

Modeling and Analysis of Leakage Currents in PWM-VSI-Fed PMSM Drives for Air-Conditioners with High Accuracy and within a Wide Frequency Range

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Abstract

Leakage currents occur in pulse-width-modulated voltage source inverter (PWM-VSI)-fed permanent magnet synchronous motor (PMSM) drives for air-conditioners, which seriously affect system safety and operation performance. High accuracy modeling and prediction of leakage currents are key issues for the design and implementation of air-conditioning products. In this study, the generation mechanism of leakage currents is discussed. A systematic modeling approach of leakage currents is proposed, including the modeling of leakage current sources and leakage current paths. By using the proposed approach, the complete model of leakage currents in PWM-VSI-fed PMSM drives for air-conditioners has been developed based on the extraction of all parameters. A comparison between the simulated leakage currents based on the developed model and measured leakage currents in the outdoor unit of an air-conditioning product is conducted. The comparison verifies the effectiveness of the proposed modeling approach, and the developed model exhibits high accuracy within a wide frequency range.

Key words: Air-conditioner, Leakage current, Modeling, Permanent magnet synchronous motor (PMSM), Pulse-width-modulated voltage source inverter (PWM-VSI)

I. INTRODUCTION

Pulse-width-modulated voltage source inverter (PWM-VSI)-fed permanent magnet synchronous motor (PMSM) drives have been extensively employed in air-conditioning products because of their features of high efficiency and remarkable steady-state/dynamic performances, particularly within a high-speed range [1], [2]. However, high-speed switching patterns of PWM-VSIs induce high pulsating common-mode voltages, which are imposed on

parasitic capacitances between the motor drive system and the ground and can cause high-frequency leakage currents [3], [4].

These leakage currents result in several serious problems when the current amplitude exceeds the standard values [1]: (1) deterioration of motor dielectric insulation; (2) bearing failures caused by leakage currents flowing through the shaft and bearing; (3) drive nuisance trips during operation; (4) lower speed/position control performances of motor drives; and (5) conductive electromagnetic interferences (EMI) that affect the controller and other equipment [4]-[9]. Thus, the analysis and suppression of leakage currents are important to ensure stable and reliable operation of PWM-VSI-fed PMSM drives for air-conditioners. High-accuracy modeling of leakage currents is the most significant basic work for analysis and suppression, including the modeling of leakage current sources and leakage current paths.

According to related literature published during recent

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years, three main factors affect the common-mode leakage current characteristics of PWM inverter-fed motor drives: (1) inverter topology (two-level or three-level), (2) PWM method (pulse pattern), and (3) filters if active/passive mitigation methods are used. The efforts on the suppression of leakage currents are also conducted in terms of these three aspects.

Different topologies and PWM methods of voltage source inverters have been investigated and evaluated on the reduction effects of common-mode voltages and common-mode leakage currents. For topologies, conventional two-level and neutral-point-clamped (NPC) three-level inverters are investigated. PWM methods, such as space vector PWM (SVPWM), discontinuous PWM, near-state PWM (NSPWM), and active zero-state PWM (AZSPWM), have been compared and discussed. The two-level VSI with RCMV-PWM (NSPWM or AZSPWM) exhibits comparable performance on leakage current reduction of NPC-VSI with SVPWM, which can be regarded as two cost-effective solutions for motor drives [10]. Zero-sequence voltages are added to the PWM pattern of inverters to reduce common-mode voltages, which lead to the reduction of common-mode leakage currents [11]. A small-sized passive EMI filter is proposed for the elimination of high-frequency shaft voltages and ground leakage currents from an AC motor driven by a PWM-VSI. By using this passive filter, a specific circuit configuration is established. A common-mode inductor is connected between the inverter and motor. The neutral point of the motor is connected to the DC-bus midpoint via a resistor. This unique circuit configuration makes the common-mode inductor effective in reducing common-mode voltages [12]. Furthermore, an improved passive EMI filter is developed to reduce ground leakage currents in inverter-fed motor drives, as well as bearing currents [13].

Based on the previously presented review of the literature, studies on leakage currents in PWM-VSI-fed motor drives mainly focus on the investigation on leakage current sources and its suppression methods by filters. However, these works are insufficient for the high-accuracy modeling of leakage current mechanism. The modeling of leakage current paths must be considered not only through inverter circuits but also through the motor and heat sinks.

In this study, a systematic modeling approach for leakage currents in PWM-VSI-fed PMSM drives based on the combination of impedance measurement and three-dimensional (3D) parameter extraction is proposed. The entire modeling procedure of leakage current sources and paths has been described and discussed in detail. Comparisons between the simulation results based on the developed leakage current model and the experimental measurement results were conducted to verify the high accuracy of the developed model and demonstrate the effectiveness of the proposed modeling method.

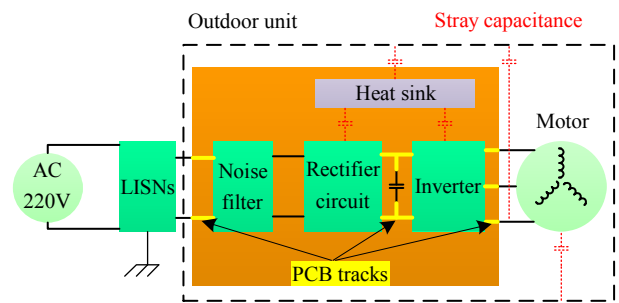


Fig. 1. Overall view of the outdoor unit of air-conditioners together with LISNs.

TABLE I
DIFFICULTIES IN LEAKAGE CURRENT MODELING

1)	Equivalent circuit modeling for stray capacitances associated with heat sink
2)	Equivalent circuit modeling of hermetic motor with high-frequency parameters
3)	Modeling of the leakage current sources in PWM inverters

II. DIFFICULTIES IN SYSTEM MODELING

Fig. 1 shows the typical circuit diagram of the outdoor unit of air-conditioners, which mainly consists of a noise filter, a rectifier circuit with power factor correction (PFC), an inverter, and a PMSM. Due to the high-speed switching pattern of PWM inverters, high pulsating common-mode voltages are induced, which cause leakage currents through stray capacitances between the motor/inverter with heat sink and the ground. Thus, the key issue in system modeling of leakage currents is accurate modeling of leakage current sources (pulsating common-mode voltages) and paths (particularly stray capacitances).

