e-Prime - Advances in Electrical Engineering, Electronics and Energy 10 (2024) 100874

Contents lists available at ScienceDirect

e-Prime - Advances in Electrical Engineering, Electronics and Energy

journal homepage: www.elsevier.com/locate/prime

HVDC transformer insulation system: Present research, trends, challenges, and prospects

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ARTICLE INFO

Keywords:
High-voltage direct current
Transformer insulation systems
Mineral oil
Prospects

ABSTRACT

High-voltage direct current (HVDC) has attained significant consideration owing to numerous valuable characteristics, for instance, lowest transmission losses, improved stability, and control operation. The HVDC transformer is one of the significant elements in the HVDC transmission system. Thus, it is noteworthy to ensure the optimal working of this vital component for the reliability, efficiency, and safety of power grid. The mineral oil (MO) is generally applied together with paper as an insulating medium in a majority of HV apparatus. For the insulation of power transformers, the oil/paper insulating system has demonstrated itself for several years as a major component. As a result of continuous growth in high-performance semiconductor components, HVDC power transmission becomes more and more significant due to key gains associated with these systems. This may develop challenges specifically in the case of converter transformers as the insulation is not subjected entirely to a simple AC stress. Based on the topology, the transformer insulation is exposed to a combined voltage stress (both AC with DC). This, conversely, leads to significant impacts and encounters regarding the electric stress of insulating elements of oil and paper. In the context of simple AC voltage stress, capacitive field distribution occurs corresponding to permittivities. Conductivities in the case of AC electric field are not significant nonetheless initiate trivial dielectrics losses. In the event of DC stress, they are pivotal as field distribution develops depending on their values. In contrast to AC stress, it results in a decrease of stress on oil however to a rise in stress on insulating paper. Through switching activities or polarity reverses, a shift from the dielectric displacement field to the steady-state electric DC field occurs. This could turn challenging specifically in the case of converter transformers as the insulation is not subjected solely to a simple AC stress. Polarization mechanisms, particularly interfacial polarization, and noticeably contrasting polarization durations between the materials of oil and paper should be considered. This article exhibits a thorough review of the HVDC transformer insulation system. The importance of this article lies in outlining the previous research, arranging the research core, and inducements, and forecasting imminent research trends. Furthermore, it describes an independent assessment of the challenges, opportunities, scenarios, and restraints being faced in developing the HVDC transformer insulation system more efficiently are clearly stated. The information documented in this review is projected to present an essential guideline for potential research in HVDC transformer insulation systems. This article is valuable for both academia and industry experts as it summarizes meaningful outlines of research in the field.

1. Introduction

Economic development and expansion in the emerging world have provoked severely the necessity to transfer huge extents of power to urban regions distant from power generation. A possible reply to this rising need for electricity is to adopt HVDC networks with higher voltages. Transmission of huge sums of bulk energy over extended distances is achieved by employing HVDC power transmission. Also, the denationalization of national utilities around the globe and liberalization of the energy market have changed power flows in particular power grids (e.g. Europe). Currently, electricity is negotiated like other commodities: consequently, it has become crucial to realize a greater level of control on power streams in power grids. Hence, utilities are launching modern HVDC connections and/or employing phase shift transformers.

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https://doi.org/10.1016/j.prime.2024.100874
Received 10 July 2024; Received in revised form 15 November 2024; Accepted 2 December 2024
Available online 5 December 2024

A polarity reverse process in an HVDC network may now be connected to everyday variations in energy rates and thus may occur more repeatedly than in the past [1].

The growth of potential low-carbon links and smart grids has induced extreme stress on the consistency and functioning of insulation materials applied in electric grids to deal with dynamic and volatile operating environments. The electrical industry encounters nowadays imperative demand to enhance its over operational performance and the overall quality of its products. Utilization of HVDC equipment for electrical transmission is developing increasingly widespread in electric grids around the globe. One of the elementary components of such an HVDC arrangement is a converter transformer in which an electrical insulation system involves mainly MO and pressboard (PB).

A transformer that converts voltage and transfers energy is among the most critical elements of a power grid. HVDC transformers remain the main elements for the consistency of the network. This consistency is affected both directly and indirectly by their insulation structures. The key component of a transformer is the insulation system that comprises insulation oil (transformer oil), cellulose paper, and PB is subjected to mixed AC and DC stresses [2]. These insulating materials have been applied in HVDC transformer insulation systems for almost 60 years without considerable modifications. To realize better performance and superior reliability of such an insulation structure, it must be proposed by considering both dielectric permittivity and electric conductivity values of its elements. The first is a significant factor for AC design while the second decides the attitude of the insulation under DC stress. Porcelain has been eliminated for epoxy and silicon rubber because of the alteration from oil-immersed to resin-immersed paper for DC bushing. Through a normal operating situation, the insulation system experiences different reactions because of thermal and electrical stress in a transformer. Consequently, supervising the status of the transformer, particularly the insulation system, is critical in warranting the performance, reliability, and lifespan of the apparatus [3]. The critical components of an oil-paper insulation system are outlined in Fig. 1.

1.1. Brief overview of HVDC transformer insulation systems

HVDC transmission system has developed as a vital component for today's power transmission as energy demand significantly emerges. HVDC is an efficient approach to transporting bulk electrical power over long distances with lower transmission losses by using direct current over long distances as compared to conventional AC systems [4]. HVDC technology for long transmission, asynchronous interconnections, and long submarine cables is usually accepted as being efficient and technically beneficial. Moreover, HVDC systems may be integrated with smart grid technology better than AC systems when utilizing DC renewable energy sources e.g., photovoltaic or electric vehicles [5]. Other advantages of HVDC transmission include environmental friendliness and power controllability as compared to HVAC systems. HVDC transmission systems are on the increase in the world and power systems with HVDC technology are not possible without solutions stipulated for developing technological problems e.g., converter stations, circuit breakers, and insulations [6]. This mode of transmission demands reliable critical components cited in functional converter transformers and subsequently, the insulating material utilized should ensure the safe function of transformers. The HVDC converter transformer is an extremely critical element of the HVDC transmission system for its reliable and sustainable operations.

The reliability of the converter transformer directly impacts the security and stability of the power system. Among the above-stated problems, insulation configuration for HVDC converter transformers is particularly a huge challenge to design since they are subjected to a variety of electric stress conditions. Contrasting to typical transformers, HVDC transformers operate in complicated circumstances where AC, DC, and DC polarity reversal stress occurs.

The electric field within the main insulation of the power transformer encounters an abrupt change in polarity during polarity reversal. This change in polarity may lead to the redistribution of charges within the insulation material, resulting in the enhancement of electric field strength. The electric field lines within the insulation material may realign themselves in response to polarity reversal, resulting in changes in the distribution of electric field strength within the insulation. This electric field change within the main insulation of the converter transformer during polarity reversal may result in localized areas of enhanced electric field strength, which may increase the risk of electrical breakdown within the insulation material. Proper design of insulation materials is vital to warrant that the electric field changes within the insulation material of the converter transformer during polarity reversal do not exceed safe levels and result in insulation breakdown. The current design practices are dependent on human experience and experimental statistics, the new design challenges may lead to delays in design development and enhancement in size and weight of the insulation system.

The insulation system of an HVDC transformer is a critical component that must withstand AC and DC stresses. The principal means of insulating transformers at HVDC converter stations are generally mineral oil (MO) in conjunction with various forms of oil-impregnated paper/pressboard) being used as a dielectric material, e.g., for converter transformers. HVDC transformers are subject to operating conditions that set them apart from conventional systems or power transformers, including combined voltage stress with both AC and DC, high harmonics content of the operating current, and transient voltages from outside caused by lightning strikes or switching operations. The insulation to the ground and between line and valve winding must withstand AC and DC stresses, and HVDC transformers contain a much higher share of solid insulation than AC transformers. The insulation system is designed to isolate the station from the AC supply, provide local earth, and ensure the correct eventual DC voltage. The insulation system of a converter transformer varies from that of a conventional power transformer since it must endure combined AC and DC stresses as well as transient processes. Transients result in a shift of stress from oil into board and vice versa due to the diverse dielectric behavior at displacement and steady-state electric fields.

The insulation system of the converter transformers is exposed to AC and superimposed (composite) DC stresses. In the AC mode, the field distribution is fully dependent on the dielectric constant, where the material parameter determining the AC field distribution is the dielectric constant (permittivity) but in the DC mode, the electric field distribution is primarily influenced by the electrical conductivity, where the DC field distribution is determined by the resistivity [7,8]. For DC stresses, conductivities are significant, and field distributions are determined by the conductivity ratios of various materials interrelating in the insulation system.

On the contrary, in the case of mere AC voltage stress, capacitive

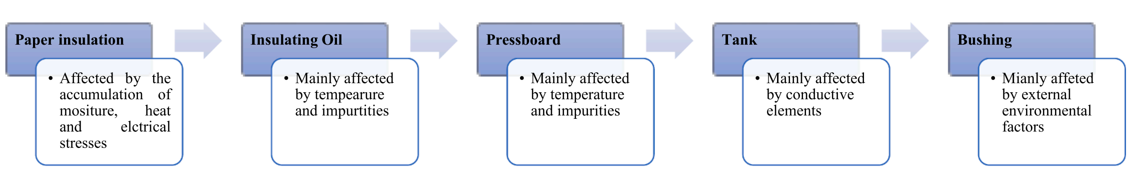

Fig. 1. Critical components in oil-paper insulation system.

field distribution arises according to the permittivity values of insulation components. The conductivities in the case of AC electric field are not significant, nevertheless originate trivial dielectric losses. Conductivities in the context of the DC electric field play a critical role as field distribution depends on their value. In AC mode, the field distribution is entirely contingent on the dielectric constant, nevertheless, in the DC mode, the electric field distribution is primarily influenced by the electrical conductivity.

