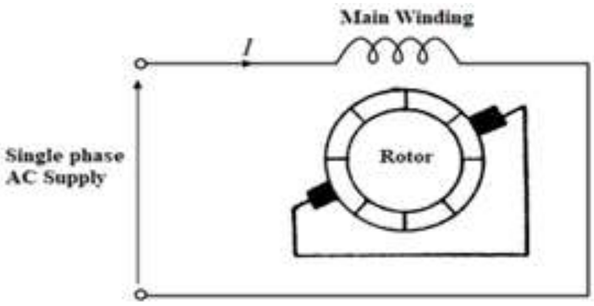

Fig. 5: Repulsion Induction motor (RIM)

The characterized parameters of the four motors are summarized in Table 1.

Table 1. Motors Parameters.

Parameter	CSIM	PCIM	SPIM	RIM
Nominal Voltage (V)	220	220	220	220
Nominal Current (A)	2.2	1.3	2.2	2.7
Nominal Frequency (Hz)	50	50	50	50
Nominal Power (W)	175	175	175	175
Nominal Speed (tr/min)	1400	1440	1400	1350
Mian Winding Resistance (Ω)	9.8	23	9.8	9.8
Mian Winding Inductance (H)	0.226	0.252	0.226	0.2
Auxiliary Winding Resistance (Ω)	23.3	21.7	23.3	/
Auxiliary Winding Inductance (H)	0.137	0.281	0.137	/
Capacitor (μF)	86	10	/	/

3 Experimental Methodology and Measurements

The fact that the four motors studied have different configurations and wiring diagrams means that each motor has a different EMC behavior. Since impedance plays a critical role in determining the electromagnetic compatibility (EMC) performance of a motor, this work aims to conduct a comparative study of the differential-mode impedance of these different types of electric induction motors.

In this section, we detail the experimental approach used to investigate the differential-mode impedance of the four types of electric induction motors studied: Split-Phase Induction Motor, Permanent Capacitor Induction Motor, Capacitor Start Induction Motor, and Single-phase Repulsion Motor.

3.1 Measurement Setup

Our measurements were performed using a Wayne Kerr 6500B spectrum analyzer, which can detect impedance and phase angles up to 120 MHz. We selected this analyzer due to its high precision, especially in the EMC-relevant frequency range of 150 kHz to 30 MHz. Before each cycle of tests, the analyzer was calibrated to ensure accuracy and reduce measurement drift.

Figure 6 illustrates our experimental setup for differential-mode impedance measurements. All motor types are tested using this arrangement to ensure accurate and consistent impedance measurements.

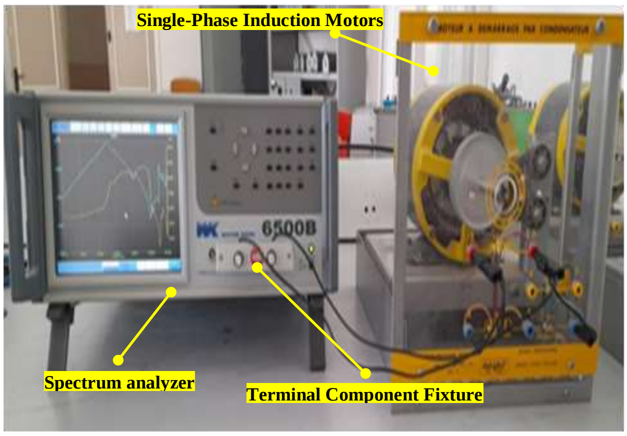

Fig. 6: Experimental setup for differential-mode impedance measurements.

3.2 Impedance Measurements Procedure

Impedance measurements were conducted using a systematic approach to capture differential-mode EMC behaviors:

1. Environmental Control: To ensure accurate measurements, a controlled environment free of electromagnetic interference was developed.
2. Terminal Component Fixture (TCF): Each induction motor type was connected to the TCF. This fixture allows for stable connections and impedance matching, which are required for reliable impedance measurements.
3. Calibration: The Wayne Kerr 6500B analyzer was recalibrated between tests to ensure measurement accuracy. Calibration data was stored and compared to verify consistency between tests.
4. Frequency Sweep: A frequency sweep was performed using the Wayne Kerr 6500B analyzer, spanning frequencies from 150 kHz to 30 MHz. This range aligns with EMC standards and facilitates a comprehensive analysis of impedance variations across relevant operational frequencies, [34].
5. Stability: At each frequency point, the system was allowed to stabilize before taking a measurement, ensuring that transient responses did not affect the results. In addition, multiple sweeps were performed on each motor to ensure repeatability.
6. Data Collection: Impedance magnitude and phase angle were measured at discrete frequency points within the sweep range.
7. Data Analysis: The impedance data obtained from each motor type were plotted to visualize their frequency-dependent characteristics. This visualization aimed to identify resonant frequencies, marked by impedance peaks, and critical impedance values, which potentially

signify areas of concern for differential-mode EMC performance. By comparing impedance profiles across different motor types, insights were gained into how specific design variations impact EMC behavior.