The high-frequency equivalent circuit model of the outdoor unit of air-conditioners for leakage current analysis has been built by the software Pspice with detailed considerations of the leakage current sources and paths. Fig. 2 shows an overall view of the simulation model, which consists of eight parts, namely, (1) line impedance stabilization network (LISN), (2) noise filter, (3) heat sink, (4) motor, (5) stray capacitances, (6) PCB tracks, (7) cables, and (8) leakage current sources.

Three main problems are encountered when modeling the leakage current analysis model (Table I): (1) Given that the heat sink has a complicated shape and several power devices are mounted on the same heat sink, many capacitive paths are coupled to each other and the related stray capacitances are complex. Thus, detailed modeling of stray capacitances is difficult to achieve. (2) Calculating and determining the high-frequency parameters of the hermetic motor are difficult given that insufficient information on the windings, core, and peripheral layout of the motor is provided by the manufacturer. (3) The third issue is modeling of leakage current sources in PWM inverters. Pulsating common-mode

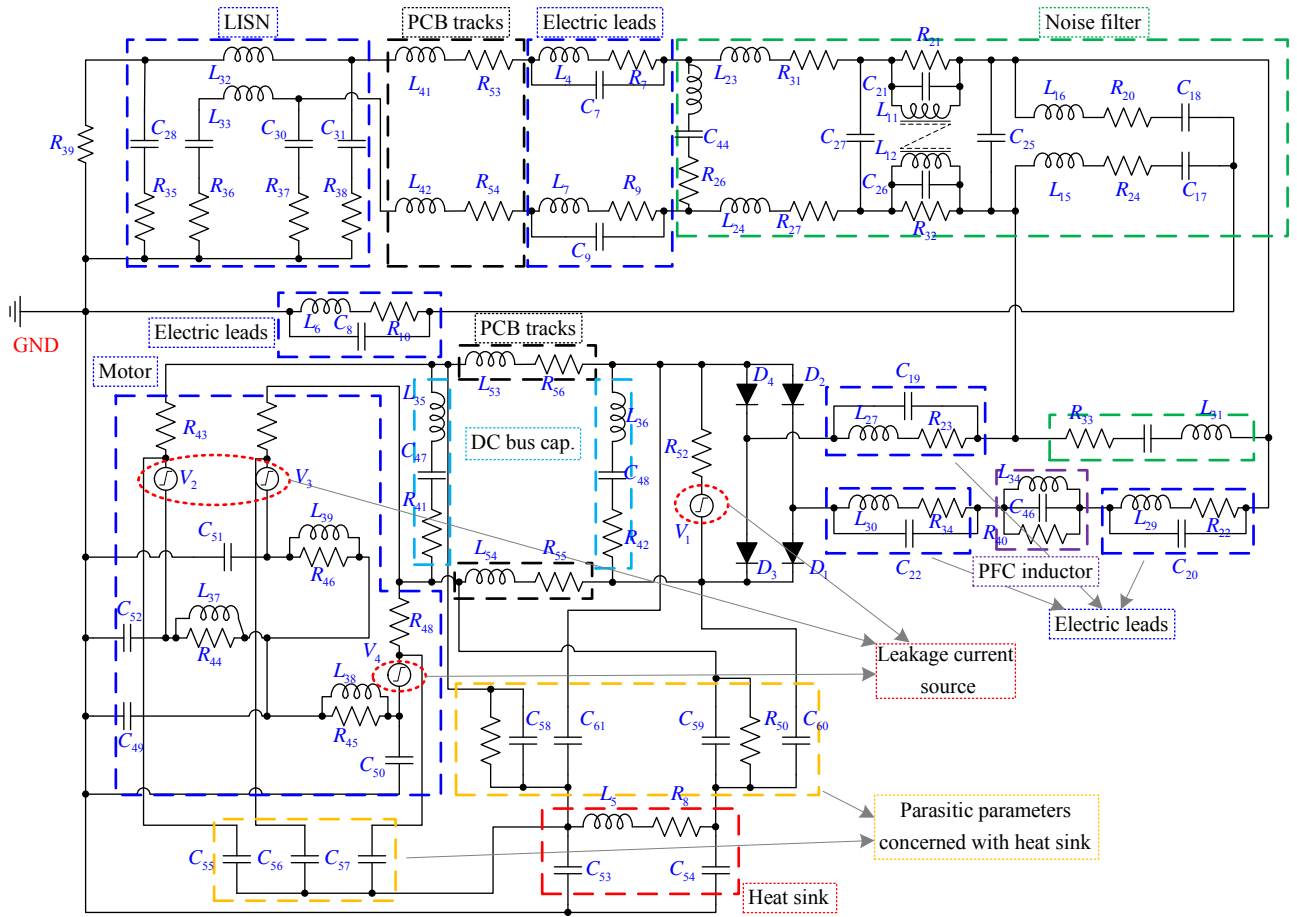


Fig. 2. High-frequency equivalent circuit model for leakage current analysis.

voltages are highly dependent on the employed PWM method and the characteristics of power devices because the switching waveforms of inverters are determined by the PWM method and the key parameters, such as rise/fall time, voltage overshoot, and voltage oscillation, are determined by the power devices. The complex PWM process and the nonlinear power device characteristics increase the difficulty of leakage current sources modeling.

The current through a capacitor can be expressed in Eq. (1), which shows that the current value is directly related to the capacitance value and the voltage change rate imposed on the capacitor. Therefore, accurate modeling of pulsating common-mode voltages and parasitic capacitances related to the heat sink and motor has a significant influence on the accuracy of leakage current modeling.

$$i_c = C \frac{dv_c}{dt}. \quad (1)$$

This study aims to obtain the rules for leakage currents in PWM-VSI-fed PMSM drives and provide a cost-effective design tool for air-conditioning products, rather than the high precision of the simulation model. Thus, a tradeoff between accuracy and complexity of the simulation model has been applied to simplify the model and to conduct a simulation analysis easily.

III. PROPOSED SYSTEMATIC MODELING APPROACH

A. Overview of the Systematic Modeling Approach

A systematic modeling approach based on the combination of impedance measurement and 3D parameter extraction method has been proposed to achieve accurate modeling of the leakage currents. For passive components, such as inductors and capacitors in the noise filter, the impedance measurement method is used to simulate impedance characteristics over a wide frequency range precisely and determine the high-frequency equivalent models of passive components to improve model accuracy. Given that the heat sink has no direct electrical connection with the main power circuit, the impedance measurement approach is inapplicable, which requires two determined terminals connected in circuits. Therefore, the equivalent circuit of the heat sink and its related stray capacitances are quite difficult to determine. Under the systematic modeling approach, 3D parameter extraction software is used to obtain these parameters with high precision.

