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Pollution Flashover Voltage of Transmission Line Insulators: Systematic Review of Experimental Works

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ABSTRACT Over the past decades, extensive experimental-based research works have been carried out to investigate the flashover phenomenon on the performance of polluted transmission line insulators. The critical focus has been on developing methods that can determine the safety, reliability, and sustainability of the overall power transmission network based on experimental results obtained from polluted insulators' flashover voltage tests. In this paper, a systematic review of available scientific works, published as early as the 1990s, for the analysis of pollution flashover voltage, is undertaken. The review mainly focuses on factors influencing the efficiency of transmission line insulators under polluted conditions. Specifically, publication databases utilizing various synonyms and keywords associated with the terms "contaminated insulators" and "flashover voltage test" have been scrutinized. The search has resulted in 1364 articles, from which 97 articles have satisfied the review requirements and have been subsequently analyzed to determine the parameters associated with polluted insulators. Major factors that affect the performance of insulators, including electrical and environmental impacts, are discussed. Variations in factors affecting flashover test development and insulator efficiency are also considered. Overall, the current analysis provides an important insight toward successful evaluations of the health of transmission line insulators and research advancements of electric power transmission line insulators.

INDEX TERMS Flashover voltage test, polluted insulators, high voltage insulators, transmission line.

I. INTRODUCTION

With the rising demand for modern-day electricity, the topic of overhead power transmission lines has become important and prominent to ensure minimally interrupted electricity supply. A transmission line comprises several types of components with different functions, and one of the most important components is the insulator, as illustrated in Figure 1. Due to pollution and unstable weather in the outdoor environment, insulators may get damaged from time to time [1]. The damage or failure of insulators may arise from the flashover voltage, or in general, due to a combination of multiple damaged components, including fitting faults, which may result in power outage [2]. Once the flashover occurs in a power transmission line, it may lead to super regional blackouts and may even cause catastrophic accidents as suggested by [2]. Often, site engineers can provide actual insights into factors that influence the performance of insulators, as well as yielding guidance into the fitting characteristics of the transmission line insulators. It is therefore crucial

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to understand the flashover mechanisms of insulators based on the views and perspectives of engineers and researchers worldwide [3]–[5].

To date, various pollution flashover models, including static and dynamic models, have been pursued by many researchers in predicting the flashover voltage characteristics of polluted insulators [6]–[13]. For this, the collection of experimental data in identifying factors affecting the performance of polluted insulators are key elements to understanding the failure of polluted insulators. Moreover, in-depth exploration of experimental parameters in relation to the performance of polluted insulators is vital to gain an insight into problems faced by high voltage insulators.

Nevertheless, no systematic reviews have thus far been carried out with regard to factors affecting pollution flashover voltage tests. This paper therefore aims to systematically review experimental studies dealing with pollution flashover voltage tests conducted on high voltage insulators under polluted environmental conditions. Specifically, pollution flashover tests carried out by researchers between 1990 and 2021 have been reviewed and factors, limitations, and criteria relevant to pollution flashover characteristics have been critically discussed.

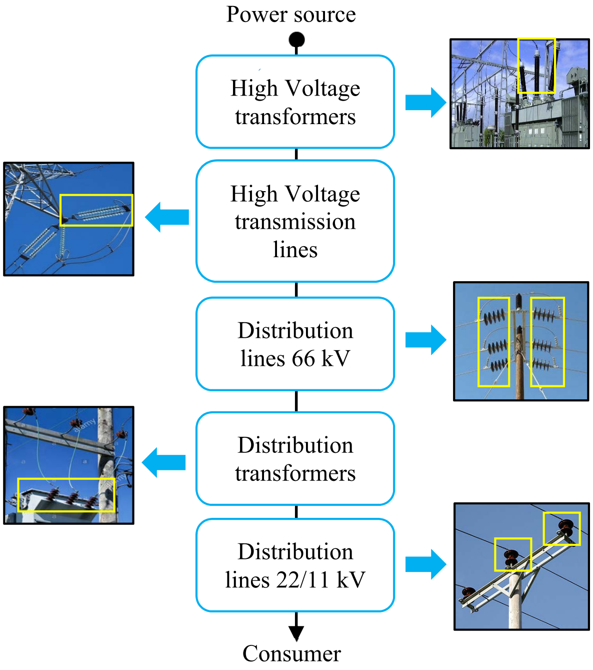

FIGURE 1. Location and usage of insulators in transmission lines.