Contrary to AC stress, this results in a decline of stress on the oil however rise of stress on the pressboard. Through switching activity or polarity reversal, a transition from the dielectric displacement field to the steady-state electric DC field occurs. Polarization mechanisms (due to the orientation of diploes), specifically interfacial polarization, and substantially contrasting polarization intervals between the oil and pressboard should be considered. Moreover, the conductivity of insulation materials depends on multiple factors e.g., temperature, electric field strength, moisture, and aging. The subsequent stress on the insulating board in the event of steady-state field stress demands comprehensive findings that emphasize conductivity about conductivity changes resulting from stresses ensuing during operation. These factors should be kept in mind while designing/diagnosing impregnated pressboards for DC applications. Applying a DC electric field to an insulating material, electrical current is generated due to different mechanisms. Parts of this current abate into steady state current according to time constants. This abated portion of current develops from polarization phenomenon and this consists of electronic polarization (also named as deformation polarization), atomic polarization (also known as deformation polarization), lattice polarization, orientation polarization, and interfacial polarization [9]. Generally, pressboard and oil differ by a factor of 2 in permittivity and by a factor of 100 in resistivity-consequently more solid insulation is needed for a converter transformer.

To design cost-effective and vigorous DC insulation, a deeper knowledge of the physical processes under DC stress as well as material information is critical. Generally, insulation is designed via basic calculations based on an equivalent RC circuit. Nevertheless, it cannot include aspects e.g., space charge accumulation and complex resistivity behavior of transformer oil.

1.2. Importance of research in this area

Research in the field of HVDC transformer insulation systems is vital due to its considerable impact on the safety, reliability, and efficiency of power transmission. The current research mainly focuses on reactions, fault detection, market trends, and prospects related to HVDC technologies. It mainly focuses on producing new materials and practices to improve insulation performance, handling challenges e.g. partial discharge and aging, improve overall system reliability. Understanding the latest developments in insulation materials, detection techniques, and system design is critical for improving the efficiency and life of HVDC systems [10].

Developments in the subject include the employment of modern diagnostic instruments, analytical maintenance approaches, and the incorporation of digital tools for real-time monitoring. Potential research in this area will likely consider novel tools such as AI and big data to further advance HVDC insulation systems. Nevertheless, challenges continue, for example, the necessity of standardization, economical solutions, and ecological sustainability. Forthcoming prospects involve the development of smart insulation schemes, improved insulation design for extreme voltage levels, and the incorporation of renewable energy sources [11]. Furthermore, addressing challenges e.g. aging of dielectric materials, breakdown inhibition, and interaction between insulation systems and their environment is critical for warranting the reliability of power grids. Overall, research in HVDC transformer insulation systems plays a significant role in shaping the future of HVDC transmission by focusing on prevailing problems, predicting imminent trends, and evolving solutions to enhance system efficiency and reliability. The novelty in this field is critical for steering innovation and development in HVDC transformer technology [12].

2. Present research

2.1. Recent state of HVDC transformer insulation systems

Research in this field is ongoing, to enhance the efficiency and reliability of insulation systems for HVDC transformers. A few vital fields of interest involve preparing new materials with improved dielectric attributes, analyzing the aging conduct of insulation materials, and discovering innovative insulation design concepts. The present research on HVDC transformer insulation systems includes studying current configurations, trends, challenges, and solutions to improve the performance and reliability of HVDC transmission [1]. Researchers are aiming to recognize the distinctive requisites of HVDC systems e.g. dedicated insulation systems and materials, to deal with concerns like constant voltage stress and electrostatic stress. Active trends involve developments in insulation materials, maintenance procedures, and monitoring practices to identify early warnings of degradation. Overall, researchers aim to develop more effective and lasting insulation systems to meet the rising demands of HVDC technology [13].

2.2. Current progress and advancements

The insulation systems for HVDC transformers are designed to withstand the unique operating conditions of HVDC transmission. These systems generally use oil and different forms of oil-impregnated paper or board as the primary means of insulation for the windings and bushing of the transformers [1]. HVDC transformers encompass a much greater segment of solid insulation than AC transformers, as they are subject to collective voltage stresses with both AC and DC, great harmonics portion of the operating current, and transient voltages from outside originated by lightning strikes or switching conditions. The insulating system is critical for providing a galvanic partition between the AC and DC systems, inhibiting direct current from entering the AC systems, and confirming the correct eventual DC voltage. The trend in insulation systems for HVDC transformers involves addressing higher operating voltages and harmonic content, as well as developing solutions to meet the challenges posed by these unique operating conditions [14].

The present research and trends in insulation materials for HVDC transformers focus on addressing the specific stress conditions and physical phenomena associated with HVDC technology. Researchers are seeking optimal solutions for insulating materials that can withstand the joint voltage stresses of AC and DC, great harmonics content, and transient voltages from lightning strikes or switching operations. The development of HVDC technology has led to a focus on new solutions, including biodegradable insulating liquids and nano-fluids, to ensure the correct, continuous, uninterrupted, and safe operation of HVDC transformers under high-temperature, high-electric field, and mechanical stress conditions [15].

Challenges in HVDC transformers include the need for high-quality materials that do not change over time under the specific operating conditions of HVDC technology. The increasing operating voltages and harmonics content present additional challenges that require ongoing research and development of insulation materials to meet these demands [1].

Prospects in this field involve the continued development of insulation materials to address higher operating voltages, harmonic content, and environmental safety considerations. This includes the exploration of alternative dielectric liquids, statistics in electrical engineering, partial discharges, and insulation of power transformers. In summary, the research, and trends in insulation materials for HVDC transformers are focused on developing solutions that effectively address the unique operating conditions and challenges posed by HVDC technology, while also ensuring environmental safety and uninterrupted operation of the transformers.

2.3. Research gap and major results from existing findings

Existing research on HVDC transformer insulation systems has produced various key outcomes. A few of these results include:

1. Insulation in HVDC systems is vital for efficient power transmission over long distances, with lower losses compared to HVAC systems. Advanced insulating materials with high dielectric strength are essential to withstand high voltages in HVDC systems [16,17].
2. Researchers are aiming to explore innovations in insulation materials to manage problems such as aging of dielectric materials, breakdown restraint, and warranting the long-term stability of HVDC systems. Moreover, the impact of temperature and environmental factors on the aging of insulation materials are examined to emphasize the significance of thermal management in HVDC transformers [1].
3. Challenges in HVDC insulation systems involve constant voltage stress and electrostatic stress, compelling specified insulation design, grading, and maintenance. Repeated maintenance and supervising are vital to confirm system reliability by identifying problems early and avoiding collapses [1].
4. Forthcoming research may imply to incorporation of advanced tools e.g. AI and big data to further optimize HVDC insulation systems for enhanced efficiency and lifespan of insulation system The future research prospects involve the potential use of nanotechnology to improve insulation features and shrinking space demands in HVDC transformer designs [18].
5. Furthermore, the research includes smart insulation systems with real-time monitoring capacities to enhance reliability and inhibit breakdown. The research aims to examine the effect of partial discharge on insulation performance and the need for effective monitoring and mitigation strategies. [19,20].

3. Methodology for literature search

This literature scrutiny offers a necessary study of cutting-edge research into HVDC transformer insulation systems and the subsequent sections specify the assessment phases applied to accomplish this systematic evaluation of the literature. A wide literature assessment can provide significant learning in terms of critical evidence of the prospective of HVDC transformer insulation systems, present research, trends, challenges, and prospects, and recommend forthcoming research guidelines. The subsequent main proceedings have been organized for literature collection.

3.1. Preliminary evaluation

This stage implies initial searching in Springer and Direct Science accesses. In this investigation, prominent journals incorporating “HVDC transformer insulation systems” and “Insulation systems of HVDC transformers” keywords in titles and keywords were allocated. Keywords correlated to the exceeding field were also searched for and allied knowledge was acquired from relevant publications.

3.2. Articles collection methodology

A five-step assessment method (Fig. 2) was employed to search for articles for the study. At first, two leading scientific libraries (Thomson Reuters Web of Science [WOS], Google Scholar, and Scopus) were utilized for keyword searches. Afterward, a mix of keywords and expressions were selected involving available scientific data and data of the research group.

3.3. Selection and conclusive collection of papers

Afterward, a manual collection practice was employed in agreement with summaries, headings, and keywords. The importance of this effort was peer-reviewed journal items, conference papers, dissertations, and several reports. Through the 4th stage, the invasion assumptions are applied to titles and selected editorials are excluded. Subsequently, needed editorials were attained about their abstracts. Accordingly, in the final phase, afterward evaluation of the total contents of the rest editorials, papers that were openly and indirectly linked to the topic are picked for this comprehensive scrutiny. The objective of the assessment is to report broad facts regarding HVDC transformer insulation systems. This paper also examines the challenges that are required to be focused on for developing an advanced HVDC transformer insulation system. In the end, this paper suggests the potential paths for approval of advanced HVDC transformer insulation systems for power transmission in the electrical grid.

