A Review of Broadband Frequency Techniques for Insulation Monitoring and Diagnosis in Rotating Electrical Machines

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***Abstract*—Rotating electrical machines greatly suffer from insulation degradation and failure. The adoption of wide band-gap semiconductors in Variable-Frequency Drives (VFDs) hinder the utilization of traditional techniques such as on-line Partial Discharges (PD) to monitor and diagnose the insulation status and failure. Alternative techniques exploiting the broadband frequency behaviour of machine windings, and the increased high-frequency content of VFD excitation arise as a valid alternative. The present work provides a comprehensive analysis and review of cutting-edge broadband frequency techniques aimed to diagnose winding insulation degradation and faults. First, the broadband nature of machine windings is illustrated by explaining the per-turn equivalent circuit and the physical interpretation of its parameters. Then, the different insulation monitoring and diagnosis methods are thoroughly reviewed. The analysed methods include the Frequency Response Analysis (FRA) applied to rotating electrical machines, the analysis of Common Mode (CM) broadband impedance and parasitic capacitances, and methodologies based on the analysis of transient high-frequency current ringing. Specific focus is placed on the instrumentation, which often represents the main applicability limitations.**

***Index Terms*—Insulation, condition monitoring, predictive maintenance, ac machines.**

I. INTRODUCTION

THE reliability of rotating electrical machines represents a key aspect in several industries, where machine failures lead to catastrophic repairs and downtime economic costs. The different faults that occur in traditional industrial rotating machinery are of diverse nature. These can be related to the rotor, stator, bearings, load, etc. Industrial surveys point out that the major causes of failure are related to the stator winding and the bearings with a possibility of failure of 26% and 44% respectively [1]. With the utilization of modern Variable Frequency Drives (VFDs), the percentage of stator winding faults is expected to be higher for many applications.

The insulation of the different windings of the machine (i.e., generally stator, but also windings allocated in the rotor) represents one of the weakest constructive elements. These are normally formed by materials with adequate dielectric properties such as polymers and some minerals (e.g., epoxy resins, mica, polyesters, etc.). Several insulation degradation mechanisms take place depending on the rotating machine operating context, such as thermal and electrical ageing [2]. The degradation of the insulation may lead to the short-circuit fault of different elements of the winding (e.g., inter-turn, ground, phase-to-phase, etc.). These short-circuits generally trigger the partial or total rewinding, and the outage of the machine. Thus, the close monitoring of insulation systems represents a key feature for predictive maintenance implementation.

Traditionally, the status of the different insulation elements is determined off-line. Standardized techniques such as the surge, polarization index, and off-line Partial Discharges (PD) tests have the ability to diagnose the status of several insulation elements [2], [3]. These present obvious drawbacks related to the need of machine disconnection, disassembly and the non-continuous nature of these tests. According to Stone et al. [2], several on-line insulation monitoring methodologies are commercially available. The most widespread technique is the on-line PD monitoring, which is successfully applied to a large amount of machines rated 6 kV and above in the last 20 years [4]. It consists of detecting high-frequency signals from discharges around insulation elements to diagnose insulation status. This is achieved by utilizing different types of sensors such as radio-frequency antennae embedded within the winding or capacitively coupled sensors in the winding terminals. The main issue of on-line PD is the separation of the discharge pulses and the high-frequency spectra induced by the utilization of VFDs [5]. The adoption of wide band-gap semiconductors with increased voltage gradient (dv/dt) and switching frequencies represents the most critical limitation of on-line PD future development [6].

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Lee et al. [7] presented a methodology based on leakage current tracking at mains frequency, which allows to estimate the value of the insulation equivalent resistance, capacitance and dissipation factor. This requires the utilization of High-Sensitivity Current Transformers (HSCT) that enclose the machine single phases and the neutral point. According to Stone et al. [2] the methodology is not yet widespread for the continuous monitoring and only devoted to periodic testing. In addition, it requires the winding to be wye-connected and the neutral point to be accessed. However, it represents a close alternative to the on-line PD method.

Several comprehensive studies and surveys were previously developed to identify challenges and research opportunities in the field. Inter-turn fault detection is recognized as one of the main research gaps for both low-voltage and medium-voltage machines [3], [8]. This was recently confirmed by the study of Lee et al. [6]. This work also highlights the lack of methods dealing with the monitoring under VFD operation and the non-invasive detection of rotor field winding insulation failures. The application of methodologies exploiting the broadband excitation and behaviour of machine windings provides new solutions to these challenges. The broadband excitation is related to frequencies ranging from the kHz until the MHz band, which cover the spectrum above the machine operating range (i.e., hundreds of Hz). However, the acquisition and interpretation of high-frequency signals poses several challenges in terms of hardware, signal processing, and accurate understanding of high-frequency electromagnetic phenomena. This article is aimed to the detailed analysis and review of monitoring and diagnosis techniques that utilize broadband frequency excitation. It extends the conference version in [9] by broadening the review, providing further insights about hardware and further detailing the most relevant works. The examined studies demonstrate satisfactory sensitivity for the designated applications in a broad context. Nevertheless, certain investigations exhibit notable constraints, which are elucidated within this manuscript. The paper is organized as follows. Section II describes in detail the broadband response and per-turn equivalent circuit of windings. Section III describes the research progress on the application of Frequency Response Analysis (FRA) to rotating machines. Section IV discusses techniques based on parasitic capacitance and Common-mode (CM) broadband impedance analysis. Section V studies methodologies related to the current high-frequency ringing analysis. Section VI offers conclusions, discussions, and insights on challenges and opportunities in the topic.