The detailed characteristics of pulsating common-mode voltages are dependent on the employed PWM method and switching performances of power devices, such that it is impossible to be determined by theoretical analysis. Thus, the

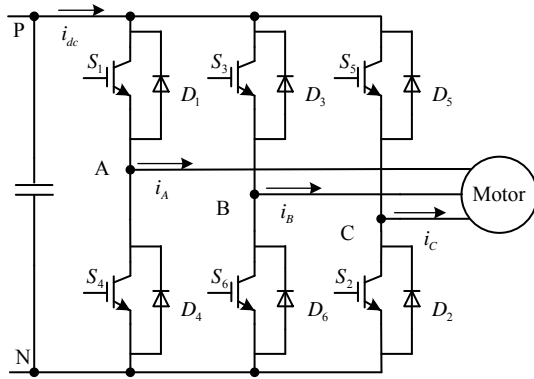


Fig. 3. Circuit diagram of the PWM-VSI-fed motor drive system.

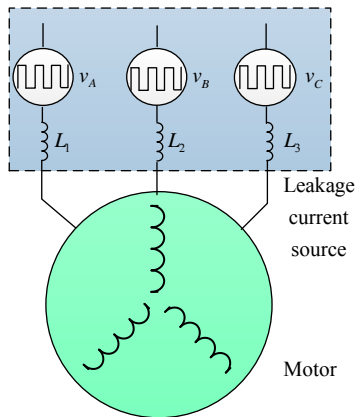


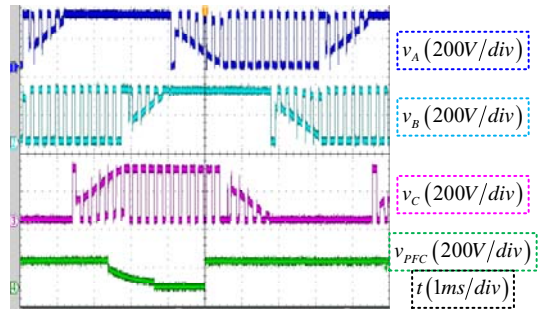
Fig. 4. Equivalent circuit model of leakage current sources in the PWM inverter.

experimental waveforms of pulsating voltages are measured and converted into mathematical data, which are used in the simulation model of leakage current sources.

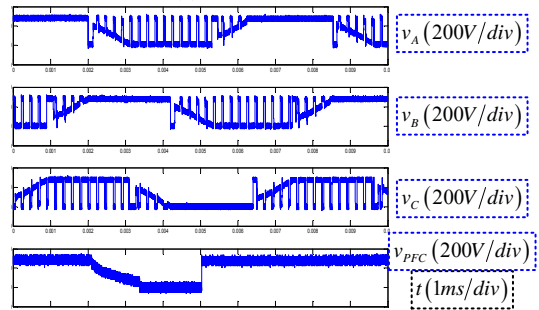
B. Modeling of the Leakage Current Sources

Generally, the high voltage variations produced by the high-speed switching patterns of PWM inverters result in leakage currents through stray capacitances to the ground. In the outdoor unit of an air-conditioner, the pulsating voltages are generated in the PFC circuit and the inverter circuit with PWM control, which are regarded as the leakage current sources. Experimental measurements have been conducted on the actual pulsating voltage waveforms to describe the characteristics of leakage current sources accurately. Then, the measurement data are passed as input into the simulation model.

In the PFC circuit, only one active switch (IGBT) is used and the collector-to-emitter voltage v_{PFC} is considered as the leakage current source. For the three-phase inverter, certain simplifications have been performed for the analysis of leakage current sources. The circuit diagram of the PWM-VSI-fed motor drive system is shown in Fig. 3. Given its symmetrical structure, the phase A circuit is taken as an example to analyze the conduction states of the active



(a) Measured results.



(b) Simulated sources in the simulation model.

Fig. 5. Leakage current source waveforms.

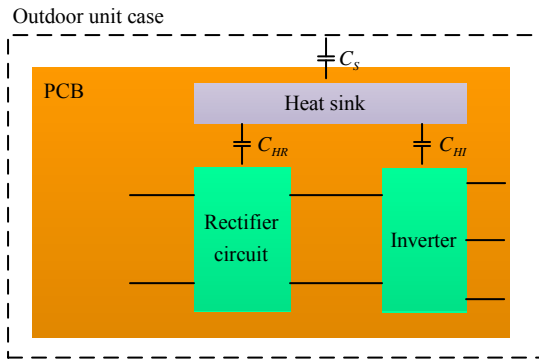


Fig. 6. Schematic diagram to illustrate the high-frequency parasitic parameters related to heat sinks.

switches, which determine the leakage current sources. When the current $i_A > 0$, i_A will not flow through the IGBT S_4 but through the diode D_4 . Thus, during this process, the pulsating voltage induced by the switching behavior of S_1 can be regarded as the leakage current source of the phase A circuit. Based on the symmetry of the inverter circuit, transient voltages produced by S_1 and S_4 have the same amplitude with a 180° phase difference.

According to the previously presented discussion, the equivalent leakage current source of phase A can be represented by the v_{CE} waveform of S_1 . Similarly, the v_{CE} voltages of S_3 and S_2 have been used as the leakage current sources for phases B and C, respectively. The equivalent circuit model of the leakage current sources of three-phase PWM inverters is shown in Fig. 4.