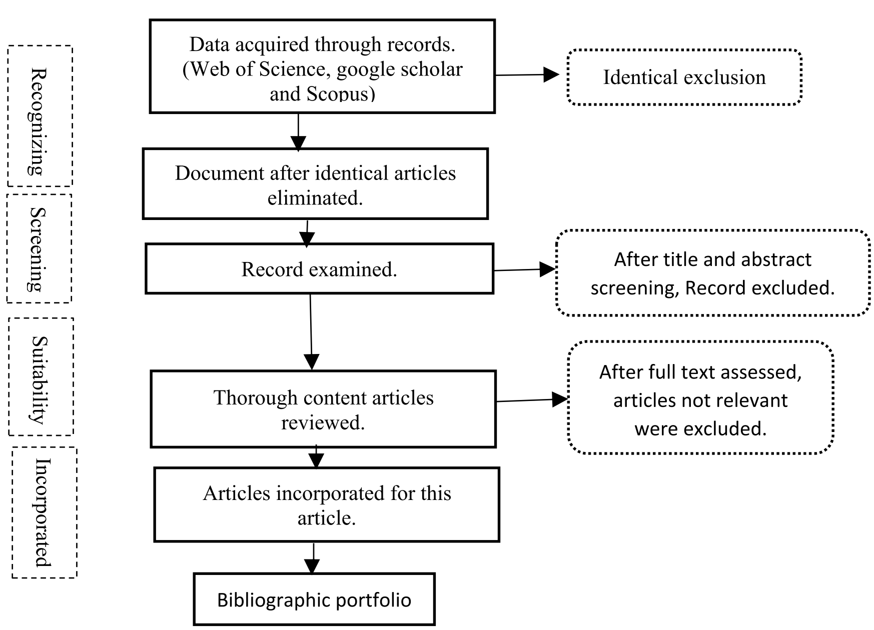

Fig. 2. Flowchart for screening the recovered items in this research.

4. Literature evaluation on performance and analysis of HVDC insulation systems

With the enhanced integration of renewable energy sources, HVDC will become more dominant in the power system. Several factors are generally neglected under AC however that are taken into consideration to design HVDC insulation systems such as the dependency of conductivity on temperature and field and the problem of electric field transient through energization and polarity reversal [21].

HVDC transformer insulation systems play a significant role in ensuring the safe and effective operation of HVDC power transmission systems. These transformers transform alternating current (AC) to direct current (DC) for long-distance electric power transmission. The insulation system in HVDC transformers must be designed to withstand high voltage stress and ensure the integrity of the transformer throughout its operational life. Insulation systems in power transformers consist of fluids together with solid materials [2]. Petroleum-based oils have been used to insulate power transformers since the 1940s. The main function of insulating oil in a transformer is to provide electrical insulation between the various energized parts; it also acts as a protective coating layer to prevent oxidation of the metal surfaces. The fundamental function of dielectric liquids is the impregnation of all types of hollow gaps in an aspect where electrical strength is as high as possible. Furthermore, in transformers, dielectric fluid functions as a cooling medium. Consequently, dielectric liquids must demonstrate the following required features. (a) sound electrical properties, specifically high BDS (b) great aging resistance, principally hindrance from oxidation (c) sufficiently low viscosity supporting oil circulation and heat transference (d) compatibility with solid materials of electric apparatus. (e) flame-inhibiting characteristics are also important in specific applications. Given the projected prospective oil emergency, the price of crude oil is increasing, and consequently, its availability might be doubtful [12,22]. Nevertheless, the dielectric features of MOs are broadly recognized, and they have offered reasonable insulation and cooling performance but with the advent of HV transmission levels such as HVAC and HVDC, conduct demands for insulation systems of transformers are on the rise. The alternative insulating liquid material development is directed by numerous properties e.g., higher electrical insulation obligations and additional safety and economic concerns. The required features of good dielectric fluids for transformers are specified in Fig. 3. HVDC transformer insulation systems commonly include solid insulation materials e.g. paper, pressboard, and oil-impregnated insulation. These materials are used to insulate the windings and provide dielectric strength to withstand high-voltage stress [12,23].

Important properties of HVDC transformer insulation system

It is significant to identify the facts about dielectric and thermo-physical characteristics of HVDC transformer insulation systems of HVDC transformer. There are various properties of fluid insulation systems mainly taken into account e.g. thermal conductivity, density, specific heat, and viscosity. The thermal conductivity of a fluid is directly associated with the heat transfer capacity of the fluid; however, viscosity is related to pressure drop, flowing affluence, and pumping power. Various significant properties desired for transformer insulation systems include physical, chemical, and electrical properties, (Fig. 4) which are presented in the following section.

4.1. Electrical properties

The insulation system of the transformer is required to meet AC and DC withstand voltage, lightening impulse, and switching impulse standards. The most notable and frequent condition that an insulation system must survive is the AC breakdown voltage, which is defined as the value of an applied AC voltage at which disruptive discharge originates [2].

4.1.1. Breakdown (BD) characteristics

The major insulation system in the HVDC transformer contains oil-paper insulation. HVDC transformer is generally stressed with AC, DC, and superimposed stresses throughout working. Opposing AC field distribution, DC field stresses are affected by the conductivity of the dielectric materials, which involves MO and cellulose-built transformer board [24]. One of the significant issues associated with any HVDC insulation systems is the effortless development of space charge inside the bulk and at interfaces [25]. The development of space charge in

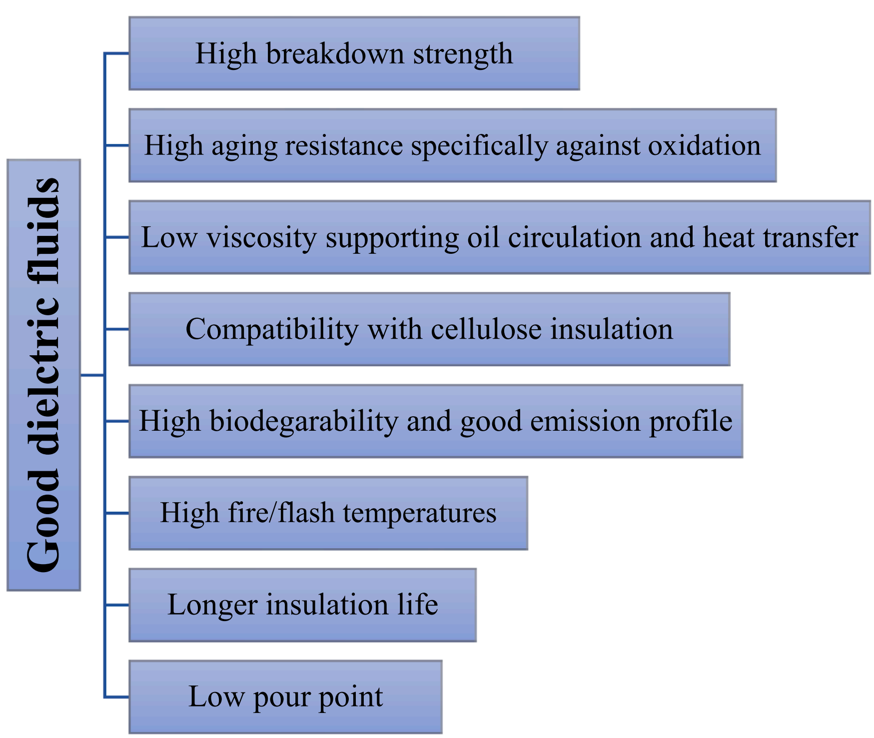

Fig. 3. Required properties of good dielectric fluids for transformers.

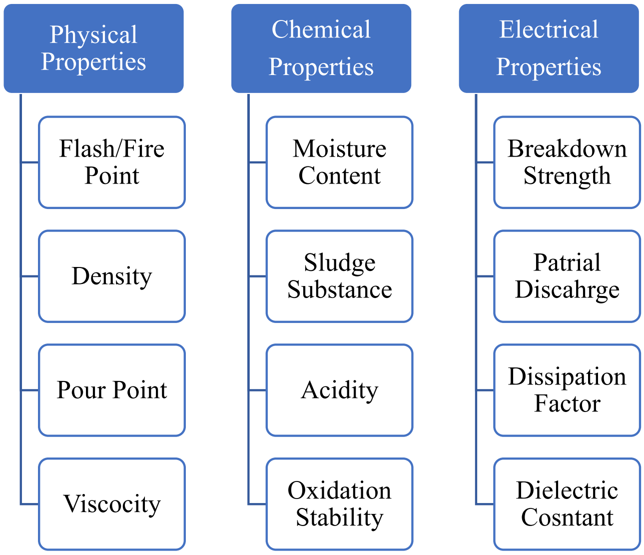

Fig. 4. Important characteristics of transformer insulation systems.

oil/paper insulation systems may not only impact the dielectric strength but also be associated with the stability and safety of HVDC transformers [26]. The space charge impact is the main insulation problem for HVDC apparatus and there is a link between space charge and BD in the HVDC transformer insulation system. As stress is greater, injection of homo carriers happens initially at the cathode and shortly at the anode. The space charge within oil/paper leads to electrical field distortion. The conductivity of oil/paper insulation is higher, so the space charge dissipated rapidly when depolarized. The rapid dissipation of space charge will perform a major task in oil/paper insulation conduct in the event of polarity reversal under HVDC. When the applied negative stress increased, the oil/paper insulation caused BD in a short time [27].