A. BACKGROUND OF INSULATOR POLLUTION FLASHOVER

Failure of insulators occurs due to flashovers or discharges. The main cause of insulator flashovers or discharges is the environmental conditions [12]. These include contamination, aging, and moisture. These conditions are subjected to insulators during the insulators' in-service lifetime, thus resulting in insulator failures and subsequent electrical grid outages [14]. To date, a significant amount of both theoretical and experimental works have been devoted to the study of flashover that occurs on polluted insulators. This huge amount of works resulted in the development of numerous models capable of predicting various characteristics related to the pollution flashover phenomenon. For example, the insulator shape, the pollution distribution layer and its resistivity, the heat exchange, and the presence of moisture have been correlated with pollution flashover to determine key factors affecting the pollution flashover phenomenon.

Significantly, the contamination of an insulator associated with the presence of moisture degrades the dielectric performance of the insulator [2]. The presence of moisture in addition to the pollution of insulator results in the dissolution of salt contaminants, leading to the formation of a conductive layer on the insulator [6]. The conductive layer, which is subjected to different values of voltages across the insulator, becomes an easy path for the leakage current to flow. This causes the conductive layer to heat up through the Joule effect, thus resulting in the formation of dry bands on the insulator. The potential difference, which initially appears between the line and the ground electrode of the insulator, will be at the limits with the presence of the dry band regions [12]. Due to high electric fields, a spark will occur, originating from the wet area where the voltage is high, above the dry bands, ionizing the surrounding air [8]. The spark will grow at high intensity and may propagate over the whole length of the polluted layer. This causes the passage of the current in the AC state and leads to the line short-circuit, changing the insulator to a conductor [15]. Of note, a flashover will take place whenever the electric field exceeds a threshold value, commonly known as the threshold voltage [15]. Figure 2 demonstrates the flashover process of a polluted insulator.

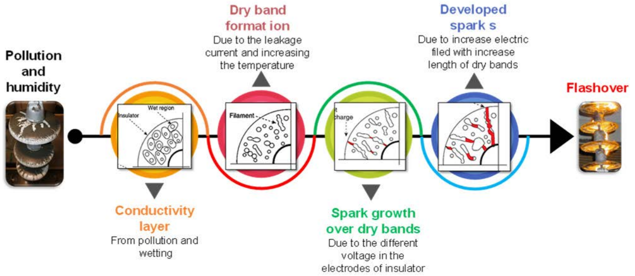

FIGURE 2. Pollution flashover process on an insulator.

B. RESEARCH QUESTIONS

Although a huge number of insulator flashover tests have been carried out globally in the last two decades, a systematic review that summarizes the development of flashover tests on polluted insulators has yet to be available in the literature. Therefore, the current work intends to review available literature with regard to pollution flashover tests on polluted insulators. For this, the following research questions have been addressed.

1) What have been done in the studies of contaminated insulator flashover?
2) What are the techniques, parameters, methods, conditions, and insulator samples used in pollution flashover tests?
3) What are the crucial factors affecting the flashover voltage due to the pollution of high voltage insulators?