The measured pulsating voltage waveforms of the PFC and inverter circuits are shown in Fig. 5(a), and the simulated

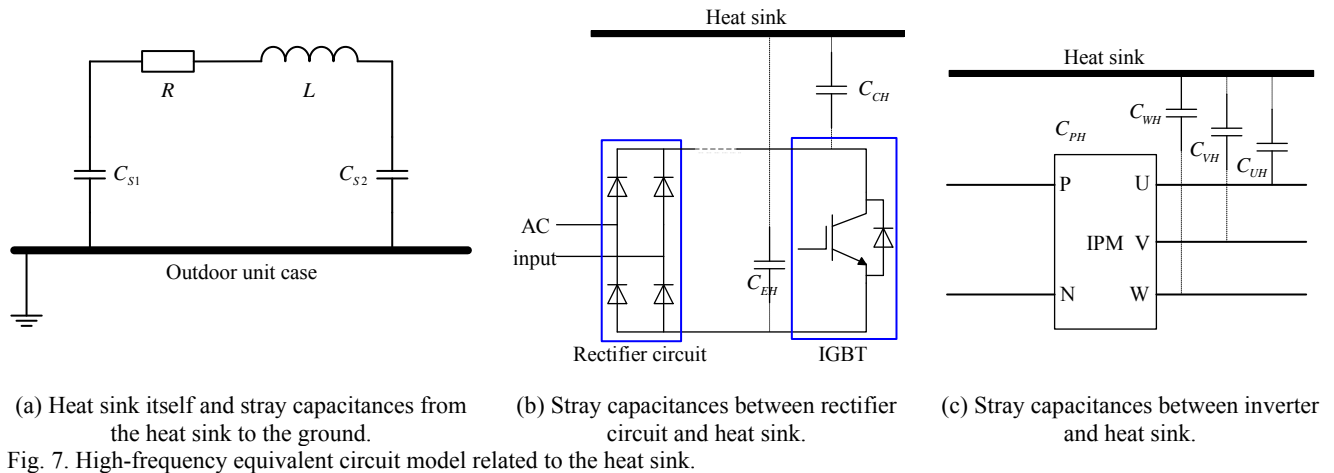
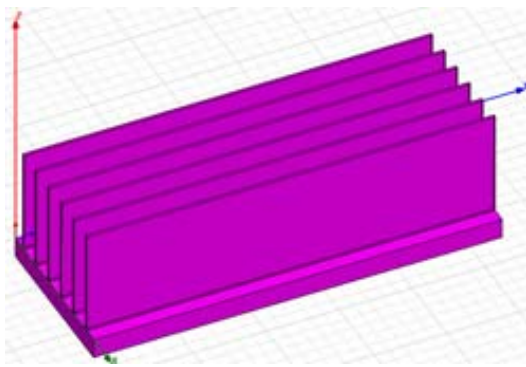
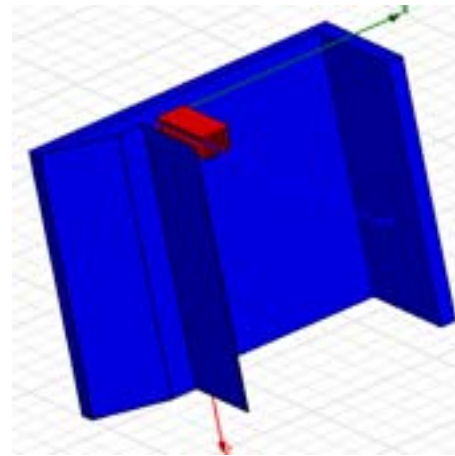


Fig. 7. High-frequency equivalent circuit model related to the heat sink.



(a) Heat sink.



(b) Heat sink and outdoor unit case.

Fig. 8. 3D analysis model.

source waveforms used in the leakage current simulation model are given in Fig. 5(b).

C. Modeling of the Leakage Current Path through the Heat Sink

The layout diagram of the power devices and the heat sink is shown in Fig. 6. From the figure, high-frequency parasitic parameters related to the heat sink can be divided into three parts, namely, (1) the equivalent high-frequency parameters of the heat sink itself and the stray capacitance between the heat sink and the ground; (2) the capacitances between rectifier circuit and heat sink; and (3) the capacitances between inverter circuit and heat sink. These high-frequency equivalent circuits are illustrated in Fig. 7(a) to Fig. 7(c).

The high-frequency parameters of the heat sink and its parasitic capacitances to the ground are extracted based on a 3D geometric model using Ansoft Q3D software, which is shown in Fig. 8. The calculated results of these parameters by the 3D extraction method are as follows:

$$C_{S1} = C_{S2} = 3.892 \text{ pF} \quad L = 47.195 \text{ nH} \quad R = 2.6419 \text{ m}\Omega. \quad (2)$$

Given that the pulsating voltages are directly applied to the power device pins, the stray capacitances between device

pins and heat sinks are selected to represent capacitive coupling between the rectifier/inverter and the heat sink. A high-precision LCR (Inductance-Capacitance-Resistance) meter is used to measure these parameters, and the results are given in Table II.

D. Modeling of the Leakage Current Path through the Hermetic Motor

The high-frequency parameters of the hermetic motor are complex. These parameters are related to the windings, the core in the motor, and the peripheral layout of the motor. Stator winding is represented by the circuit with lumped parameters for each phase to simplify the model, as shown in Fig. 9. The lumped parameters are as follows:

L_d is the phase leakage inductance; C_1 is the capacitance representing the distributed capacitive coupling effect between input leads of stator winding and ground; C_g is the capacitance representing the distributed capacitive coupling effect between midpoint N and ground; and R_e is the resistance representing eddy currents inside the magnetic core and the frame.

The impedance characteristics of the motor from the phase terminal (W) to the ground (G) can be measured by an

TABLE II
MEASURED STRAY CAPACITANCES BETWEEN RECTIFIER/INVERTER
AND HEAT SINK (UNIT: PF)

Parameter	C_{CH}	C_{EH}	C_{UH}	C_{VH}	C_{WH}
Value	124.04	118.73	98.69	98.76	97.63

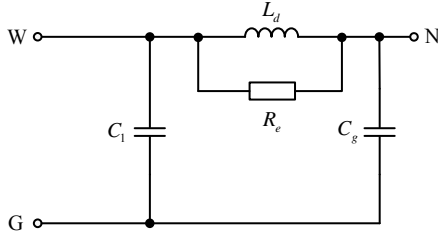


Fig. 9. Equivalent circuit of the motor (one phase).