H. Okubo et al. concluded that discharge at the polarity reversal started after the sum of the applied electric field and electric field arose due to the amassed charge on PB surpassing the breakdown electric field strength EBD of the oil gap. Discharge at the polarity reversal happens occasionally during hundreds of milliseconds in the entire region as Eoil surpasses EBD. Additionally, the occasional discharge did not intersect with each other. The surface charge on PB at the polarity reverse could counteract the gathered charges on PB and halt the discharge transmission. Discharge presence at negative to positive polarity reversal is distinct from that of positive to negative. This contrasts outcomes from polarity amassed charge on PB [28]. H. Okubo et al. studied the discharge features at polarity reversal for different configurations of MO/PB combined insulation systems. The field strength in the case with discharge was decreased than that of without discharge. It is deemed that when surface discharge spreads on PB, the gathered charges on PB in the discharge region could be defused by the surface discharge. The discharge at the polarity reversal happened occasionally and did not coincide with each other [29]. D. Liu et al. studied the impact of TiO_2 nanoparticles (NPs) with various diameters and loading ratios on the development of insulation cellulose paper in the HVDC insulation system. Their findings revealed that DC BD voltage and PD inception voltage of oil-impregnated composition insulating paper are notably enhanced by the addition of NPs [30]. B. Qi et al. applied Kerr electro-optic measurement to explore the field distribution oil-PB insulation under various ratios of AC/DC voltage application. Their findings indicated that AC electric field distribution in oil is uniform and proportionate for overlapping oil-PB insulation. The field strength makes a linear relation with the applied voltage. The DC electric field distribution in oil is diverse and uneven as the overlapping PB insulation is related. The field strength near the single-layer PB protecting the upper electrode is much less than that of the lower electrode. Under DC voltage, the gathering of interface charges establishes the main source leading to the unbalanced distribution of the DC electric field [31]. H. Okubo used a Kerr electro-optic electric field system to measure field distributions and charging activities for PB positions in an oil-impregnated configuration, under DC voltage. They concluded that this technique could promote improved electric field assessment as well as enhance the HVDC insulation behavior in liquid insulation systems [32]. Y. Wang et al. investigated BD characteristics of oil-paper insulation for mixed AC/DC voltages. Short-time and constant-stress analyses were performed. The short-time test findings indicated the BDVs for oil-paper insulation under AC/DC mixed voltages were lower than those under DC voltages but higher than those under AC voltages [33]. G. Lan et al. studied BD properties in transformer oil under mixed AC/DC voltages. The findings show that AC BDV drops linearly as the DC pre-voltage rises and vice versa. Moreover, various pre-applied voltages impact the test outcomes surprisingly e.g. the BDV under AC pre-voltage is larger than that under DC pre-voltage [34].

4.1.2. Dielectric properties

The insulating system of an HVDC transformer includes an insulating fluid (MO/easter fluid) and cellulose-built substances (paper and PB). The dielectric characteristics of a dielectric material could be stated about relative permittivity and conductivity. The conductivity normally impacts electric fields in equipment subjected to DC voltages (e.g. HVDC transformers), however, relative permittivity is more pertinent in power transformers exposed to power frequency [35].

It is widely understood that the electrical conductivity of dielectric liquids and PB may differ significantly. Moreover, the conductivities and PD conduct of both materials depend on multiple factors e.g. time, temperature, moisture content, aging, and local field strength. The conductivity and permittivity of MO and oil-impregnated paper rise considerably with rising temperature, particularly in the range of low frequency. The relative permittivity of insulation materials reduces with rising frequency, and the change of conductivity is contrary. The temperature and frequency reliance of the insulation materials must be taken into consideration in the computation of the nonlinear AC-DC combined electric field of an HVDC transformer. Therefore, it is hard to determine the field distribution of this complex insulation system precisely [36,37].

The understanding of the conduct of electric conductivity in MOs for potential use in HVDC converter transformers is of utmost significance for the appropriate design of their insulation system. The conductivity of oil greatly depends on oil temperature and oil nature [38]. Generally. The Conductivities of MO are greater than that of PB making charge transfer through the liquid phase more intensive. This, in turn, grants circumstances for interfacial charge build-up in oil-impregnated pressboard and re-distributions of electric fields. The manner is dynamic and contingent on various parts, consisting of oil quality (structure, humidity, aging), the configuration of the insulation system, the extent of applied stress and vibrations, etc. Thus, understanding of electric conductivity of MO and its performance regarding temperature and electric field strength is of utmost significance for the appropriate design of an HVDC transformer insulation system [39]. M. Kharezy concluded that the conductivities of insulating materials (oil/paper) indicated strong nonlinear dependence on temperature and electric field that makes the functioning of the insulation of the transformer dependent on the operating environment. Moreover, results indicated that the characterization of insulation materials is significant for realizing an enhanced design of the transformer insulation system [40]. F. Schober et al. concluded that oil conductivity is a significant quantity for the design and condition monitoring of HVDC insulation systems [41,42].

Pressboard is one of the major elements in HVDC converter insulation. By expanding the understanding of conduction processes in PB, it will be feasible to enhance cellulose insulation materials and insulation designs. The conductivity of PB is a significant measure for HVDC field distributions and is conditional on several factors. F. Schober et al.

concluded that the conductivity of oil-impregnated PB is much greater than air-impregnated PB. Consequently, oil conductivity has a substantial impact on the insulating conduct of the entire HVDC insulation system [43]. For the low-conductive oil, the impact of the PB density is low, as conductivities and electric field stresses are alike, both for PB fibers and for oil. By impregnating with high-conductive oil, the PB pores have a much greater conductivity than the adjoining PD fibers and consequently, the conductivity of the oil-immersed PD varies on PD density over again. In this event, a low-density PB thus has a greater conductivity than a great-density PB relating to the discrete fiber volume and oil volume. The PB density may be altered during fabrication and the designer may select which PB density and which oil with suitable conductivity must be applied in HVDC equipment resulting in required conductivity values for the oil-PB insulation system [44].

4.1.3. Partial discharge (PD) and PDIV

PD happening in oil/PB insulation systems is one of the major reasons for insulation BD and is the key dynamic of electrical aging of materials. Identifying insulation defects in HVDC equipment, where PD can happen may assist in inhibiting breakdowns, even if the deterioration rate under PD is moderate than in AC conditions [45]. PD happening in a void surrounded by insulating material is considered to be one of the major reasons for insulation BD and it is the key element of the electrical aging of materials [46]. It is widely recognized that the electrical conductivity of dielectric liquids and PB may differ considerably. Furthermore, the conductivities and PD performance of both materials rely on numerous factors e.g. time, temperature, moisture content, aging, and local field strength. Consequently, it is hard to determine the field distribution of this complicated insulation system precisely. Moreover, PD analysis is more challenging compared to AC, as a phase relation is absent at DC. Through traditional measurement methods, it is hard to detect disturbances, other methods for PD are generally adopted e.g. acoustic or optical detection [36].

The impact of voltage notches on PD activity has been hardly considered in the literature. McDermid et al. studied the likelihood of observing PD in an HVDC system and were capable of highlighting PD in a bushing regardless of high-intensity noise [47]. The PD inception voltage (PDIV) under DC and a blend of AC and DC have been observed as analogous to internal discharges in paper/oil insulation systems. The blend of both forms of voltage resulted in a vital enhancement in the PD repetition rate [48]. The peak value of PDIV under notched waveforms [49,50] is statistically greater than attained under sinusoidal voltages. T. Jiang et al. found that PDIV under notched voltage becomes greater by raising firing and overlapping angles. PD shapes alter with HVDC voltage waveforms indicating that huge PD tending happens at the arising front of the notches. PD amount and repeating rate are both related to notch depth. It is projected these findings may enhance the design of UHV converter transformers [51]. M. Florkowski et al. studied the impact of chosen AC harmonics in an HVDC system on PD. They noticed that superimposed harmonic content on DC voltages at levels in a deep amplification of PD existence and this a degradation of the HV insulation system [52]. J. Li et al. investigated the features of void in the oil-PB under combined voltage. Their findings show that the PB endures most of the DC element and void bears most of the AC element when combined voltage is employed. For PDIV, it is decided by the AC factor and DC element. For PD development, the AC factor has a more important impact than the DC component. The DC element advances the PD activity under the AC half cycle with a similar DC polarity and deters the PD activity under the AC half cycle with an opposite DC polarity [53]. PD proved to be a significant diagnostic factor during the technical lifetime of operated HV equipment [54].