II. BROADBAND FREQUENCY REPRESENTATION AND INTERPRETATION OF WINDINGS

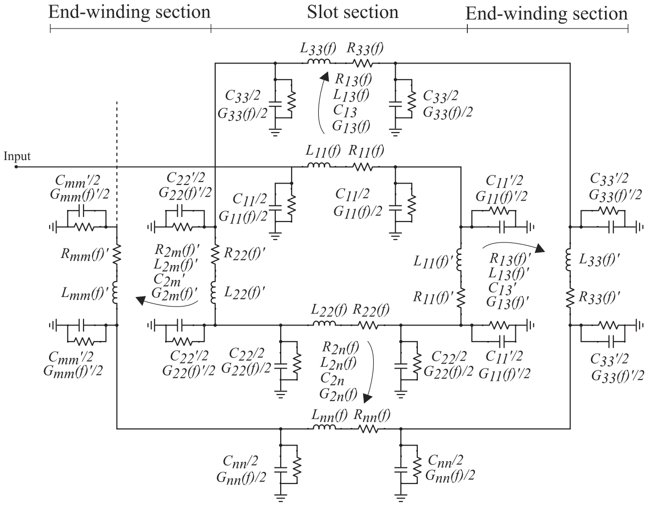


Fig. 1. Lumped-pi per-conductor equivalent circuit of a coil with slot and end-winding sections.

The electromagnetic coils can be physically described in detail by utilizing multi-conductor transmission line theory [10]. The single conductors within the machine slots and forming the end-winding are represented by lumped-pi equivalent circuits by assuming that the conductors are electrically short [11]. These circuits are described by per unit length parameters (i.e., series resistance and inductance, and shunt capacitance and conductance). Different physical representations are described in [12], [13]. Fig. 1 shows the lumped-pi equivalent circuit of a coil with n slot conductors and m end-winding conductors. Each parameter of the equivalent circuit symbolizes different electromagnetic phenomena. The series resistance and inductance (i.e., R_{ii} and L_{ii}) represent the losses and magnetic flux linkage of the conductors respectively. These parameters are frequency dependent because of the skin and proximity effects, and the limited flux penetration due to the reduced penetration depth at high-frequencies. Moreover, high-frequency eddy-currents flowing within single laminations cause a shielding effect of the main flux within the slots, which dramatically affects the series inductance and resistance [14]. The mutual resistance and inductance (i.e., R_{ij} and L_{ij}) represent the losses and flux linkage induced by the current flowing within neighbouring conductors [11]. The shunt capacitance and conductance (i.e., C_{ii} and G_{ii}) represent the storage of electric field, and current conduction and the dielectric losses of the groundwall insulation respectively. The mutual capacitance and conductance (i.e., C_{ij} and G_{ij}) represent these same phenomena in the inter-turn and phase-to-phase insulation elements. The different works found in literature for machine winding modelling consider capacitances as frequency independent even if the dielectric material permittivity varies with frequency [15]. Note that depending on the machine section (i.e., slot or end-winding) the parameters adopt very different values since the boundary conditions for electric and magnetic field distribution dramatically vary [16].

The geometry, connection and material properties define the value of the per-unit length parameters that form the equivalent circuit. The addition of all these elements together defines the overall winding impedance. The characteristic features of the broadband impedance are the amplitude at different frequencies, the location of the resonant points (i.e., frequencies at which the magnitude presents an inflection point) and the phase. For three phase rotating machines, the measurement can be performed in different modes depending on the measurement objective. Some of the most popular modes are the phase impedance, which is

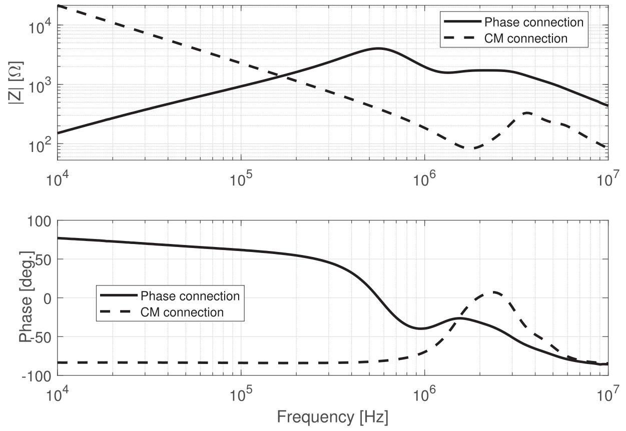


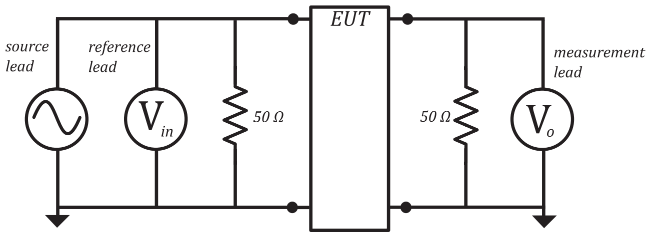
Fig. 2. Phase and CM broadband impedance stator winding measurement for a 4.7 kW PMSM with concentrated winding.