4 Results

In this section, we present and analyze the results of our experimental measurements, focusing on the differential-mode impedance of the four types of electric induction motors studied: Split-Phase Induction Motor (SPIM), Permanent Split Capacitor Induction Motor (PCIM), Capacitor Start Induction Motor (CSIM), and Single-phase Repulsion Motor (RIM).

The Figure 7, Figure 8, Figure 9 and Figure 10 illustrate the impedance and phase angle profiles for each motor type.

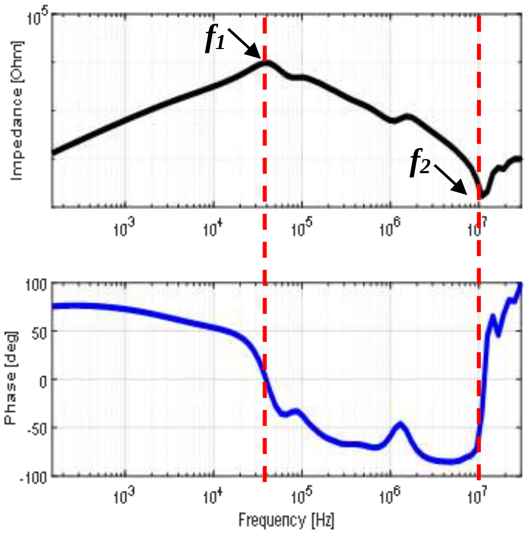

Fig. 7: Impedance and phase angle of CSIM

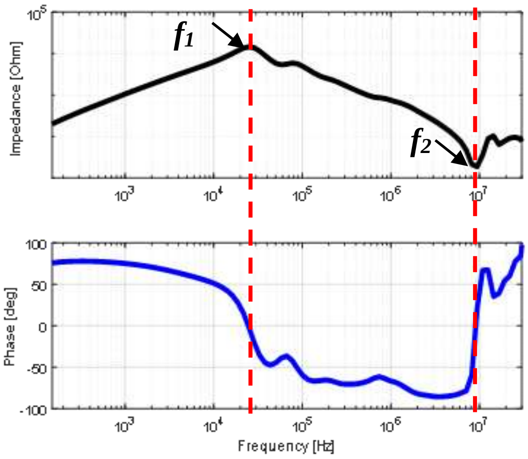

Fig. 8: Impedance and phase angle of PCIM

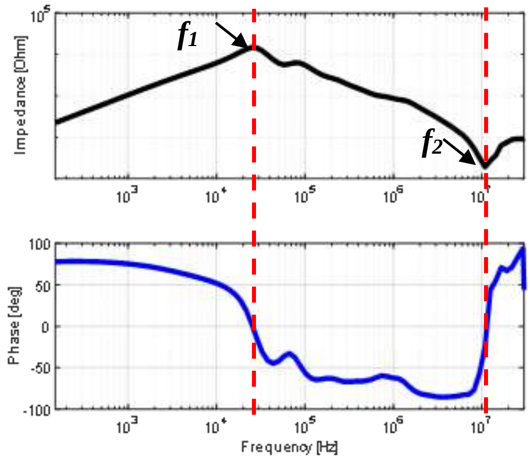

Fig. 9: Impedance and phase angle of SPIM

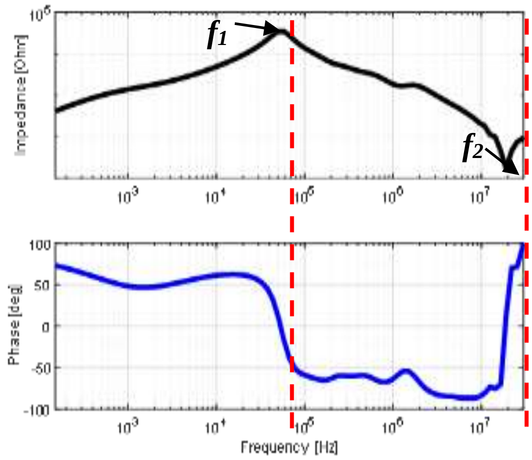

Fig. 10: Impedance and phase angle of RIM

The impedance and phase angles are plotted across the frequency range from 150 kHz to 30 MHz. This comprehensive analysis exposes key similarities and differences in the behavior of the motors, highlighting critical values and frequencies that influence their performance.