II. RESEARCH METHODOLOGY

The research methodology of this study consisted of four main stages as demonstrated in Figure 3. The first stage was meant for incorporating the right strategy for searching the literature and setting the criteria for the literature to be included in the current review. This was needed to complement extensive theoretical questions implemented on any existing research, which were proposed to include adequate search questions and answers from the related scientific literature. The second stage was intended for the selection of the literature, and it comprised data classification and data extrapolation. This information processing operation constituted of data collation accompanied by data definition. Then the extraction and evaluation of the data was carried out in the third stage by applying accurate estimation criteria. Finally, in the fourth stage, synthesis of data was carried out, in which a step-by-step analysis of data was performed to deliver a satisfactory conclusion of the selected study characteristics.

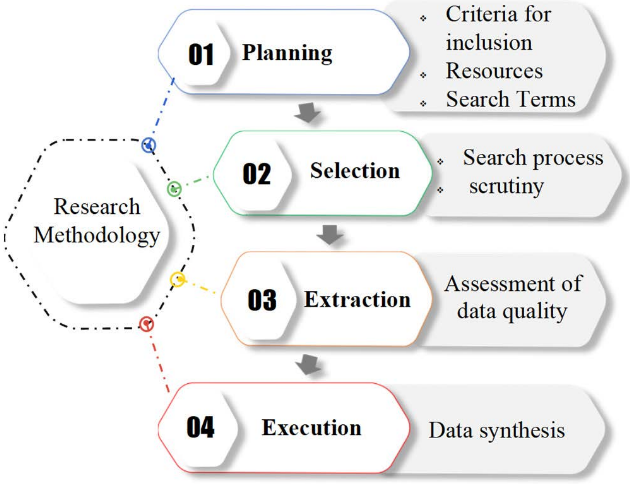

FIGURE 3. Processes and stages of the review.

A. PLANNING

1) INCLUSION AND EXCLUSION CRITERIA

A systematic review of all peer-reviewed and published papers relevant to the study of pollution flashover of polluted insulators were finalized for exploration. The articles that were written in the English language on the tested pollution flashover during the last four decades from 1980 to 2020 were reviewed. Accurate criteria for the addition were established to include relevant articles and exclude articles that were not related to the study of pollution flashover. Therefore, only peer-reviewed papers that concentrate essentially on pollution flashover studies were taken into consideration. For this, articles that presented the results from laboratory tests, field tests, static models, dynamic models, analytical studies, numerical models, mathematical models, statistical analysis, and prediction models on flashover of polluted insulators were included. Papers selected from references of relevant papers were also included. Finally, all papers were compiled. The inclusion and exclusion criteria are summarized and tabulated as in Table 1.

TABLE 1. Search criteria of the review.

Inclusion Criteria	
1	Studies that addressed the objectives of the flashover voltage on polluted insulators.
2	Studies of pollution flashover voltage on polluted insulators published between 1990 and 2021.
3	Studies related to flashover voltage factors affecting polluted insulators.
4	Studies related to flashover voltage experiments on polluted insulators.
Exclusion Criteria	
1	Duplicated studies or redundant articles of the same authorship.
2	Articles that are irrelevant to this study.
3	Articles that could not reach their text using the specified search engines.
4	Studies in which the focus was not on the flashover on solid surfaces of high voltage polluted insulators, such as gas insulation, transformer bushings, and breakers.

2) SEARCH TERMS

The search terms used to conduct the review were devised to identify studies that introduced aspects of pollution flashover tests and models on high voltage insulators. To select search terms, pilot searches in an iterative way were performed. Terms that did not produce articles matched to the inclusion criteria were excluded. To ensure to include the synonyms of the essential terms, the synonyms of the specified terms were determined. Therefore, the ‘‘flashover’’ synonyms are ‘‘discharge’’, ‘‘arc’’, and ‘‘breakdown’’. Keywords used to define the term ‘‘pollution’’ included ‘‘pollutions’’, ‘‘polluted’’, ‘‘contamination’’, and ‘‘contaminated’’. The ‘‘method of studies’’ term has the following synonyms: ‘‘study’’, ‘‘investigate’’, ‘‘test’’, ‘‘experiment’’, and ‘‘experimental’’. Finally, the ‘‘model’’ synonyms were ‘‘model’’ and ‘‘approach’’. In the searching process, the Boolean operators ‘‘AND’’ and ‘‘OR’’ were employed to search for relevant scientific papers. The word ‘AND’ covers all selected keywords, ‘OR’ covers any of the selected keywords, and the wildcard asterisks provide the plurals and other suffixes. After many iterations, the keywords used in this search within title, abstract, full text, and keywords of the published papers were defined as (Flashover OR ‘‘arc discharge’’) AND