measured between machine phases, and the CM impedance, measured between three short-circuited phases and the stator housing. Fig. 2 shows an example of broadband impedance measurement of two different modes for a low voltage Permanent Magnet Synchronous Machine (PMSM) between 10 kHz and 10 MHz. Broadband frequency techniques for condition monitoring and fault diagnosis are based on the analysis of changes of this electrical signature over various frequency bands. The variation of the impedance response depending on different circuit elements is presented in [17]. Moreover, the machine impedance affects the high-frequency oscillations of the current in the machine terminals. Thus, the monitoring of such current components provides information about the machine impedance variation in an indirect manner, which is exploited by the methods presented in Section V.

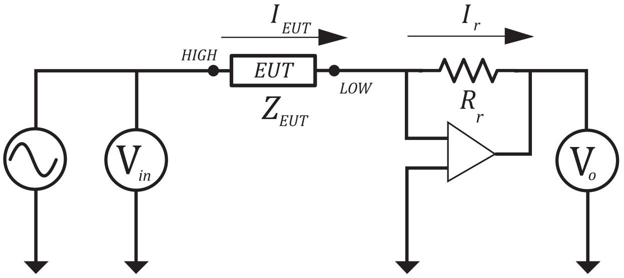
III. FRA Applied to Rotating Machines

The FRA applied to power transformers is a standard procedure utilized to detect mechanical movement or damages under different scenarios such as installation, relocation, condition alarms, etc. [18]. The FRA measurement is based on the transformer winding admittance or impedance mapping over a broadband frequency. The diagnosis is performed by comparing different measurements with a baseline reference. Deviations between the diagnosis and the baseline measurements indicate different faults and defects. The applicability of FRA to rotating machinery is not found in standards so far. However, the method triggered some research attention over the last years since it presents many advantages for detecting a wide variety of faults by utilizing an on-site and quick test.

The most common type of FRA for rotating machines is the off-line Sweep Frequency Response Analysis (SFRA). The measurement equipment applies a swept sinusoidal signal to the input port of the Equipment Under Test (EUT), and measures the response in the end port. Two different instruments are mainly present in literature to obtain the electrical signature of a rotating electrical machine. The first one is known as gain-phase analyser, which is commercially available for application to the power transformer diagnosis. This apparatus injects a swept voltage signal in the input port and measures the voltage in the output port. The transfer function of the EUT is given by (1) and the test set-up is shown in Fig. 3(a). The second apparatus for electrical signature measurement is known as impedance analyser, which is an auto-balancing impedance bridge that provides the impedance amplitude and phase, among other possible options (i.e., R-X, G-B, etc.). The apparatus has four terminals named as High Potential (H_p), High Current (H_c), Low Potential (L_p) and Low Current (L_c). Two of the terminals are connected to the high port and the remaining two to the low port of the EUT. Fig. 3(b) shows an auto-balancing bridge equivalent circuit [19] highlighting the most important parameters and (2) describes the impedance computation. Besides the connection schematics and the working principle, the most important difference between the two equipments lays on the voltage level of the oscillator and on their input impedance. Gain-phase analyser utilizes matched 50 Ω resistances in the measurement terminals while the impedance analyser uses an undefined large input impedance. The Vector Network Analyzer (VNA) represent a valid alternative even if not deeply spread in literature. Its utilization is mainly aimed at microwave frequency bands (10 MHz - 50 GHz) [20]. Nevertheless, some commercial models offer broadband frequency impedance measurement from few Hz covering the frequency range of interest for SFRA. Another valid alternative for SFRA is the utilization of a custom sinusoidal function generator and a broadband current sensor. The impedance is obtained by performing the voltage-current ratio in the frequency domain [21].