Examining the impedance characteristics of each motor, we can observe that the impedance of all four motor types: CSIM, PCIM, SPIM, and RIM increases with frequency up to the resonance frequency f_1. At f_1, each motor exhibited a peak in impedance, reflecting resonance. Specifically, the resonance frequencies f_1 were 37.936 kHz for CSIM, 24.822 kHz for both PCIM and SPIM, and 50.334 kHz for RIM. The corresponding impedance values at f_1 were 9.76 kΩ for CSIM, 14.61 kΩ for PCIM, 14.66 kΩ for SPIM, and 34.88 kΩ for RIM. The phase angles at f1 varied: 4.10° for CSIM, -1.50° for PCIM, 3.74° for SPIM, and 10.87° for RIM.

Table 2 summarizes the resonance and antiresonance characteristics for each motor type:

Table 2. Resonance and anti-resonance characteristics of various Single-Phase Induction Motors

Characteristic	CSIM	PCIM	SPIM	RIM
Resonance Frequency (f_1) (kHz)	37.936	24.822	24.822	50.334
Impedance at f_1 ($Z(f_1)$)(kΩ)	9.76	14.61	14.66	34.88
Phase Angle at f_1 ($\varphi(f_1)$)(°)	4.10	-1.50	3.74	10.87
Antiresonance Frequency (f_2) (MHz)	10.846	9.416	10.846	19.094
Impedance at f_2 ($Z(f_2)$) (Ω)	17.10	18.87	19.26	16.83
Phase Angle at f_2 ($\varphi(f_2)$) (°)	-34.79	21.17	-24.94	13.86

Beyond f_1, the impedance decreases until reaching its minimum at the antiresonance frequency f_2. The antiresonance frequencies f_2 were 10.846 MHz for CSIM, 9.416 MHz for PCIM, 10.846 MHz for SPIM, and 19.094 MHz for RIM. The impedance values at f_2 were 17.10 Ω for CSIM, 18.87 Ω for PCIM, 19.26 Ω for SPIM, and 16.83 Ω for RIM. Despite the impedance being at its minimum, the phase angle at f_2 remained non-zero: -34.79° for CSIM, 21.17° for PCIM, -24.94° for SPIM, and 13.86° for RIM.

To illustrate both the similarities and differences, Figure 11 and Figure 12 provide a global comparison of all motors (impedance and phase angle).