TABLE III
HIGH-FREQUENCY PARASITIC PARAMETERS OF THE HERMETIC
MOTOR

Parameter	C_1 (nF)	C_g (nF)	R_e (Ω)	L_d (μ H)
Value	0.001	5.89	1,180.40	13.80

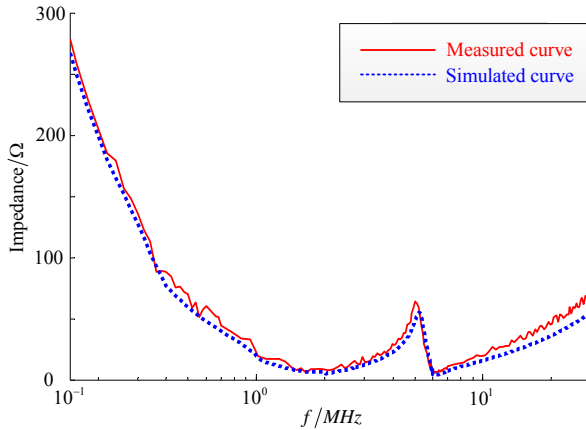


Fig. 10. Measured and simulated impedance characteristics of the motor.

impedance analyzer. Moreover, the theoretical expression of $Z_{WG}(s)$ can be obtained based on the equivalent circuit shown in Fig. 9 and is expressed in Eq. (3). Then, the parameters can be determined by using the curve fitting method; the results are given in Table III. From the measured and simulated impedance curves shown in Fig. 10, the simulation results match the measured results well, which indicate that modeling using the curve fitting method is highly accurate.

$$Z_{WG}(s) = \frac{S^2 L_d C_g + S \frac{L_d}{R_e} + 1}{3S \left[S^2 L_d C_1 C_g + s \frac{L_d}{R_e} (C_1 + C_g) + (C_1 + C_g) \right]} \quad (3)$$

E. Modeling of the other parts of the drive system

Common-mode filter capacitors are also important leakage current paths in the outdoor unit of air-conditioners. The

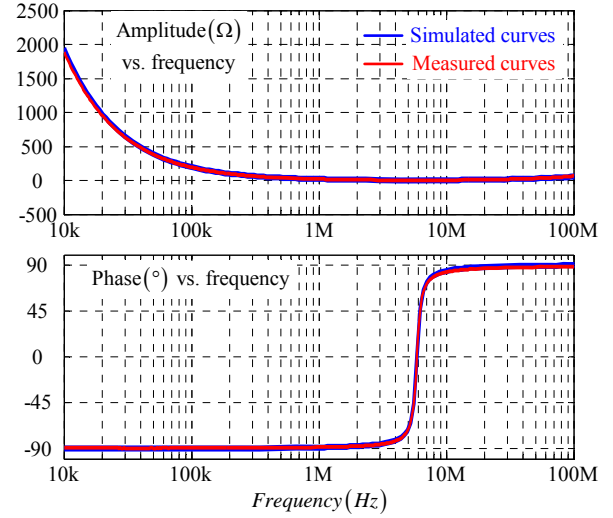


Fig. 11. Measured and simulated impedance characteristics of the common-mode filter capacitor.

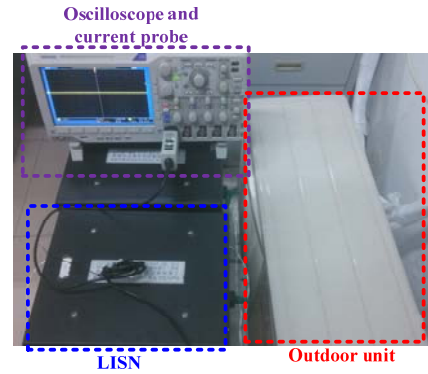


Fig. 12 Experimental setup for the leakage current measurements.

serial connected $R-L-C$ circuit is used as the equivalent circuit model for the capacitors. The impedance measurement and curve fitting methods are used to determine the parasitic parameter values, which are:

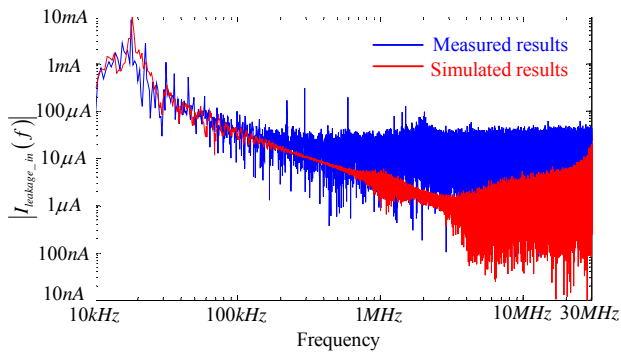
$$R = 365.304 \text{ m}\Omega \quad L = 89.926 \text{ nH} \quad C = 8.169 \text{ nF} \quad (4)$$

The measured and simulated impedance characteristics are shown in Fig. 11. The simulated curves show almost no difference compared with the measured curves. Moreover, high modeling accuracy of the common-mode filter capacitor has been achieved. For other passive components, such as the common-mode filter inductors, differential mode filter capacitors, and cables, high-frequency equivalent circuit models and parameter values can also be determined by this impedance measurement approach.

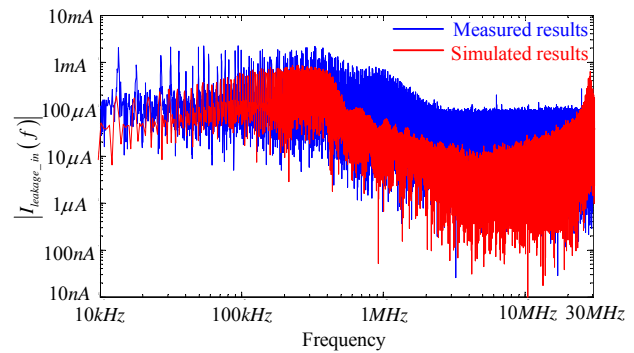
The PCB tracks on the main power circuit board function as part of the leakage current paths, which have different layouts and various dimensions, as well as carry currents with different values. A 3D analysis method is employed to extract the high-frequency parameters to model the PCB tracks with high accuracy, which is as the same as the method used for the modeling process of heat sinks.

TABLE IV
SUMMARY OF THE SYSTEM MODELING APPROACH FOR LEAKAGE CURRENTS

No.	Parts	Modeling approach	Parameters extraction method
1	Passive components/motor	Impedance measurement	Curve fitting method
2	Stray capacitances related to the heat sink	Measurement and 3D analysis software	Curve fitting method and 3D extraction method
3	PCB tracks	3D analysis software	3D extraction method
4	Leakage current sources	Measurement	Measurement

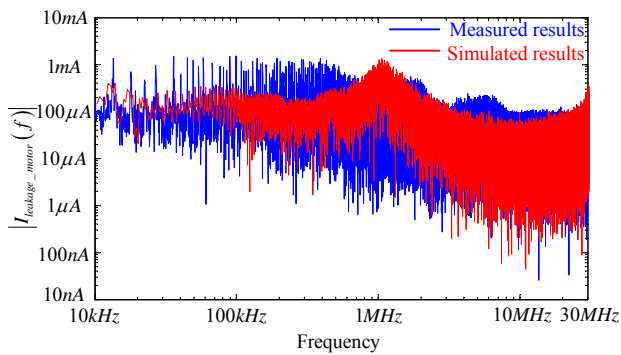


(a) With noise filter.