(Test OR experiment OR investigate OR predict OR prediction OR analysis OR analytical) and (pollution* OR polluted OR contamination* OR contaminated) AND (insulator* OR dielectric*). Figure 4 shows the bibliometric analysis of 97 articles issued on the pollution flashover of insulators according to the Scopus database using particular keywords such as ''pollution flashover'' AND ''insulators''.

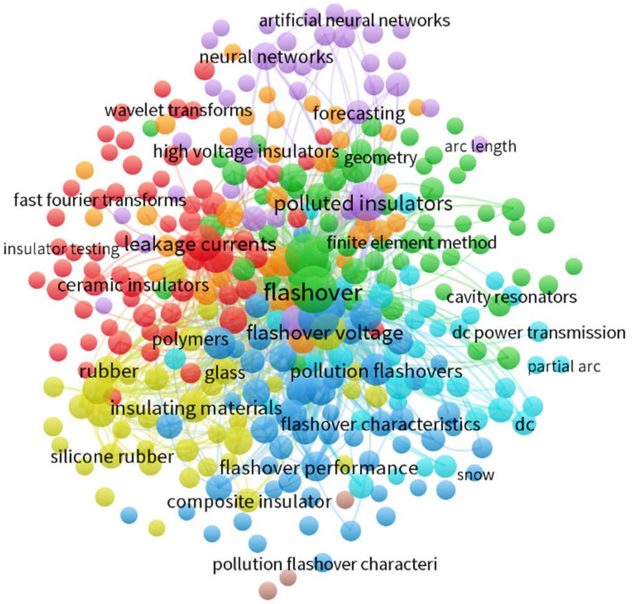

FIGURE 4. Bibliometric analysis of search keyword.

3) RESOURCES

Six research databases were used as sources for this systematic review, namely, Web of Science (WoS), Scopus, Science Direct, IEEE Xplore, Springer, and Google Scholar. Various existing papers were also searched for their title, abstract, and keywords and were employed to operate more search terms to locate published journals or papers, conference proceedings, workshops, symposiums, books chapters, and IEEE bulletins.

B. SELECTION

1) LITERATURE SEARCH PROCESS AND SCRUTINY

The search process steps advocated by Khan *et al.* [16] were adopted in this work to choose the relevant papers. Figure 5 shows the steps used to classify papers that are relevant to the pollution flashover topic. First, comprehensive searches of six research databases or publishers (as mentioned above), as well as a database that relates to systematic reviews, were administered to select relevant articles.

Second, the journals that include papers relevant to studies on the flashover models and tests of polluted insulators were selected. Then, the reference lists of all the relevant papers that matched the conditions of inclusion were checked. Each list of references was searched for any additional citations that could point to new articles and collected. Finally, when the search process entered the saturation stage when searches did not add any extra studies, the filtering process began. The primary selected list of articles was filtered and examined to ensure relevance. The steps involved in this filtering have been summarized as follows: First, the titles were evaluated for pertinence, and the article's contents were scanned to ensure relevance to the subjects under examination. They were subjected to further assessment according to the following conditions: typed in English, journal rank, and conference indexing. Papers that discussed the same topic and the most recent were included.