4.1.4. Aging of insulating materials under DC voltage

High voltage apparatus intended for DC applications is stressed contrarily to AC apparatus. Moreover, polarization and space charge phenomena entail a time-dependent performance on stress distribution. This has leading effects on how deterioration of insulation under DC stress occurs. The nature of the stresses under DC can result in accelerated deterioration processes that may lead to early breakdown of the insulation [48]. M. Florkowski et al. concluded that AC harmonics may lead to strong acceleration of the degradation of insulation materials under DC voltages and partial discharge [52]. H. Cui et al. investigated the aging performance of the HVDC transformer insulation system. Results showed that gas production of the insulation system under united AC and DC voltages along with the harmonic content is significant when compared to insulation aging under AC voltages only. The last gas production was noticed when a DC voltage was applied in an accelerated manner. Findings also indicated that high insulation aging was observed in HVDC transformers as compared to typical AC transformers. The reliability of the oil-PB insulation system applied in HVDC transformers may be impacted by the existence of space charge. M. Hao investigated space charge performance by pulse electroacoustic (PEA) method at room temperature for both short-term and long-term tests. Two kinds of oil with various aging conditions were applied for evaluation. The status of interfacial charges is very distinct for fresh and aged oil. The maximum electric field happens in the center of the PB, which is substantially increased in the aged oil. The interfacial and bulk influences result in a considerable electric field augmentation in the middle of PB, particularly in aged oils [55]. M. Hao et al. investigated the impact of applied HVDC stress and oil conditions on space charge performance. They concluded that oil condition is the leading factor in impacting the space charge performance of the HVDC insulation system [25]. They also noted that at greater applied stress, the more charge accumulation in the insulation bulk; the service-aged oil may significantly increase the charge injection and mobility leading to rigorous electric field distortion in the center of PB [56]. L. Pu et al. studied the influence of aged PB on the space charge conduct of an HVDC transformer insulation system. They concluded the significant impact of aged PB on the space charge performance of the overall HVDC insulation system [57]. Z. He et al. investigated dissolved gases produced after PD and electrical BD in oil/paper insulation under AC-DC mixed voltages. The findings indicate that the properties of dissolved gases in oils under AC-DC mixed voltages are considerably distinct from those under AC voltage [58].

4.2. Chemical properties

4.2.1. Moisture content

Moisture content in dielectric fluid not only impacts its dielectric properties but also affects paper insulation severely. Cellulose insulation absorbs the highest degree of moisture due to its hygroscopic traits. High water content lowers the dielectric strength and augments the dielectric loss of dielectric liquid. Water content builds up in the transformer with the time primarily absorbed by the solid insulation, although it can persist in other forms. These may imply dissolved or free water hovering as droplets in the dielectric liquid. A small amount of water is observed in the dielectric fluid, most of it is distributed in the cellulose insulation. The presence of moisture in the transformer may lead to a problem of oxidation which in severe cases may result in arcing/flashover and ultimately to dielectric breakdown [12,59].

4.2.2. Acidity

The acidity of liquid insulation weakens dielectric features and supplies corrosion in the iron elements in the transformer. The acidity rises as insulation ages through functioning. Examination of acid value during functioning is an important instrument to validate the safe working of the transformer. Acidity is employed to gauge the presence of free organic and inorganic acids in fluid insulation. Rust and deformation rise with an increase in the acid substance of the fluid insulation. The higher value of acidity does not mean a high deterioration either in the liquid or solid insulation. It means the solid insulation is drying and fatty acids are developing due to hydrolysis reactions [12,60].

4.2.3. Oxidation stability

The oxidation stability of dielectric liquids is a significant factor as it is enormously vital that the liquid must not be oxidized with time. The reliability of dielectric fluids is significantly influenced by oxidation and aging processes. The oxidation of insulating liquid is a vital element as it leads to the development of by-products, e.g. sludge and acids, conversely originate issues in HV apparatus by decreasing the dielectric properties of the solid insulation system [12,61].

4.3. Physical properties

4.3.1. Density

The density of dielectric liquid is one of the most important aspects of its physical features. It has a massive influence on the working of transformers. The specific density of oil will be modified based on the manufacturer and region where the oil will be essentially applied. It is usually defined as the ratio of the masses of the substance to the volume of the substance. In simple terms, it is the ratio of the weight of the oil to the volume/quantity of the oil. As the temperature increases, the density of oil decreases. The density of liquid insulation is assumed to be a measure for deciding its other critical characteristics such as viscosity and specific internal friction coefficient.

4.3.2. Viscosity

Viscosity is the interior friction force that opposes the flow of dielectric fluid. Good dielectric liquid has a small value of viscosity. When the temperature of the insulating fluid reduces, the viscosity of oil will rise. The viscosity of insulating fluid impacts the competence to transfer the heat by conduction; consequently, cooling of the transformer by conduction is the major heat-removing method. A trivial value of viscosity facilitates a great rate of heat transfer in transformers [62]. If the oil has a larger viscosity, heat transfer capability is significantly reduced, and vice versa. The value of viscosity determines the flow traits of liquid insulation in a transformer which in turn is associated with the cooling capacity of oil. Fluids with smaller values of viscosity will have excellent heat-elimination capacity. For better heat transfer, free circulation of liquid insulation is essential which is likely with reasonable viscous oil. Viscosity is inversely proportional to temperature [12].

4.3.3. Flashpoint and fire point

The lowest temperatures at which fluid may result in a vapor near its surface that will flash or momentarily ignite when exposed to an open flame. Flashpoint is a typical indicator of the flammability or combustibility of a fluid. The temperature that is required to initiate spontaneous ignition causes generates vapors to develop a flammable blend. The flammability in transformers is very critical for the safety of power systems. There are various instances of transformer explosions leading to flames in the event of fluid spillage. Fire and flash points are measures of the liquid's opposition to provoke a fire. Fire and flash points are important for transformers for their indoor applications for security measures. Flash and fire points are temperatures that imply the flammable nature of fluid insulations. Fluid insulation with higher flash and fire points will have good fireproof features.

4.3.4. Pour point

It indicates the lowest temperature at which dielectric fluid will flow. The pour point is the smallest temperature at which dielectric fluid starts to pour/flow when examined under the proposed specifications. It is critical in freezing environments to validate that fluid will flow and execute its object as an insulating and cooling agent. Transformer oil stops flowing when the oil temperature is under the pouring point. A low pour point indicates a reliable insulating fluid. A larger value of the pour point signifies the presence of wax content in fluid insulation sources to raise viscosity. The pour point is a valuable measure to discover how dielectric fluid will behave under low-temperature situations especially, where it is significant to start a transformer in extremely cold environments. When the temperature of dielectric fluid falls below the pour point, it hinders convection flow and inhibits the cooling of the transformer [12].

4.4. Environmental properties

The environmental safety of the insulation system is governed by two fundamental factors: biodegradability and low toxicity. Typically, insulation systems that have a high biodegradation rate and reveal low toxicity are categorized as “environmentally friendly”. These aspects are very significant when considering the application of transformers in environmentally sensitive regions e.g. water courses. The term “biodegradability” reveals the degree to which the insulation is digested by naturally occurring microbes in soil or waterways, in the aftermath of seepage or release. It is good if the insulation system vanishes instantly and naturally without the application of costly clean-up procedures [2,12].

4.5. Research on the detection and evaluation technologies of the insulation status of converter transformers

Converter transformers play a vital role in power conversion applications, e.g. HVDC transmission systems and frequency converters. Confirming the insulation status of converter transformers is critical for avoiding electrical breakdowns and guaranteeing the reliability of power transmission systems. In this regard, different detection and evaluation technologies have been developed to monitor the insulation status of converter transformers.

One of the most common methods for detecting insulation degradation in converter transformers is partial discharge measurement. PD appears in the presence of localized insulation defects, and monitoring PD activity may offer early warning indicators of insulation deterioration. PD measurements are usually conducted employing sensors that are mounted within the transformer or external to the transformer tank. The information gathered from PD measurements may be used to evaluate the insulation condition and plan maintenance activities accordingly [63,64].

Another frequently used technology for assessing the insulation status of converter transformers is dielectric response analysis (DRA). DRA implies exposing the transformer insulation to an AC voltage signal and determining the dielectric response of the insulation. By analyzing the dielectric response data, it is probable to identify moisture content, insulation aging, and other factors affecting the insulation condition. DRA is a non-destructive testing method that may be performed during scheduled maintenance inspections [65,66].

Thermal imaging is also used as a diagnostic tool for evaluating the insulation condition of converter transformers. Thermal imaging cameras may identify hot spots in the transformer insulation, which can indicate insulation degradation or partial discharge activity. By examining temperature variations in the transformer, maintenance personnel may recognize potential insulation issues and take corrective actions [67,68].

In addition to these technologies, other methods e.g. power factor measurement, capacitive measurement, and frequency response analysis are also used for assessing the insulation status of converter transformers. These technologies provide valuable information on the insulation condition, allowing maintenance personnel to make learned decisions on the maintenance and repair of transformer insulation [69]. In summary, there are multiple detection and evaluation technologies available for monitoring the insulation condition of converter transformers. By employing a mixture of these technologies, maintenance personnel may effectively assess the insulation condition of transformers and ensure the reliability of power transmission systems.