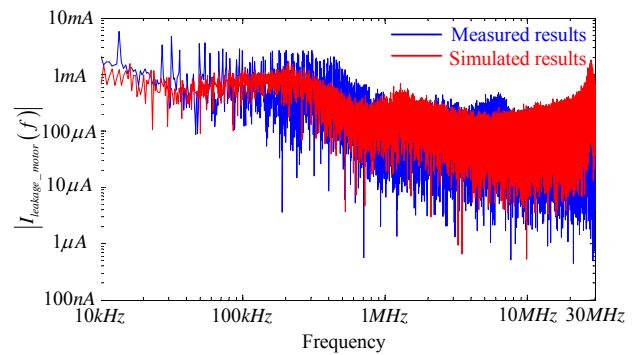


(b) Without noise filter.

Fig. 13. Input leakage current spectra.



(a) With noise filter.



(b) Without noise filter.

Fig. 14. Motor leakage current spectra.

Systematic modeling approaches and parameter extraction methods for leakage currents are summarized in Table IV.

IV. COMPARISON BETWEEN SIMULATION RESULTS AND MEASUREMENT RESULTS

A. Experimental Setup

An experimental setup for leakage current measurements of the outdoor units of air-conditioners has been built to verify the effectiveness of the proposed systematic modeling approach (Fig. 12). LISNs are connected between the power supply and the outdoor unit; these are used to prevent utility grid noises from affecting the test results.

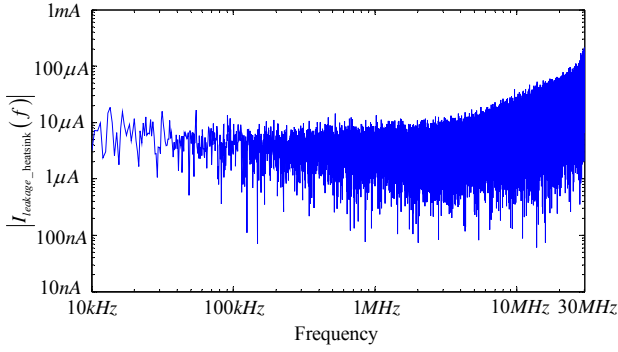
B. Comparison Results

Leakage current measurements have been conducted to verify the accuracy of the simulation model under two different working conditions, namely, (1) outdoor unit

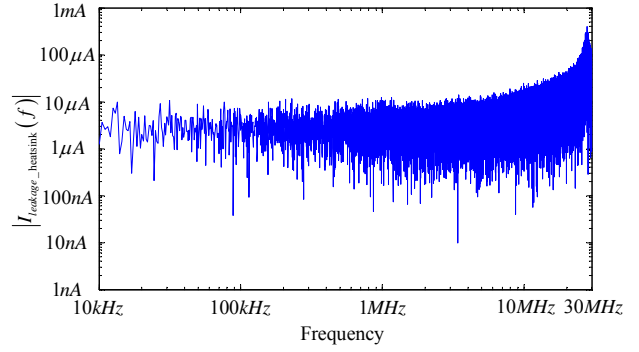
operating with noise filter and (2) outdoor unit operating without noise filter. The filter used in the experimental platform was designed by the manufacturer of the air-conditioning product and no changes were applied to the filter parameters during our research. The input leakage current measurement results are obtained by measuring the sum of currents through two AC input cables of the outdoor unit.

The measured and simulation results of the input leakage currents with noise filter are compared through the frequency spectra, as shown in Fig. 13(a). The simulation results have been obtained by the developed high-frequency equivalent circuit model with the use of the simulation software Pspice. From Fig. 13(a), the frequency and amplitude values of the peak points in the simulated leakage current spectrum are consistent with the test results.

An index that contains the complete information and the effects of the important points is required to describe the



(a) With noise filter.



(b) Without noise filter.

Fig. 15 Simulated spectra of leakage currents through stray capacitances related to the heat sink.

spectrum results accurately in general. The overall value, $I_{overall}$, is adopted to evaluate the spectrum results of the leakage currents. $I_{overall}$ is defined as the sum of the squared amplitude of each harmonic component of the leakage current, as given in Eq. (5).

$$I_{overall} = \sum_{i=1}^N I_i^2, \quad (5)$$

where I_i is the amplitude value of the i -th harmonic current. From the equation, complete information is derived from the $I_{overall}$ value because of the sum operation. The effects of the important points (such as peak points) have also been enhanced because of the square operation.

The measured $I_{overall}$ value of the input leakage current with noise filter is approximately 188.32 mA^2 , and the simulation result is 186.16 mA^2 (Table V). The relative error is only -1.14% , which indicates that a high-accuracy simulation result has been achieved. The measured and simulated input leakage current spectra without noise filter are shown in Fig. 13(b). The peak point in the simulated spectrum matches the measured results well (approximately 300 kHz). The measured $I_{overall}$ value is $1,000 \text{ mA}^2$, and the simulated value is 943.29 mA^2 with a relative error of -5.67% . These comparisons verify that the developed model exhibits a high accuracy and that the proposed modeling approach is effective for leakage current analysis during the product development process.

From the spectrum results shown in Fig. 13, the simulated spectra match the measured results with small errors within the frequency range of 10 kHz to 1 MHz. However, the amplitude values of the simulation spectra are less than those of the measured results within the frequency range of 1 MHz to 30 MHz.