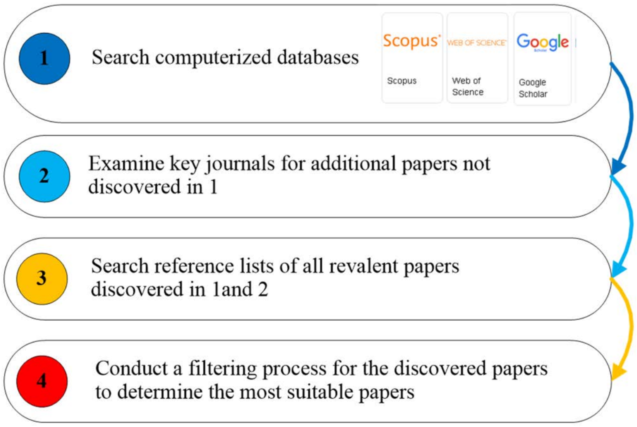

FIGURE 5. Systematic literature review methodology summary.

C. EXTRACTION (ASSESSMENT OF DATA QUALITY)

The quality assessment was aimed to boost the reliability of the selected articles in this work and in ascertaining the eligibility and comprehensiveness of the results [17]. The papers selected were assessed based on quality by a scoring method to decide the reliability, significance, and relevance of the articles. The studies were judged using a set of 10 criteria as exhibited in Table 2. The obtained papers were of different types of studies. To evaluate their quality, the included articles were classified into four categories as suggested by [18]. The categories were:

1) Evaluation Research (ER) articles: These articles comprised the techniques that were developed and implemented, and a stringent evaluation was carried out on them.
2) Validation Research (VR) articles: These articles comprised studies that discussed the assessment of a technique or method by using some experiments, i.e., work conducted in laboratories. To our knowledge these studies were novel and were carried out in practice.
3) Solution Proposal (SP) articles: These papers provided the solution to new issues or an extension of studies concerning the techniques underused. The suitability and efficiency of the solution were illustrated by a descriptive scenario or case study or discourse.
4) Opinion Articles (OA): These articles reflected the points of view of the authors on the application of the case definition methodology, emphasizing their

advantages and disadvantages. These forms of research were not dependent on the relevant studies and the research methodology.

The quality of evaluated questions was used for each category as given in Table 2 and is proposed by [19], [20], [21], as well as [17]. Each question was assessed based on three potential responses: "Yes" (score = 1), "Partially" (score = 0.5) or "No" (score = 0). This was done by the help of StArt (State of the Art through Systematic Reviews) software [20]. Subsequently, the sum of answers scores would determine the quality of the relevant study.

TABLE 2. Criteria for Research Quality Assessment.

No.	Questions	ER	VR	SP	OA
1	Is there a clear description of the aims of the study? [21]	×	×	×	-
2	Is the research methodology being clear? [21]	×	×	×	-
3	Is there a satisfactory report of the context (equipment function descripts, experiment setting, products used, and so on) in which the work was carried out? [21]	×		×	-
4	Is the sample representative of the group to which the findings can be generalized? [19]	×		×	-
5	Was the analysis of the results adequately accurate?[18]	×	×	×	-
6	Is there a debate about the research outcomes?[21]		×		-
7	Are the limitations of this work explicitly addressed? [21]	×	×		-
8	Are the concepts learned exciting? [19]	×			-
	Is there enough analysis of relevant studies? [20]	×	×	×	-

D. EXECUTION OF DATA SYNTHESIS

The information gathered from the answers to the research problems were tabulated using Microsoft Excel spreadsheets. The information was extracted according to the data described in Table 3 from each of the total number of 88 articles involved in this review. In the choice method too, the StArt tool [22] was used to aid in data extraction.

Through the synthesis stage, the terms which described the study subject was normalized and the most common keywords was employed. Three taxonomies were built utilizing those terms: (1) the approaches applied on the flashover studies of polluted insulators (model, analysis and predict); (2) the contamination methods applied in pollution flashover studies; (3) the relationships between pollution flashover-related information.

III. RESULTS

A. STUDIES SELECTION

TABLE 3. Data extraction.