(a)



(b)

Fig. 3. (a) Gain-phase analyser method for broadband impedance measurement, (b) Auto-balancing bridge equivalent circuit for broadband impedance measurement.

$$Y_{dB} = 20log_{10}\left|\frac{V_{in}}{V_o}\right| \tag{1}$$

$$Z_{EUT} = \frac{V_{in}}{I_{EUT}} = R_r \frac{V_{in}}{V_o} \tag{2}$$

The research in the field is traditionally oriented to the off-line fault detection of stator windings in low- medium-voltage machines by utilizing SFRA. The work of Florkowski et al. [22], [23] studies the effect of different short-short circuit faults in the off-line broadband admittance. Both phase-to-phase and inter-turn short circuits are physically implemented and simulated by using the model proposed by Grandi et al. [24]. The most interesting observation is how the inter-turn short circuit is detected by tracking the resonant frequencies in terms of shifting and damping both in the experimental test and in the simulation. Lamarre et al. [25] applied SFRA to the stator winding of different high-power machines with the aim of identifying insulation ageing indicators. The authors compare results between a gain-phase and an impedance analyser. Moreover, they highlight the importance of better understanding some high-frequency phenomena to provide further understanding of the FRA results. The presence of the rotor in rotating electrical machines represents on the the most important drawbacks for SFRA reliability. Platero et al. [26] analyse in detail the influence of a synchronous machine rotor on the broadband admittance curves, where a fixed reference rotor position is proposed for SFRA test standarization. Sant'Ana et al. [27] extend the knowledge about the rotor position effect stating that even cylindrical rotors could cause the broadband impedance or admittance to vary. The authors propose different statistical indexes to neglect the effect of the rotor. Lately, the study of [28] demonstrates the influence of the rotor DC field in the phase impedance in a low-voltage PMSM. However, the physical phenomena explaining the rotor dependency of the different broadband impedances is not completely understood for all machines types. In [29] the authors evaluate the applicability of SFRA to detect inter-turn short-circuits in form-wound windings. Several works are oriented towards the off-line SFRA detection of inter-turn, phase-to-phase or ground short-circuits in low-voltage machines by utilizing several statistical indicators [30], [31], [32]. In [33] the authors utilize stator SFRA analysis to detect rotor faults such as field winding short-circuits in a medium power salient pole synchronous machine, while [34], [35] study the detection of broken rotor bars of squirrel cages and damper windings in synchronous machines. Some studies devoted to detect insulation ageing can be found in [36] and [37]. The latter tracks the coil impedance evolution over several progressive ageing mechanisms, which is particularly interesting to link impedance curves and insulation degradation. A more recent research trend consists of the off-line SFRA diagnosis of salient pole windings for MVA-range synchronous generators. Thus, inter-turn and ground faults in large salient poles are studied in [38] and [39] respectively. In addition, [40] and [41] deal with the automatic detection and assessment of such faults in large salient poles.

Impulse Frequency Response Analysis (IFRA) is performed by injecting a periodic voltage pulse inducing a broad frequency band signal. The width and voltage gradient of the pulse define the frequency content of the excitation. This technique is not broadly researched for rotating machinery, while several works are found for power transformer diagnosis [42]. The work of Yu et al. [43] evaluates the applicability of off-line IFRA to detect stator short-circuits in a synchronous machine. The same authors recently presented a series of studies oriented towards the automatic detection and interpretation of IFRA curves by utilizing machine learning techniques [44], [45].

The on-line FRA technique applied to rotating machines brings interesting capabilities such as continuous monitoring of the broadband electrical signature. The most utilized approach is the superposition of a high-frequency signal in the main power bus via standard equipment. In [46] a signal generator is utilized to inject the high-frequency excitation in a low pass filtered main power cord. The response is measured by current and voltage sensors and a separated processing unit computes the impedance for each frequency. The work does not present application results that support this technology. Sant'Ana et al. propose a LC coupling that allows to link a combined signal generator/acquisition to the main power cord [47]. The main drawback of this technique is the interference of the coupling impedance with the EUT. The coupling is designed to minimise the impedance overlap between coupling and motor. An active coupling technology is introduced in [48] to avoid the direct connection between measurement equipment and power cord. In this way, the impedance overlap between coupling and motor is avoided. However, the system for active cancellation presents increased complexity when compared with the passive coupling. Another example of passive coupling for on-line SFRA can be found in [49], [50], where the authors developed small galvanically insulated RLC circuits to couple the measurement instrument and the main power cord. These circuits bring a cost-effective solution in opposition to the previously described active filtering. A novel approach for on-line SFRA is presented in [51], where a vector network analyser is utilized. Moreover, the coupling between instrument and power cord is performed in a wireless manner through the utilization of inductive couplers. Table I presents a general overview of the presented FRA methodologies.

IV. INSULATION MONITORING BY CM IMPEDANCE AND PARASITIC ELEMENT ANALYSIS

The works included in this section deal with the on-line monitoring of the different winding insulation elements by tracking the behaviour of parasitic elements or CM broadband impedance. The monitored elements are normally ground-wall, phase, and inter-turn insulation of the stator winding. One of the earliest trends of inter-turn insulation degradation monitoring is presented in [54]. In this work the authors study the effect of thermal and electrical insulation degradation on the parasitic inter-turn capacitance in twisted pair specimens. The proposed monitoring technique is based on the artificial insertion or an inductance to accentuate the antiresonance frequency of the broadband impedance of a machine coil. The variation of this point represents the progressive ageing of the global inter-turn insulation. However, the monitoring method is complex and based on the intentional injection of a signal and the acquisition of stray flux in the end-winding of a motorette. The work is