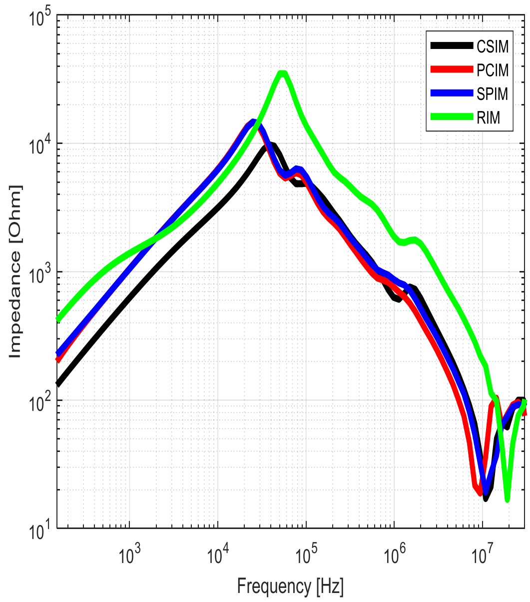

Fig. 11: Impedances comparison of the four motors

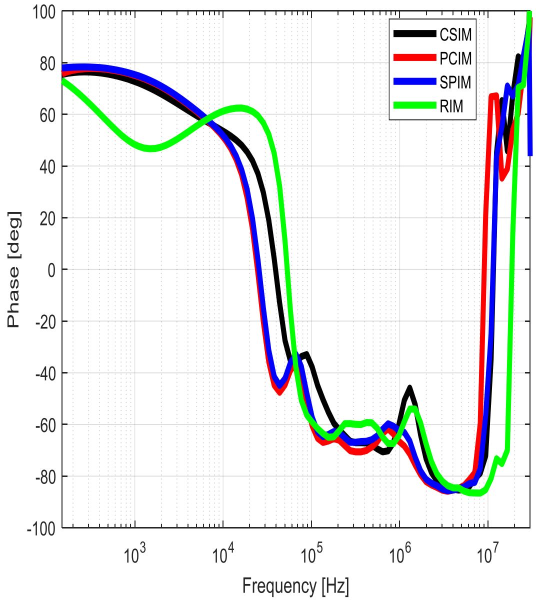

Fig. 12: Phases comparison of the four motors

4.1 Similarities in Impedance and Phase Profiles

- From 100 Hz to f_1, the impedance of all four motor types increases with frequency up to the resonance frequency f_1. This behavior is typical in motors and is largely attributed to the inductive nature of the windings and magnetic components. As the frequency rises, the inductance of the motor becomes more pronounced, resulting in a gradual increase in impedance. The phase angle in this range is positive, indicating that the voltage leads the current, which is consistent with inductive behavior.
- At the resonance frequency f_1, all four motor types exhibit a peak in impedance, marking a resonance point where the impedance is at its maximum. For CSIM and SPIM, the phase angle is positive, indicating a leading nature where the voltage leads the current. The PCIM shows a slight negative phase angle, suggesting a slight lag at resonance, likely due to the influence of capacitors. The RIM demonstrates a significantly positive phase angle, reflecting a pronounced leading nature.
- Beyond the resonance frequency f_1, the impedance begins to decrease until it reaches its minimum value at the antiresonance frequency f_2. During this range, the phase angle turns negative, indicating a lagging relationship between voltage and current, characteristic of capacitive behavior.
- At the antiresonance frequency f_2, the impedance reaches its minimum value,

highlighting a point where the motor system exhibits the least resistance to current flow. Despite the impedance being at its minimum, the phase angle is not zero, reflecting the ongoing influence of reactive components and practical considerations in motor systems.

- After the antiresonance frequency f_2, the impedance increases again, and the phase angle becomes positive, indicating a leading relationship between voltage and current. This behavior reflects the motor's response in the high-frequency range.

4.2 Differences between Motors

- The Single-phase Repulsion Motor (RIM) exhibits consistently higher impedance compared to the other motor types, likely due to its unique winding configuration or mechanical structure.
- The Capacitor Start Induction Motor (CSIM) displays lower impedance at low frequencies, a feature linked to its design incorporating a start capacitor.
- Beyond the first resonance frequency f_1, the impedance characteristics diverge among the motor types. The impedance of the PCIM is generally the lowest, while the RIM retains its higher value.
- The resonance frequency f_1 depends on the type of motor, showing that SPIM has a lower value of f_1 compared to the CSIM and RIM. However, the antiresonance frequency f_2, is the lowest for PCIM, followed by CSIM and SPIM with similar values, whereas RIM shows the highest value.

4.3 Discussion

The impedance profiles of electric motors become important when it comes to determining their EMC performance. Higher impedance corresponds to a better EMC, such that the emission of EMI is small and the susceptibility to external sources of EMI is minimal. It means that competent engineers, who understand the influence of differential mode impedance on EMI performance, can design motors compatible with modern electrical engineering and electronic applications that put very severe electromagnetic compatibility requirements on electric vehicles, industrial automation, and smart power grid applications.

In terms of the impedance, across the frequency range, the RIM always had a higher value and therefore turns out to be very suitable for EMC compliance. Increased impedance reduces the flow of currents caused by the influence of external electromagnetic fields, consequently making the motor less susceptible to EMI. With this feature, it will be qualified to work on power grids where operational stability and reliability are required. A motor like RIM in power distribution systems will reduce harmonic distortions and electromagnetic disturbances that interfere with critical electrical equipment like power transformers and inverters. Increased impedance contributes to an increased meeting of strict EMC requirements that have become very relevant in highly dense urban and industrial areas where electrical disturbances can cause considerable operational problems.

On the other hand, the CSIM has lower impedance at lower frequencies, which renders them more susceptible to EMI. The low impedance may result in high EMI emission in those applications where high-accuracy signal transmission is used, which includes sensor networks, and might lead to possible errors in data transmission, communication failure, or discontinuation of network performance. Within the CSIM, by contrast, the start capacitor plays a useful role by managing phase angles during startup and does help mitigate some of the EMI issues. Either way, to further improve its performance regarding EMC, additional measures may include improved shielding or filtering techniques, especially where low-frequency EMI control is required by a system. In sensor networks, for instance, where signal integrity is critical, motors with higher impedance, like Single-phase Repulsion Motors, are usually preferred to reduce electromagnetic interference that may completely compromise the performance of the system.