5. Trends in HVDC transformer insulation systems

5.1. Emerging technologies and materials

In the realm of HVDC transformer insulation systems, numerous emerging trends in technologies and materials are determining the prospects of this field. These trends include developments in technologies and materials to improve the efficiency, reliability, and performance of HVDC transmission. Some of the key trends include:

a. ***Nanotechnology:*** The use of nanotechnology in insulation systems is drawing attention due to their improved dielectric characteristics and potential for decreasing space requirements in HVDC transformers [22].
b. ***Advanced insulation materials:*** Researchers are investigating the application of new, novel, and innovative insulation materials with enhanced thermal and electrical features to improve the efficiency and reliability of HVDC transformer insulation systems. These materials intend to enhance insulation performance and lifespan and handle challenges e.g. aging of dielectric materials and breakdown inhibition [1].
c. ***Smart insulation systems:*** The incorporation of smart technologies e.g. sensors and real-time monitoring expertise, is developing gradually significantly in HVDC transformer insulation systems to support proactive protection and inhibit failures [70].
d. ***Eco-friendly materials:*** There is a mounting focus on building insulation materials that are ecologically friendly and sustainable, supporting the comprehensive trend towards green technologies in the electric industry [2].
e. ***Computational modeling and simulation:*** Innovations in computational instruments and simulation systems are aiding researchers to optimize insulation designs and forecast the conduct of HVDC transformer insulation systems more correctly [71].
f. ***Incorporation of monitoring systems:*** The incorporation of innovative monitoring systems employing tools such as AI and big data analytics is a developing trend in HVDC transformer insulation. These systems assist earlier discovery of problems, predictive maintenance, and improved system performance [72].
g. ***Specific insulation techniques:*** Recently research has been offered to advance specified insulation systems designed for HVDC systems, considering aspects such as constant voltage stress and electrostatic stress distinctive to DC transmission. These practices directly to improve insulation design and efficiency [73].
h. ***Higher operating voltages:*** Researchers are aiming to develop insulation systems capable of enduring elevated operating voltages in HVDC transformers to develop system effectiveness and consistency [74].
i. ***More frequent polarity reversals:*** Denationalization of domestic utilities around the globe and deregulation of the energy market have completely transformed the electricity flows in a few power grids. Recently electricity is being traded like other goods; hence it is desirable to attain a greater level of control on electric flows into power grids. Henceforth, utilities are developing new HVDC networks and/or adopting phase shift transformers. Some of the emerging technologies and materials are summarized in Fig. 5.

These trends reflect that these emerging technologies and materials are continuously driving innovation and research in HVDC transformer insulation systems, to enhance efficiency, reliability, and sustainability in HVDC transmission to meet the emerging demands of modern power grids for efficient and reliable electricity transmission over long distances.

5.2. Industrial developments and innovations

Several of the key industrial trends and innovations in this field include the development of innovative insulation materials with superior thermal and electrical characteristics, the use of nanotechnology to expand insulation performance, and the implementation of digital monitoring and diagnostic systems for real-time condition monitoring. Moreover, there is a rising emphasis on sustainability and environmental impact, resulting in the improvement of eco-friendly insulation systems for HVDC transformers. Overall, the industry is continually advancing to cope with the rising demands for efficiency, reliability, and sustainability in HVDC transformer insulation systems [1].

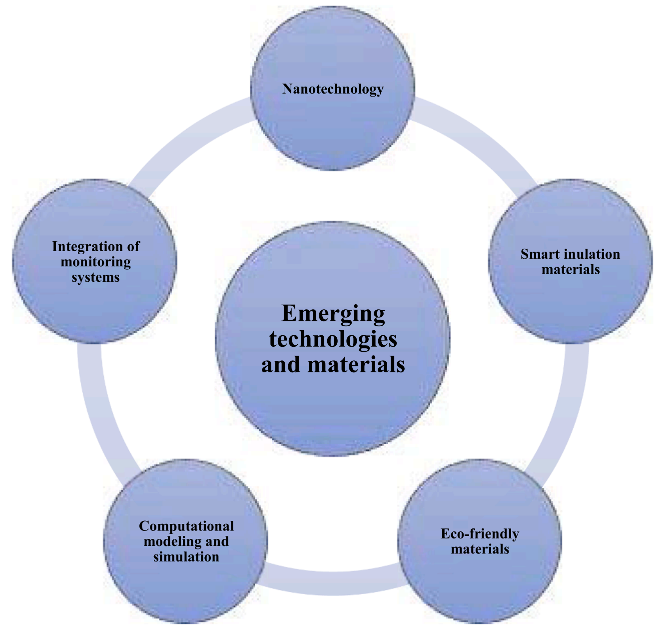

Fig. 5. Emerging technologies and materials in HVDC transformer insulation systems.

5.3. Effect of digitalization and IoT on insulation systems

The impact of digitalization and IoT on HVDC insulation systems is vital, improving security, reliability, and performance in electric grids. These solutions support real-time examination and predictive protection of insulation systems, confirming optimal working and avoiding breakdowns. IoT tools enable data collection from several sensors mounted on HVDC transmission lines, granting for distant monitoring of insulation status and early recognition of potential problems. This incorporation of digitalization and IoT in HVDC improves energy management and supports the transition to sustainable energy sources such as renewables. Digitalization and the Internet of Things (IoT) have had a critical effect on HVDC insulation systems. By incorporating digital tools and IoT instruments into HVDC transformer insulation systems, operators can now supervise and examine data in real-time, authorizing analytical maintenance and early recognition of likely problems. Overall, the integration of digital technologies and IoT in HVDC insulation systems has transformed the way these systems are administered and maintained resulting in enhanced reliability and operating efficiency [75].

6. Challenges in HVDC transformer insulation

6.1. Technical issues regarding the HVDC transformer insulation system

The insulation system of the HVDC transformer is vital for ensuring the safe and reliable operation of the transformer. Various technical problems can appear within the insulation system of HVDC transformers which are as follows:

a. Partial discharge: Partial discharge is a typical issue in HV transformers, including HVDC transformers. It may happen due to defects in the insulation system, e.g. voids, cracks, or impurities. PD may result in deterioration of the insulation and eventually lead to transformer failure.
b. Leakage current: Leakage current may happen in the insulation system of HVDC transformers due to the presence of humidity, impurities, or other factors. This may result in insulation collapse and failure of the transformer.
c. Aging of insulation materials: Insulation materials used in HVDC transformers, e.g. paper, oil, and resin, may deteriorate over time due to factors such as temperature, mechanical stress, and electrical stress. As the insulation ages, its dielectric traits may degrade, resulting in an enhanced probability of insulation breakdown.
d. Overvoltage stress: HVDC transformers are exposed to HV during operation, which may lead to overvoltage stress on the insulation system. This may result in the breakdown of the insulation and failure of the transformer.
e. Thermal stress: Thermal stress may happen in the insulation system of HVDC transformers due to high operating temperatures or temperature gradients within the transformers. This may result in deterioration of the insulation materials and eventually lead to transformer failure.
f. Contamination: Contamination of the insulation system may occur due to the presence of humidity, dust, or other impurities. Contamination may deteriorate the dielectric characteristics of the insulation and enhance the risk of insulation breakdown.
g. Mechanical stress: Mechanical stress on the insulation system may occur due to issues e.g. vibration, shock, or inappropriate installation. This may result in damage to the insulation materials and increase the risk of insulation breakdown.

Generally, appropriate maintenance, monitoring, and testing of the insulation system are critical for warranting the reliable operation of HVDC transformers and inhibiting insulation-linked technical problems. Frequent checks, insulation resistance tests, and partial discharge measurements may assist in detecting and addressing impending issues with the insulation system before they result in transformer failure. Technical issues regarding the HVDC transformer insulation system are outlined in Fig. 6.

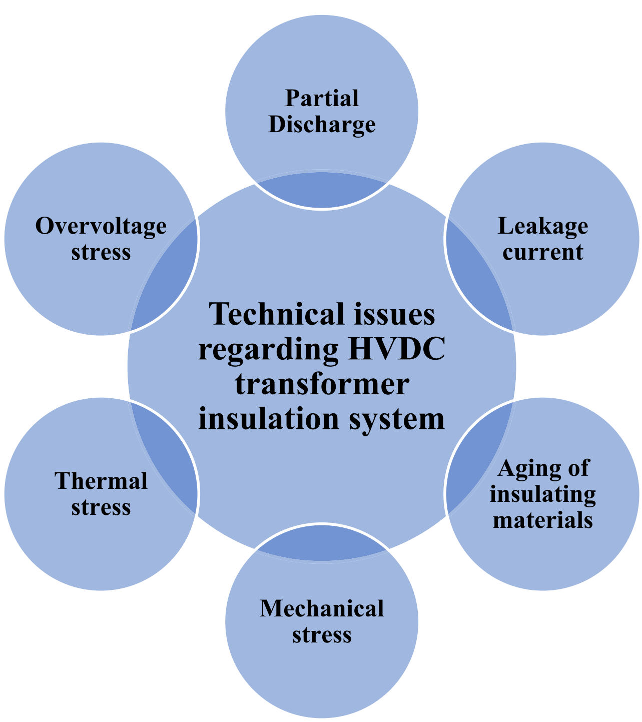

Fig. 6. Technical issues regarding HVDC transformer insulation system.