TABLE I
ROTATING ELECTRICAL MACHINE FRA OVERVIEW

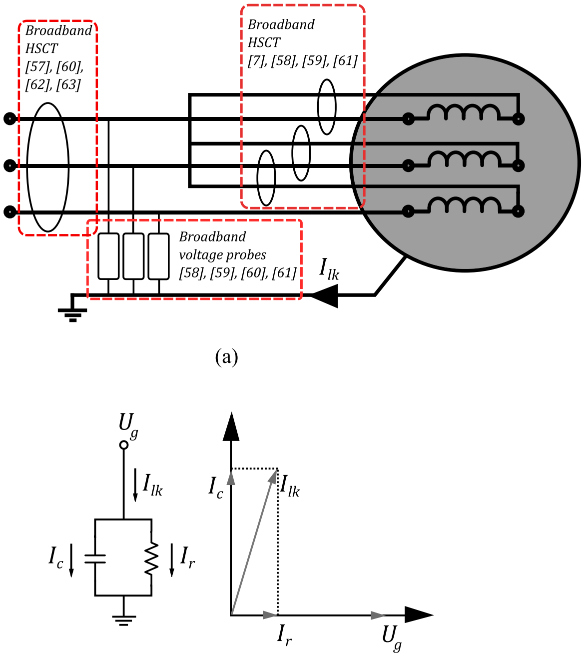
FRA type	Objective machine	Hardware	Studied faults	Frequency range	Ref
SFRA off-line	Induction machine	Phase-gain analyzer	Inter-turn and phase SC	100 Hz - 6 MHz	[23]
			Inter-turn SC	20 Hz - 2 MHz	[30]
			Inter-turn, coil-to-coil and phase SCs, and open-circuit	10 Hz - 2 MHz	[31]
			Inter-turn and ground SCs, and rotor broken bars	20 Hz - 2 MHz	[34], [35]
			Inter-turn SC	10 Hz - 10 MHz	[29]
		Impedance analyzer	Inter-turn SC	20 Hz- 30 MHz	[32]
			Inter-turn insulation artificial ageing	100 Hz - 10 MHz	[36]
	Synchronous machine	Phase-gain analyzer	Field winding inter-turn SC	10 Hz - 20 MHz	[33]
			Damper winding broken bars	20 Hz - 10 MHz	[34], [35]
			Field winding inter-turn and ground SC	10 Hz - 20 MHz	[40]
		Impedance analyzer	Inter-turn insulation artificial ageing	70 kHz - 1 MHz	[52]
	Motorette - Hand-wound coil		Insulation natural ageing	10 Hz - 2 MHz	[37]
	Motorette - Form winding sample	Phase-gain analyzer	Inter-turn SC	10 Hz - 10 MHz	[29]
IFRA off-line	Synchronous machine	Pulse generator + current sensor (40-20 MHz, 0.5 V/A) + Oscilloscope	Inter-turn and ground SC	1 Hz - 1 MHz	[43]
SFRA on-line	Induction machine	Combined generator - scope (Digilent Analog Discovery) + passive coupling	Thermal variation and bearing misalignment	3 kHz - 2 MHz	[49]
			Overheating, damaged SC ring, misalignment and winding unbalance	100 kHz - 1.5 MHz	[50]
		VNA + inductive wireless coupling	Inter-turn and coil-to-coil SC	10 kHz - 1 MHz	[51]
		Combined signal generator-scope (PicoScope 5203) + passive coupling	Inter-turn insulation artificial ageing	10 kHz - 300 kHz	[47]
	Synchronous machine	Combined signal generator-scope (STEMlab FPGA) + active coupling	Inter-turn insulation artificial ageing	1 kHz - 1 MHz	[53], [48]

continued by Perisse et al. [55], where the authors introduced a low voltage injection at different frequencies to map the antiresonance phenomenon. These works lack real case scenarios where actual machines are artificially or naturally aged and monitored. In [56] the authors map the on-line CM impedance by utilizing signal injection. This is performed for a system without VFD and thus, with lower high-frequency content. The injection is achieved by utilizing a passive coupling and a sinusoidal signal generator (10 kHz - 9.5 MHz). This work claims an adequate sensitivity for artificial variations of the ground-wall insulation but cannot track changes in the turn insulation due to the low amplitude of the injected signals.

A more modern trend is based on the broadband version of the well-known on-line capacitance and dissipation factor technique [7]. The basic working principle of these works is depicted in Fig. 4, where the different locations of current and voltage sensors are depicted. Zhang et al. [57] propose the utilization of broadband HSCT enclosing all three phases of the machine. In this way, the leakage current up to 3.5 kHz can be measured without accessing the machine neutral point. However, only the general insulation status is obtained and no phase distinction is made. The work of Zheng et al. [58], [59], [60], [61], [62] presents the most recent multi-frequency extension to the on-line capacitance and dissipation factor method. All these works present similar experimental set-up for the on-line insulation monitoring, which is close to the traditional scheme of Fig. 4 but also including broadband phase-to-ground voltage probes.The insulation ageing emulation is performed by inserting additional capacitances between turns, phases, and ground. In [58] the ground-wall and the phase insulation are monitored by tracking two different parasitic capacitances, which are obtained from leakage current and phase-to-ground voltage broadband measurements. These capacitances are tracked around the switching frequency value, which do not reach the CM impedance resonant frequency when inductance affects the impedance value. The main contribution of [59] lays on the inter-turn insulation monitoring by tracking the variation of high-frequency CM impedance above the resonant frequency. This work is extended in [60], where the location of the insulation degradation is studied. In [61] the effect the insulation state is monitored by tracking a generic capacitance value at the switching frequency. This is performed on a PMSM generator connected to the grid via rectifier inverter system. The inter-turn degradation behaviour is further studied in [62], where the main objective lays on the discrimination under combined inter-turn and ground-wall degradation scenarios.