The reason has been investigated and discussed. First, a signal cable is connected between the indoor unit and the outdoor unit in the experimental system. This signal cable provides additional leakage current paths and may cause errors. Second, the tradeoff between accuracy and complexity of the simulation model has been applied and certain simplifications have been performed to reduce model

TABLE V
MEASURED AND SIMULATED INPUT LEAKAGE CURRENT RESULTS

$I_{overall} \text{ (mA}^2\text{)}$	With noise filter	Without noise filter
Measured	188.32	1,000
Simulated	186.16	943.29
Relative error	-1.14%	-5.67%

TABLE VI
MEASURED AND SIMULATED MOTOR LEAKAGE CURRENT RESULTS

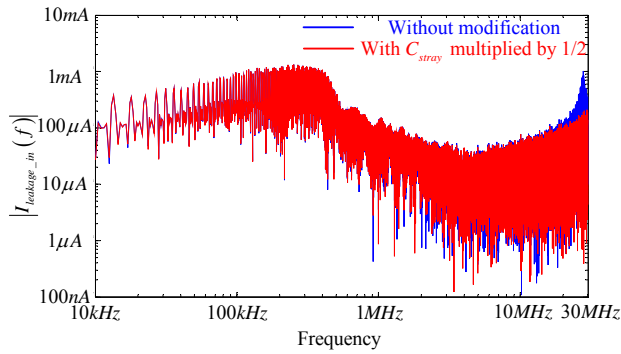
$I_{overall} \text{ (mA}^2\text{)}$	With noise filter	Without noise filter
Measured	1,300	1,100
Simulated	1,400	1,200
Relative error	7.69%	9.09%

TABLE VII
SIMULATED LEAKAGE CURRENT THROUGH STRAY CAPACITANCES RELATED TO THE HEAT SINK

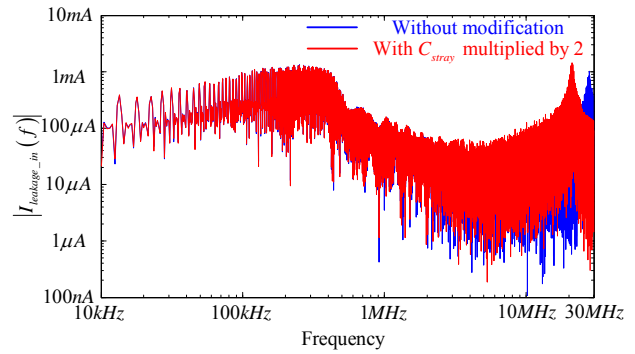
$I_{overall} \text{ (mA}^2\text{)}$	With noise filter	Without noise filter
Simulated	93.90	73.67

complexity and calculation time costs. Nevertheless, the model is still quite complex and the simulation is quite time-consuming. Taking the hermetic motor as an example, the simulation model given in Fig. 9 is constructed by several

lumped parameters, and fortunately, the simulated impedance characteristics match the measured impedance characteristics well. However, the operating temperature inside the motor is not constant and may cause parameter variations. Thus, simulation precision will be reduced. Furthermore, modeling the hermetic motor accurately by considering the temperature effect is infeasible because measuring the temperature inside the hermetic motor or measuring the impedance characteristics under normal operation is impossible for safety concern. According to the previous studies [14], [15], near-field coupling, particularly magnetic coupling (also called inductive coupling), has effects on the conducted EMI. Near-field coupling includes magnetic and electric couplings (also called capacitive coupling). The electric coupling effects behave as stray capacitances in the air-conditioning system, such as stray

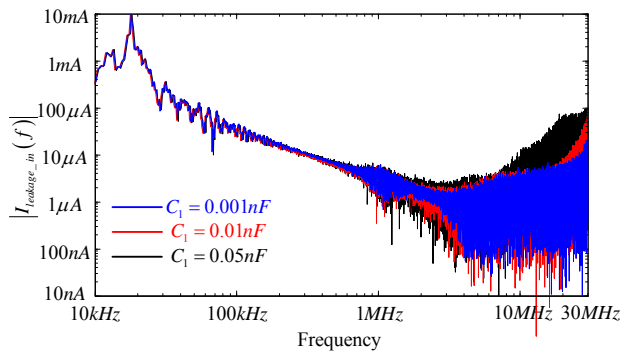


(a) With Cstray multiplied by 1/2.

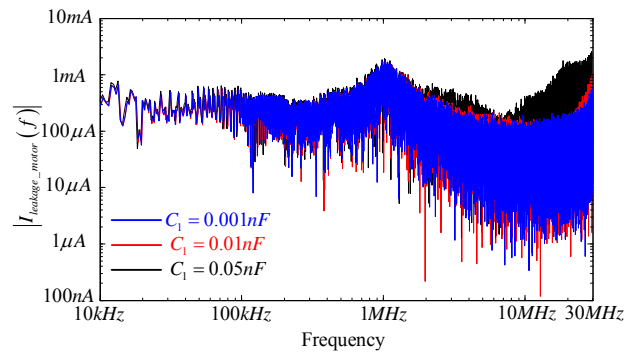


(b) With Cstray multiplied by 2.

Fig. 16. Simulated input leakage current spectra with different stray capacitances related to the heat sink (without noise filter).

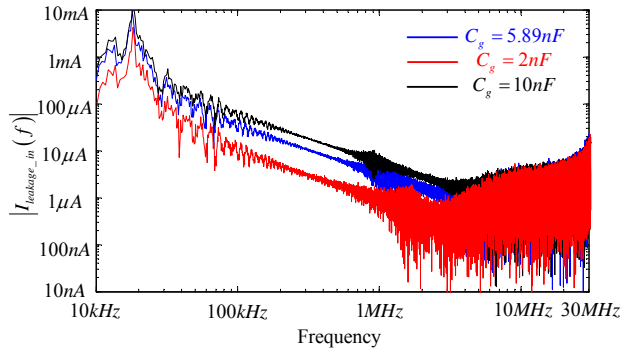


(a) Input leakage current.

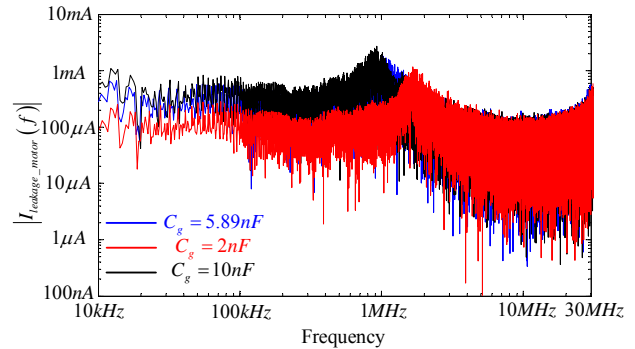


(b) Motor leakage current.

Fig. 17. Simulated leakage current spectra with different values of parasitic capacitance C_1 (with noise filter).