6.2. Technical challenges in designing effective insulation systems

Designing efficient insulation systems poses numerous challenges. One crucial challenge is choosing suitable materials that can endure HV and temperature while preserving their dielectric characteristics. Another challenge is warranting appropriate insulation coordination to inhibit electrical failure and confirm system reliability. Moreover, designing insulation systems that are compact and lightweight, yet lasting and long-enduring needs particular attention to several considerations e.g. thermal conductivity, dielectric strength, and environmental settings. Overall, evaluating these features to develop an effective insulation system that gathers performance conditions can be a complicated and demanding undertaking for inventors and engineers. The technical challenges in designing effective insulation systems imply handling different factors to warrant optimal performance and lifespan. These challenges may be as follows:

a. ***Need for reliability:*** For an AC connection, transformers are connected in parallel, hence the failure of a transformer triggers the failure of a single element of the competence of the link. The unit of such a failure is subject to the failed unit attributes (rated power, number of phases) and the overload capacity of remaining units. However, for a DC link, transformer units are connected in series (via converters), hence the loss of a transformer leads to the loss of the entire power of the connection. Additionally, a substitute HVDC unit is more challenging to source (because of a reduced sum of suppliers) and has an extended lead time than typical power transformers. These facts, jointly with increasing numbers of HVDC links and growing electricity conveyed via them, indicate that the consistency of HVDC units should be greater than the one of power transformers of comparable voltage and rating.
b. ***High Voltage Operation*:** Insulation systems should survive enhanced electric stress in HV applications, which may expedite aging and result in early breakdown [71,76].
c. ***Ambiguity about oil electrical conductivity*:** It is a general consideration that conductivities of dielectric materials have a significant role in concluding the dielectric stress distribution in insulation systems under DC voltage. For mineral oil, its conductivity may largely differ [77]. However, it is not a customary procedure to determine and examine oil conductivity in testing and during the life of an HVDC transformer. There are multiple practices to determine oil conductivity. These procedures vary for time and stress for which the oil sample is measured and provide substantially distinct outcomes. Considering likely differences, it becomes apparent that insulation systems appropriate for oil/board conductivities arrangement may not function securely with diverse oils [78].
d. ***Ion drift and effective design tools:*** Ion drift in oil may have a considerable impact on the distribution of dielectric stress among pressboard barriers and oil ducts [79]. Ignoring ion drift in the computation of dielectric transients may result in substantial error when compared to measurements [80]. Owing to differences of about 6 orders of magnitude between ions mobility in pressboard and oil, dielectric transient simulations have been, until lately, too computationally costly to use to study practical insulation systems [81].
e. ***Thermal management:*** Power transformers operate at high power densities, creating substantial thermal stress on insulation materials. Effective thermal management is key to preserving insulation reliability and motor performance [82].
f. ***Efficiency of DC and PR tests:*** Similar to AC dielectric tests, the aim is to apply increased dielectric stress for a brief time to validate the appropriateness of the insulation system for working at minimal

stress levels. Contrasting to AC, the use of an increased voltage does not relate directly to an equal rise of the applied stress. The required increased stress level is obtained only after a time interval adequate for the polarization of the insulation system. The magnitude of this time interval relies on both material traits, shape, and sum of solid barriers in the insulation system. Without elaboration, the greater the working DC voltage, the greater the number of barriers and hence the polarization time. Inadequate polarization time together with a lack of control of oil resistivity between the test and service condition may result in dielectric stress through a test that is smaller than through the service [77].

g. ***Mechanical stress:*** Vibration and mechanical stress in transportation, installation, and operation phases may lead to physical degradation of dielectric materials over time, negatively impacting their efficiency [71].
h. ***Environmental Factors:*** exposure to humidity, chemicals, and higher temperature variations may adversely affect dielectric materials, compromising their electrical, mechanical, and thermal characteristics [83].

To handle these challenges, research into new materials with superior thermal stability, and good electrical features to improve mechanical vigor, and the capacity to self-heal or show wear is critical. Moreover, the use of modern manufacturing strategies and innovative design processes is crucial for producing insulation systems that may fulfill the needs of HV operations while confirming security, effectiveness, and consistency in electric power transmission.

6.3. Environmental and sustainability challenges

The environmental and sustainability challenges of HVDC insulation systems largely revolve around the materials applied in these systems and their effect on the environment. Moreover, the development and dumping of insulation materials may have serious environmental impacts, e.g. energy consumption, resource exhaustion, and waste production. Inappropriate disposal of insulation materials may result in pollution and damage to ecosystems. The environmental and sustainability challenges of HVDC insulation systems revolve around the necessity for materials that have good dielectric features but also are environmentally friendly and recyclable. These challenges are as follows:

a. ***Environmental Impact:*** Conventional insulation materials applied in HVDC systems can have hostile impacts due to their fabrication methods, disposal, or chemical composition. Realizing substitutes that curtail environmental footprints is critical [84,85].
b. ***Recyclability:*** Confirming that insulation materials applied in HVDC systems are recyclable is critical for lowering waste and advancing the circular economy. Developing insulation solutions that may be simply recycled at the end of their lifespan is a major sustainability challenge [86].
c. ***Sustainable acquiring:*** The sustainability of insulation materials also relies on the sourcing of natural materials. Applying sustainable sourcing methods to attain materials for insulation systems collaborates in lowering the general ecological impacts of HVDC technologies [85].

Addressing these challenges of sustainability of HVDC insulation systems needs a move towards using eco-friendly materials, discovering recyclable alternatives, and implementing sustainable practices throughout the lifecycle of HVDC insulation systems to help shift towards greener and more sustainable electrical networks.

6.4. Safety and reliability concerns

Safety and reliability issues of HVDC insulation systems are significant due to the vital role insulation plays in warranting the effectiveness and life cycle of HVDC transmission systems. The major issues are as follows:

a. ***Partial Discharge (PD) and Insulation Breakdown (BD):*** PD and BD pose critical safety and reliability issues in HVDC systems, specifically in commercial aircraft applications. The rise in system voltages e.g. transitioning from 28 VDC to 115/200 VAC, may result in insulation concerns, increasing the hazard of PD phenomenon and successive BD [87].
b. ***Insulation Degradation:*** Insulation degradation is a serious concern, particularly with the increase in voltages (>1 kV) considered for hybrid/electric propulsion systems. The aging of dielectric materials under DC voltage, linked with elements such as extreme working temperatures and small air pressure at extraordinary altitudes, may expedite insulation aging and lower system life probability [76].
c. ***Maintenance and Monitoring:*** Frequent maintenance and monitoring of HVDC insulation systems are significant for confirming constant reliability. Assessments from contaminations, tracking, or PD are critical to identify beforehand and avoid damaging breakdowns. Supervising practices play an important role in detecting impending issues before they accelerate toward complete failure [88].

Addressing these safety and reliability challenges involves an inclusive methodology that incorporates advanced insulation materials, efficient maintenance schemes, monitoring techniques, and adherence to rigorous criteria to alleviate hazards connected with PD phenomenon and insulation BD and improve system performance in HVDC applications. The challenges being faced by HVDC transformer insulation systems are summarized in Fig. 7.

7. Future prospects

7.1. Potential research directions and areas for improvement

Potential research directions and areas of improvement in HVDC insulation systems include as following:

a. ***Development of new insulating materials:*** Research emphasizing on development of new insulating materials with improved characteristics e.g. higher BD strength, high-temperature resistance, and superior resistance to electrical, mechanical, and environmental stresses. All these characteristics are significant for enhancing the performance and sustainability of the HVDC insulation system [88]. The evolution of new solid insulating materials with better conductivity matching with oil is necessary to enhance the reliability of HVDC insulation systems.
b. ***Characterization of insulating materials:*** Broad classification of insulating materials for HVDC transformers as a function of dielectric

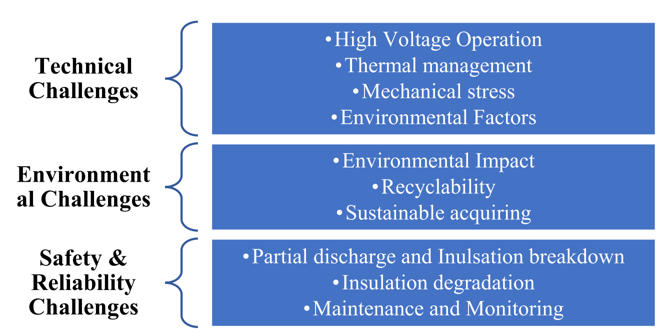

Fig. 7. Challenges being faced in HVDC transformer insulation systems.

stress, temperature, and moisture is required to improve the reliability and understanding of HVDC transformer insulation systems.

c. ***Numerical simulation and modeling***: A numerical study of ion drift on practical insulation systems with complex designs and geometries is required to better understand HVDC transformer insulation systems.
d. ***Management of stresses:*** Discovering techniques to control stresses on insulation system, e.g. through novel stress control practices which can be helpful to alleviate problems linked to insulation BD and aging, contributing to the consistency and durability of HVDC systems. Improving insulation design to decrease PD and enhance whole system reliability [89].
e. ***Space charge performance:*** Understanding and optimizing the space charge behavior in insulation materials is critical for enhancing the performance of HVDC insulation materials. Research in this field may result in developments in material characterization, insulation design, and maintenance schemes [90].
f. ***Insulation behavior under combined stress:*** Normally, HVDC transformers are tested distinctly with AC and DC voltages, though in practical application, they experience both forms of voltages at the same time, therefore research on insulation systems performance under combined AC and DC is necessary to understand the behavior of insulation system under combined stress.
g. ***Advanced monitoring and diagnostic techniques:*** Innovations in monitoring and diagnostic techniques for HVDC insulation systems are vital for the early detection of prospective problems such as insulation deterioration, granting well-timed maintenance, and avoiding expensive breakdowns. Research into new monitoring techniques may improve the reliability of HVDC systems [91]. Implementation of methodical monitoring of oil conductivity over the lifespan is essential to test the performance of the HVDC insulation system.
h. ***Application of new technologies:*** Investigating the use of advanced tools such as AI and big data analytics in HVDC systems may modernize insulation design, modeling, and condition supervising. Incorporation of these tools may result in more effective and reliable insulation systems [92].
i. ***Insulation configurations and geometries:*** Traveling novel insulation configurations and geometries to optimize the performance and efficiency of HVDC insulation systems [93].
j. ***Aging and environmental factors:*** Exploring the influence of aging and environmental features on insulation performance to produce more enduring and sustainable HVDC insulation systems [85].