TABLE II
BROADBAND CM AND PARASITIC CAPACITANCE-BASED INSULATION MONITORING METHODS FOR VFD-FED MACHINES OVERVIEW

Targeted insulation / Machine	**Acquisition hardware**	**Proposed indicator**	**Ageing emulation**	**Frequency range**	**Ref**
Ground-wall / LV induction machine	Broadband HSCT + voltage probes	Capacitance & dissipation factor	-	60 Hz - 3.5 kHz	[57]
Ground-wall & Inter-phase / LV induction machine	1MHz HSCT + 5 MHz differential voltage probes	Phase and ground equivalent capacitances	Capacitance insertion	4 kHz - 8 kHz	[58]
Ground-wall & Inter-turn / LV induction machine		CM impedance, conductance, and capacitance		4 kHz - 400 kHz	[59]
Ground-wall / LV induction machine		Equivalent capacitance value		4 kHz - 200 kHz	[60]
Ground-wall & Inter-turn / LV induction machine		Equivalent capacitances and principal components		4 kHz - 200 kHz	[62]
Ground-wall / LV random-wound stator	1MHz HSCT + Broadband differential voltage probes	Capacitance & dissipation factor	Thermal ageing	6 kHz - 42 kHz	[63]
			Moisture presence	6 kHz - 42 kHz	[64]



(a)

(b)

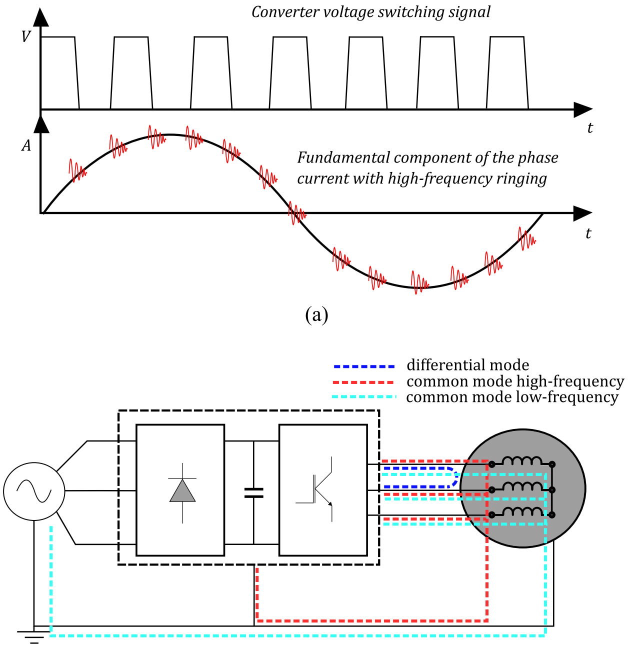
Fig. 4. (a) On-line capacitance and dissipation factor measurement schematic with recent broadband extensions, (b) Leakage current decomposition and insulation equivalent circuit, reconstruction from [7].

The work of Tsyokhla et al. [63] presents a different alternative for insulation on-line monitoring mainly aimed at low voltage machines. This work includes the monitoring of the CM equivalent capacitance value by utilizing data at different frequencies. Particularly, these frequencies are set in thee inverter switching frequency range (i.e., lower than 50 kHz). The equivalent capacitance is extracted for a natural ageing scenario where a machine stator is thermally aged in an oven during operation. Similar experiments are found in [64] to map the effect of different humidity values in the equivalent capacitance. In this case, the CM voltage is measured in an artificially created neutral point. Table II shows the overview for VFD-fed on-line insulation monitoring techniques exploiting broadband CM impedance and parasitic capacitance variation.

The measurement of CM current is identified as one of the main limitations to properly track insulation degradation in an accurate and cost-effective way. Information about CM current measurement uncertainties, challenges and tips can be found in [65]. The authors compare the performance of different broadband current sensors and analyze the influence of several factors such as sensor placement, conductor-sensor misalignment, etc. In addition, the large cost of high-frequency current transformers is reported in [66], which are commonly utilized in insulation broadband monitoring applications. Cost-effective broadband measurement solutions are pursued in works such as [67].