(a) Input leakage current.



(b) Motor leakage current.

Fig. 18. Simulated leakage current spectra with different values of parasitic capacitance C_g (with noise filter).

capacitances of the hermetic motor and those concerning heat sinks, which have been already well considered. Based on the mechanism of magnetic field coupling, mutual inductive coupling between inductors (including parasitic inductances of capacitors and cables) must be modeled, which has not been considered in the simulation model. However, many inductances exist and coupling relationships are quite complicated, which make accurately modeling coupling relationships difficult. Meanwhile, considering these couplings, the simulation model will become more complicated, which will prolong simulation time and make simulation analysis difficult. Furthermore, according to the mechanism of leakage currents, stray capacitances play

important roles and magnetic coupling may only have a slight effect on leakage currents. Based on the previously presented discussions, the tradeoff between accuracy and complexity of the simulation model must be considered and certain reasonable simplifications of the simulation model are necessary. Although the simulation cannot achieve extremely high accuracy within the entire frequency range, the overall accuracy is greater than the acceptable level.

Furthermore, the main target of this work is to obtain rules on leakage currents in PWM-VSI-fed PMSM drives for air-conditioning products. The simulated peak point and overall values of the leakage current spectra are consistent with the measured results. Complete information, with the

effects of the important points of the leakage current spectra, has been well presented based on the selected peak point and overall values. Therefore, based on the simulation results, several rules on leakage currents can be obtained: (1) The peak value of input leakage currents occurs at approximately 20 kHz with noise filter and at approximately 300 kHz without noise filter. (2) Noise filter is quite effective in suppressing leakage currents passing through the input source. Thus, the tradeoff between accuracy and complexity of the simulation model is accepted. Therefore, the proposed modeling approach and the developed simulation model are valid and can be used as design tools for manufacturers to ensure that air-conditioning products meet the product standards during the development process.

Based on the results shown in Fig. 13, increases have been observed at approximately 20 kHz after a filter is used. The reason is that filters are mainly designed to meet the traditional EMI requirements for the product, but not for leakage currents. This study mainly focuses on leakage currents, and related research achievements can be used as the basis for improving filter designs in the future.

According to the analysis during the modeling process, the motor provides the main leakage current paths because it is directly connected to the leakage current sources (PWM inverter) and has large parasitic capacitances to the ground. Thus, evaluating the leakage currents at the motor side is necessary. The measured and simulated leakage current results at the motor side are given in Fig. 14 and Table VI. The simulated motor leakage current spectra with and without noise filters are consistent with the measured results, and relative errors between the simulated and measured overall values are within the low level (<10%). These results indicate that the developed simulation model exhibits high precision. The simulated and measured motor leakage currents verify that the motor provides the main leakage current paths in the air-conditioning system.

In addition to the motor, stray capacitances related to the heat sink also provide paths for leakage currents. However, the experimental measurements of leakage currents through these capacitances are infeasible because there are no valid connection terminals of these “invisible” capacitances. Thus, only simulations are conducted; the simulation results are shown in Fig. 15 and Table VII. By comparing the leakage currents through the motor and through the stray capacitances related to the heat sink, the motor provides the main leakage current paths, whereas the stray capacitances cover only a small section of the leakage currents in the air-conditioner. Thus, the motor in the system is expected to be modeled in more detail to achieve high-accuracy simulation analysis of the leakage currents.

In summary, the PWM inverter and the motor in the air-conditioner generate most leakage currents and provide the main current paths. Leakage currents can be suppressed

by noise filter flowing through the input cables into the utility grid.

C. Discussions

For further detailed analysis, several simulations have been conducted to investigate the influences of parameters on the leakage currents. Given that leakage currents are generated by imposing common-mode pulsating voltages on parasitic capacitances, stray capacitances to the ground in the system have relatively significant effects on the leakage currents.

Fig. 16 shows the simulation spectra of input leakage currents when stray capacitances related to the heat sink are multiplied by 1/2 and 2 without noise filter in the system test. Changes in stray capacitances related to the heat sink have only a slight effect on the input leakage currents. From Fig. 16(b), a resonant peak occurs at approximately 20 MHz when stray capacitances are doubled, which is due to the resonance between the stray capacitances and the parasitic inductances. When capacitances decrease, the frequency value of the peak point increases and is consistent with the analysis.

Fig. 17 shows the simulation results of input leakage currents and motor leakage currents with different values of parasitic capacitance C_1 of the motor with noise filter in the system test. The different values of C_1 have almost no effect on the simulated spectrum within the frequency range of 10 kHz to 10 MHz. Meanwhile, the increase in the value of C_1 causes an increase in the input leakage currents and motor leakage currents within the range of 10 MHz to 30 MHz.

The simulation results of input leakage currents and motor leakage currents with different values of parasitic capacitance C_g of the motor are shown in Fig. 18 while the system is tested with noise filter. In contrast to the influence of C_1 on leakage currents, the increase in C_g leads to an increase in input leakage currents and motor leakage currents within the frequency range of 10 kHz to 10 MHz. Meanwhile, its effect on leakage currents is small, within the range of 10 MHz to 30 MHz.

Based on the aforementioned simulation analysis, stray capacitances to the ground, particularly parasitic capacitances of the motor, have a significant effect on the leakage currents. In particular, capacitance C_1 has a greater influence on leakage currents within the frequency range of 10 MHz to 30 MHz, whereas C_g has a more significant effect on leakage currents within the frequency range of 10 kHz to 10 MHz.

V. CONCLUSION

In this study, a systematic modeling approach of leakage currents in PWM-VSI-fed PMSM drives for air-conditioners is proposed. By using the proposed modeling approach, a complete high-frequency equivalent circuit model of leakage currents in the drive system has been developed. Comparisons between the simulated leakage current spectra based on the developed model and the experimental

measurement results under different working conditions have been conducted. The comparisons reveal that:

1) The developed model exhibits a high accuracy over a wide frequency range because all relative errors between the simulated spectra and measured spectra are within $\pm 10\%$ in the range of 10 kHz to 30 MHz.

2) The proposed modeling approach is a feasible and effective way to establish the high-frequency equivalent circuit model of leakage current sources and paths.

Therefore, the proposed modeling approach and the developed simulation model of leakage currents in PWM-VSI-fed PMSM drives can be used as design tools for manufacturers to ensure that air-conditioning products meet the product standards during the research and development process.

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