By concentrating on these research directions and fields for enhancement, advancements may be made in enhancing the efficiency, reliability, and sustainability of HVDC insulation systems, eventually supporting the continued success of these critical components in modern electrical grids. Some of the potential research directions and areas of improvement are outlined in Fig. 8.

7.2. Predictions for the future of HVDC transformer insulation systems

It is expected that HVDC transformer insulation systems to persist to meet the rising challenges of the power industry. Various estimates include developing more developed insulation materials with advanced performance features e.g. higher BD strength and superior resistance to electrical and environmental stresses. There can also be improvements in insulation design and development practices to improve system reliability and efficiency. Furthermore, it is expected that the incorporation of smart monitoring and diagnostic strategies to facilitate real-time evaluation of insulation health and analytical maintenance approaches. Overall, the prospectus of HVDC transformer insulation systems is prone to emphasize on improving performance, reliability, and sustainability in line with the increasing demands of the electrical grid [94,95].

7.3. Opportunities for collaboration and interdisciplinary research

There are several prospects for relationship and interdisciplinary research in HVDC transformer insulation systems. Cooperating with professionals from numerous fields e.g. material science, electrical engineering, power systems, and insulation technology may result in new solutions and developments in this field. By linking knowledge and skills from various disciplines, scholars may handle complicated challenges and foster cutting-edge insulation materials, design practices, and diagnostic instruments for HVDC transformers. Interdisciplinary collaboration may also enable the integration of evolving tools, e.g. AI and IoT to improve the performance and consistency of insulation systems. Prospects for cooperation and interdisciplinary research in HVDC transformer insulation are abundant, offering avenues for innovation and advancement in this critical field. By leveraging skills across several fields, investigators may address complicated challenges and drive progress in HVDC insulation technology. Some key opportunities for collaboration and interdisciplinary research are as follows:

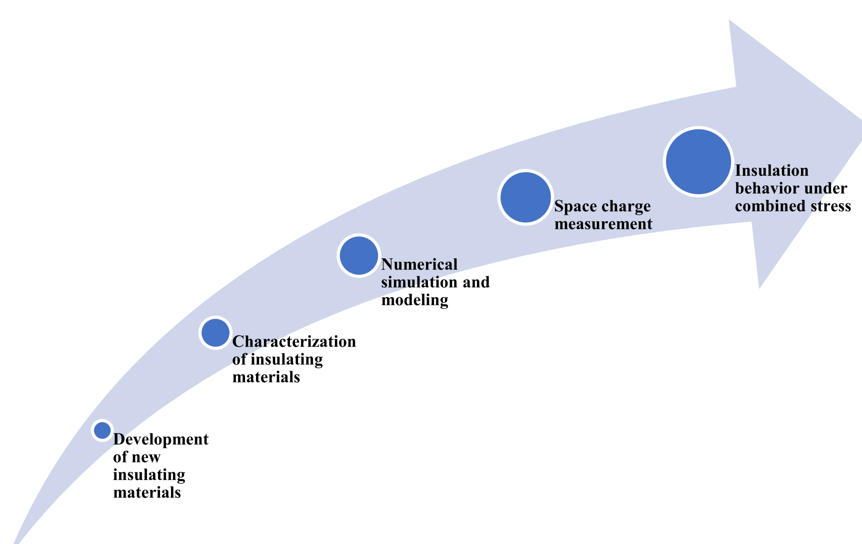

Fig. 8. Potential research directions and areas of improvement.

a. ***Engineering and material science collaboration:*** Collaboration with experts from material science may result in the development of innovative insulating materials with improved characteristics, e.g. enhanced conductivity, thermal stability, and environmental sustainability. This interdisciplinary technique may lead to innovation in insulation design for HVDC transformers [16].
b. ***Insulation coordination studies*:** Engaging with scholars aiming at insulation coordination studies may offer significant insights into improving insulation design, grading, and maintenance strategies. This cooperation may contribute to developing standardized techniques and procedures for warranting the consistency and protection of HVDC insulation systems [93].
c. ***Renewable energy integration:*** Collaboration with specialists in renewable energy systems may investigate the incorporation of HVDC transformers into renewable energy grids. This interdisciplinary research may handle challenges linked to extreme working conditions, intrinsic flaws, space charge dynamics, and power quality to attain reliable and secure operation of HVDC links in renewable energy infrastructures [96].

By promoting cooperation across these distinct fields, scholars may reveal new prospects for improving the performance, reliability, and sustainability of HVDC transformer insulation systems. Interdisciplinary research attempts have the prospective to drive substantial developments in HVDC technology and impact the advancement of advanced power grids toward a more effective and sustainable future.

8. Conclusion

The insulation system is one of the most critical components of HVDC transformers. Consequently, the properties of the insulation system should be continually improved and monitored. This paper examines the current state of research on insulation systems HVDC transformers including recent trends and challenges being confronted in the field of research. This paper depicted a broad overview of HVDC transformer insulation systems, targeting readers from diverse backgrounds. It covers topics e.g. new materials and technologies being explored for insulation, issues related to HVDC transmission, and the need for improved insulation systems to enhance the efficiency and reliability of HVDC transformers. This paper also highlights the significance of addressing challenges in this field to meet the growing demands of the energy sector. Moreover, it also summarizes the potential research fields that have the potential to improve the HVDC transformer insulation systems. The paper emphasizes the crucial role of insulation in HVDC transformers due to the distinctive features of HVDC transmission, which demands unique insulation systems and materials to confirm safety and efficiency. It discusses challenges being confronted in HVDC insulation systems, e.g. voltage stress and electrostatic stress, and reviews solutions like proper insulation design, grading, and maintenance to alleviate these challenges. Overall, the paper underscores the significance of ongoing research and advancements in HVDC transformer insulation systems to address challenges, enhance reliability, and pave the way for potential advances in HVDC transmission technology.

8.1. Implications of research findings

Present research trends, challenges, and prospects are important for the area of HVDC technology. The paper likely discusses the present state of research on HVDC transformer insulation systems, classifies developing trends in the subject, highlights the challenges that researchers and engineers are facing, and offers an understanding of the prospects of HVDC transformer insulation technology. By understanding the research outcomes manifested, experts in the HVDC industry may gain useful insights into up-to-date advances in transformer insulation systems, forestall forthcoming trends, and handle challenges that may occur in the design and implementation of HVDC systems. The major implications are as follows:

i. The research underlines the significance of developing new insulating materials with improved insulation and cooling properties. This implies a shift towards more efficient and reliable insulation materials that can withstand dielectric stress, temperature variations, and moisture exposure in HVDC transformers.
ii. The research implies a need for constant monitoring of insulation systems to warrant reliability. This stresses the significance of implementing advanced monitoring tools to discover potential concerns early and avoid failures in HVDC insulation systems.
iii. Understanding the performance of insulation systems under combined AC and DC stress during operation is critical. The research outcomes suggest a need for examining how HVDC transformers react to both forms of voltages simultaneously to confirm reliability and safety in practical operation settings.

Overall, the research outcomes summarized have implications for advancing insulation materials, monitoring tools, design methods, and general reliability of HVDC transformer insulation systems. By handling these implications, researchers and industry experts may drive development towards more efficient, reliable, and sustainable HVDC insulation systems solutions for advanced electrical grids.

8.2. Recommendations for potential research in this field

Suggestions for upcoming research on HVDC transformer insulation systems could incorporate discovering advanced materials for insulation to enhance performance and reliability, exploring new insulation design systems to augment efficiency, reviewing the effect of environmental features on insulation deterioration, and examining the potential for integrating smart technologies for real-time monitoring and maintenance of insulation systems. Moreover, research on the advancement of sustainable and eco-friendly insulation solutions could also be valuable in addressing prospective challenges in this field. Future research should emphasize the development of innovative insulating materials with improved characteristics like enhanced conductivity, thermal stability, and environmental sustainability. Moreover, research should focus on the implementation of modern monitoring tools to constantly monitor the condition of HVDC insulation systems to identify potential hazards and assist preemptive maintenance to hider failures in HVDC insulation systems. There is a need for detailed research on the performance of insulation systems under united AC and DC stress during operation. By concentrating on these upcoming research directions, scholars may contribute to developments in insulation materials, monitoring tools, design practices, and overall reliability of HVDC transformer insulation systems, finally driving the evolution towards more efficient, reliable, and sustainable HVDC for contemporary power grids.

Funding

The Alexander von Humboldt Foundation funded this research, and the authors are thankful for and acknowledge their support.

CRediT authorship contribution statement

Muhammad Rafiq: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation, Conceptualization. **Muhammad Shafique:** Writing – review & editing, Resources, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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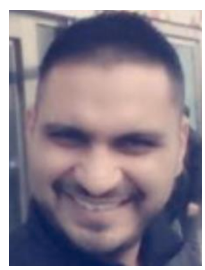

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