V. HIGH-FREQUENCY TRANSIENT CURRENT MONITORING

The impedance variation caused by insulation ageing induces an alteration in the transient current ringing when VFDs switching takes place. Fig. 5 depicts the interaction between the voltage switching and the high-frequency transient current components. In addition to the broadband machine impedance, several physical phenomena influence the transient current oscillation and its spectrum. On the one hand, the mismatch between cable and motor impedance causes the voltage signals to be partially reflected back towards the inverter. If the incident voltage wave is not completely absorbed due to the impedance mismatch, the reflected wave overlaps causing an overshoot in the motor terminals. This phenomenon particularly affects motors with long cables and inverter fast rising pulses (i.e., specially critical for wide band-gap semiconductors) [68]. On the other hand, according to Ran et al. [69] the different absorbed high-frequency current components propagate in different modes within the winding, which is known as multi-modal propagation. Particularly, the CM current propagation can be divided into a high-frequency component immediately following the switching event, and a much lower frequency component. The first, flows towards ground through the parasitic capacitance of the terminal and first turns of the winding while the second penetrates the winding and leaks to ground all along its length. Fig. 5 shows the multi-modal



(a)

(b)

Fig. 5. (a) Phase current high-frequency oscillation generation mechanism, reconstruction from [70], (b) multi-modal current propagation schematic.

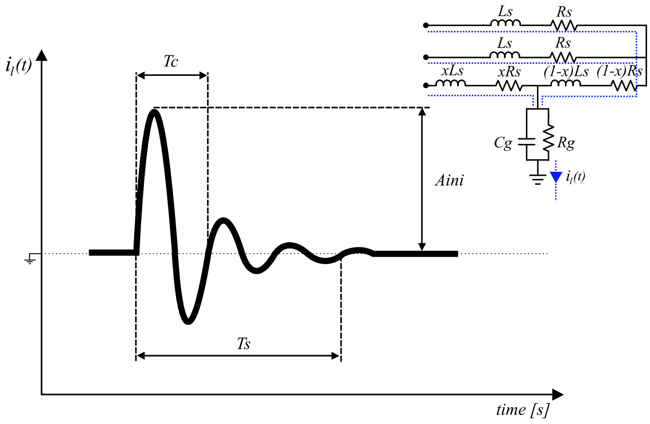


Fig. 6. Parametrization of leakage current signal and equivalent circuit proposed in [79].

decomposition schematic for a motor fed by a rectifier-inverter system.

The method presented in [71] focuses on the measurement of phase current high-frequency transients to detect variations on the high-frequency impedance. The measured signal is processed and transformed to obtain its spectra via Fast Fourier Transform (FFT). By comparing the healthy and faulty measurement spectra different insulation state indicators are extracted. In addition, different motorettes of form-wound coils are tested in [72], where the ability of the method to detect natural thermal ageing and moisture presence is demonstrated. The methodology performs one measurement per-phase, enabling the phase discrimination of the indicator. The authors report adequate reproducibility even if absolute accuracy in the MHz range is reduced. Leuzzi et al. [73] study the impact of natural electrical ageing on the high-frequency current and on the off-line broadband impedance. The ageing is artificially induced by an accelerated ageing test that impose high amplitude voltage signals in the machine terminals. Several indicators are obtained from the measured current in time and frequency domain. One of the main conclusions is that the progression of the electrical ageing shows high randomness thus, not concluding on the adequacy of the method. The work presented in [74] introduces similar technique based on frequency decomposition of high-frequency current ringing measured in the machine phases. The same authors propose a different alternative in [75], where randomly-wounded induction machines are thermally and electrically aged. The indicator is based on the current ringing maximum amplitude. One of the main novel points of these works lays on the utilization of magneto-resistive sensors featuring a 5.3 MHz bandwidth. These sensors are placed within a custom converter where a FPGA architecture manages simultaneously the sensor acquisition and the control of the inverter. The working principle of these sensors and furter insights are found in [76].

Xiang et al. [70] present a novel methodology based on the multi-modal current propagation principle described in Fig. 5. The authors propose an insulation health indicator extracted from the low-frequency CM component of the phase current. The required sampling frequency is reduced, which represents a significant advantage. However, only the phase insulation overall status can be tracked. A similar approach is presented in [77], where the authors pursue the insulation status monitor of the first coil (or line-end coil). This is particularly important for randomly-wound low-voltage machines fed by fast rising VFDs, where the risk of PDs in the first coils dramatically increases. In this work, the different modal components of the phase current are separated by utilizing the Variational Mode Decomposition (VMD) technique, which provides three different intrinsic mode functions each of them related to one of the propagation modes. The high-frequency CM component is utilized to track the variation of the line-end coil capacitance. The major drawback of this methodology is the utilization of high sensor bandwidth and high sampling frequency.