Having similar impedance characteristics up to the resonance frequency f_1 would suggest similar PCIM and SPIM EMC performances in the case of lower-frequency operations. This kind of motor could be useful in various applications with low levels of EMI control, like consumer electronics, small industrial machinery, or any application where low-cost solutions with modest EMI control are employed. Above the resonance, impedance profiles of PCIM start to diverge from SPIM, with the PCIM impedance being lower. This behavior may need customized EMC mitigation solutions for HF activities, especially when these motors are used in sensitive applications such as automated manufacturing systems, wherein electromagnetic interference may interrupt complex automation processes.

In the high-frequency domain, the impedance characteristics of the motors become much more important for their EMC performance. If systems were exposed to high levels of electromagnetic radiation in the high-frequency environments of smart grids or sensor networks, the RIM would be at an advantage, thus having higher impedance at high frequencies and hence less susceptible to external electromagnetic interference. It means that the operation will be robust and reliable under conditions of continuous monitoring and control, for example, sensor-based industrial networking or distributed energy management. Motors with lower impedance at high frequencies, such as the CSIM, may require extra electromagnetic compatibility precautions to assure compliance with the industry requirements and operational reliability in such an environment. These results confirm, therefore, the recommendation of higher-impedance motors like RIM in such high-EMI environments for both EMC compliance and system stability.

Achieving EMC compliance in motor design necessitates a thorough understanding of impedance characteristics across a wide frequency range. Motors that are basically designed for high impedance, like the RIM, will normally provide certain advantages in minimizing EMI emissions and susceptibility. It would be ideal to use them in areas like power grids and industrial automation. Motors with lower impedance, such as the CSIM, should be designed against additional components like capacitors, shielding, and filtering to enhance EMC performance in applications covering sensor networks or consumer electronics. The type of motor and related design questions must therefore be decided within the context of a particular application requirement and ambient environment in view of obtaining optimum EMC compliance and system performance.

The stability of the obtained results was guaranteed by repeated tests through precision instruments such as the Wayne Kerr 6500B analyzer. Indeed, the consistent and reliable impedance profiles, extending over a number of tests and frequency ranges reflect the basic electrical characteristics of the motors accurately. It follows, then, that further studies into numerical modeling techniques to better optimize motor designs for the improvement of EMC are well founded.

5 Conclusion

In this paper, we have discussed the differential mode impedance characteristics of four types of single-phase induction motor: split-phase induction motor (SPIM), permanent split capacitor induction motor (PCIM), capacitor start induction motor (CSIM), and single-phase repulsion motor (RIM). The experiment carried out on the motors over a frequency range from 150 kHz to 30 MHz showed distinct impedance profiles and phase angle characteristics for each type.

It is obvious that RIM had generally higher impedance, indicating an appropriate design in cases of required EMC compliance. This will make the RIM very suitable for application in industrial automation systems and power grids where EMI control is of prime importance to maintain stable and reliable operations. On the other hand, CSIM had a much lower impedance for low frequencies due to its start capacitor. While that start capacitor significantly improved its startup efficiency, it may also raise its susceptibility to EMI. Further EMI mitigation strategies are probably required for this topology because of this possibility, to perform well under conditions where low-frequency EMI control becomes significant, such as in sensor networks.

Contrarily, PCIM has always shown lower impedance beyond the first resonance point, reflecting that it had unique design optimizations that perhaps call for higher frequency-specific EMC mitigation strategies. This kind of motor would serve well in applications with minimum EMI controls, which include consumer electronics and small industrial machinery.

This convergence tendency of the impedance profiles of PCIM and SPIM at lower frequencies may indicate that both kinds of motors can provide interchangeable solutions that exhibit similar EMC behavior. The phase angles showed complex interactions internal to the motors that weighted significantly from zero at resonance and anti-resonance frequencies, thus carrying important information on their electromagnetic behavior.

This study has underlined how impedance characteristics play a vital role in determining the expected EMC performance in motors of different types. Concluding our work hence represents important input toward the optimization of motor design, with a view to both fulfilling the requirements as laid down in EMC regulations as well as improving the performance in practical applications.

In future investigations, numerical methods, like simulations with MATLAB or other computational tools will be integrated in supplementing our experimental findings. This would allow us to simulate motor performance under different conditions and make more specific conclusions on how the parameters of the motor design impact its EMC performance.

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process
During the preparation of this work the authors used Quillbot in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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