The time-domain transient analysis of the leakage current is presented in [78] in an off-line mode. The magnitude of the current ringing is utilized as overall health indicator for a naturally aged randomly-wound machine stator. In [79] the leakage current in time-domain is parametrized, modelled, and monitored on-line. Fig. 6 shows the proposed parametrization and the equivalent circuit describing the signal, where x represents the distance of the lumped capacitance insertion. The waveform parameters are defined by RLC parameters and the physical location of the defect. The diagnosis of the ground-wall insulation is performed by analyzing the variation of such parameters when lumped capacitors are inserted in different points of the winding. This includes the identification of the insertion position along the winding. Another trend worth to analyze is the non-continuous monitoring presented in [80]. The authors

TABLE III
ONLINE HF CURRENT RINGING-BASED INSULATION MONITORING METHODS OVERVIEW

Targeted insulation / Machine	Acquisition hardware / Location	Proposed indicator	Ageing emulation	Frequency range	Ref
General insulation / LV & MV induction machine	300 kHz BW current sensors / Three-phase terminals	Frequency spectrum (FFT) of the HF current ringing	Capacitance insertion	0 Hz - 1 MHz	[71]
General insulation / MV induction machine	150 kHz BW current sensors / Three-phase terminals			0 Hz - 500 kHz	[72]
General insulation / motorette			Thermal ageing	0 Hz - 6 MHz	[72]
General insulation / LV induction machine	20 MHz BW Rogowsky sensor / One phase terminal		Electrical ageing	0 Hz - 15 MHz	[73]
General insulation / LV induction machine	Magneto-resistive sensors 5.3 MHz BW / Inverter-embedded	Current ringing RMS and peak values	Capacitance insertion	-	[74]
General insulation / LV induction machine		Current ringing peak value	Thermal ageing	-	[75]
Inter-turn insulation / PMSM	5.46 MHz BW Rogowsky sensor / One phase terminal	Averaged CM low-frequency component amplitude	Capacitance insertion	approx. 200 kHz	[70]
First coil ground insulation / PMSM	5.46 MHz BW Rogowsky sensor / Three-phase terminals	VMD CM high-frequency component		approx. 4.3 MHz	[77]
Ground-wall insulation / not-specified motor	60 MHz BW current sensor / Enclosing three phases	Leckage current time-domain parameters		-	[79]

propose the leakage current monitoring in VFD-fed induction machines off-line when the machine is periodically stopped. The methodology requires the intentional off-line injection of CM voltage. This solution represents a compact alternative where all instrumentation is embedded within the VFD. In this case, the current is sensed by utilizing a current transformer for differential protection purposes enclosing the three motor phases. Table III provides a detailed overview of the analyzed on-line diagnosis methodologies based on the analysis of time-domain current-ringing.

VI. CONCLUSIONS AND DISCUSSION

This article performs the analysis and review of several rotating electrical machine insulation status diagnosis and monitoring techniques based on broadband signal excitation. The physical representation and equivalent circuit of a winding is presented, where the meaning of each parameter is discussed in depth. Then, the FRA applied to rotating machines both in the off-line and on-line mode is analysed. Following, the utilization of parasitic capacitance and CM impedance to monitor different insulation elements is explained and reviewed. Finally, the working principle and propagation of high-frequency current transients is presented and the techniques exploiting this method are analysed in depth. Emphasis is placed on the required hardware and instrumentation due to the challenge of cost-effective and accurate acquisition and processing of high-frequency signals.

Regarding FRA in rotating machines, the analysis of existing literature points out that off-line diagnosis techniques offer interesting solutions in the case of sensitive constructive parts of the machine which cannot be easily accessed (e.g., large power damper windings, salient pole windings etc.) since it represents an on-site and quick test. In addition, it presents potential application for quality control of winding manufacturing in low-voltage machines. The application of off-line SFRA for insulation fault diagnosis still requires further research and industrial expertise in order to be standardized. Regarding on-line techniques, the coupling between instrument and main power cord represents the most challenging aspect. Improvements on the noisiness of the signals and reliability of the results are required. The source of the on-line noise (i.e., rotor position variation, coupled electric noise, etc.) is still not completely identified up to date. Overall, further research is required to better understand the variations of the electrical signature under different types of faults, degradation, and machine operating conditions and topologies.

The monitor of parasitic capacitances and CM impedance presents interesting features regarding sensitivity and identification of the ageing location. Particularly, novel methodologies based on multi-frequency extension of the traditional capacitance/dissipation factor monitoring arise to better exploit the broadband behaviour of windings. On the one hand, a challenge lays on the cost-effective acquisition of the leackage current in comparison with the cost of the protected asset. In addition, the inter-turn insulation ageing and the sensitivity to natural ageing poses a challenge and an opportunity to further develop new techniques.

High-frequency current transient analysis presents an easy and straight way to obtain information. These methods are able to detect overall insulation ageing when measuring phase current, with differentiation between phases. Fast and efficient signal processing techniques for mode decoupling and the elimination of other components influence (e.g., cable influence on the high-frequency components) may need to be further explored. The single measurement in the machine terminals offers modular and cost-effective capabilities such as the integration of acquisition units within the VFD. The non-continuous monitoring represents a possible solution for applications with non-continuous service requirements. Further research is required to test the sensibility of several methods under realistic ageing scenarios instead of inserting lumped capacitances. In a similar way, cost-effective hardware solutions need to be pursued. Overall, industrial expertise and validation is required to further improve the TRL of the proposed broadband monitoring techniques.

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