Information	Description
Study goal	The unique aim of the study.
Study details	Authors, Year, Title, Country.
Study source	IEEE, IET, Scopus, Since direct, Springer and IOP.
Study Type	Journal, conference.
data analysis	Quantitative/qualitative analysis.
Study methodology	Experiment, model, evaluation, prediction, optimization, numerical.
Tools	What are the tools used in the study of the flashover of polluted insulators?
Study environment	What are the environmental circumstances under which a flashover of a polluted insulator is studied?
Benefits	What are the advantages of the proposed research in electrical power insulation systems?

The selection process of studies was conducted as in Figure 6. The articles were collected from electronics database with the help of the keywords that were mentioned in Section II (search term). These papers were carried out strictly according to the requirements for inclusion and exclusion. 1364 articles were obtained, and their abstracts were reviewed. As shown in Figure 7, the obtained papers consisted of 567 articles from Scopus, 423 articles from IEEE Explore, 147 articles from Science Direct, 136 articles from Web of Science, 51 articles from Springer, 16 articles from Institute of Physics, 7 articles from references lists, and 19 articles from other sources. Out of 423 IEEE articles, there were 159 journals papers, 247 conferences papers and 11 magazines. The collected studies (1364 articles) were inserted and arranged into the StArt software to start the selection process. Moreover, 5 papers were included manually. Out of 1364 articles, 376 appeared to be duplicated studies and were excluded. After reviewing the abstract for 988 articles, 747 papers were rejected based on the lack of relevance to the noted study. Therefore, the remaining 244 papers were eligible for full text review and 97 met all eligibility criteria and were included in this systematic review process. Figure 8 depicts the processing of selection and extraction for relevant studies using Start software. Out of 241 full text articles, 144 articles were excluded because the flashover on polluted insulators was not the main concern of the papers or included only secondarily study or as a case study in a larger study. Figure 8 illustrates the selection process using StArt tool software. Based on the eligibility criteria, rejected papers were classified as low and very low levels while accepted papers were classified as high and very high levels. Accepted papers that achieved three or four of inclusion criteria were classified as very high level while accepted papers with less than three of inclusion criteria were classification as high level. Meanwhile, rejected papers that met all the exclusion criteria were classified as very low level; rejected papers that met less than four exclusion criteria were classified as low level. Figure 9 demonstrates the number of papers that met inclusion and exclusion criteria. As can be seen from

Figure 9, most of the included papers were concerned with experimental studies for the pollution flashover of insulators. In addition, most papers were rejected because the objectives of those articles were improved in new articles under the same authorship members.

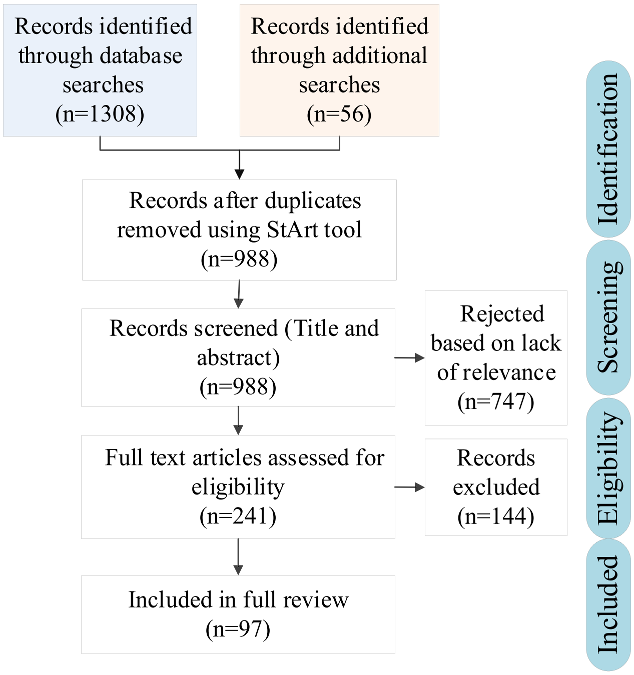

FIGURE 6. Studies selection flowchart.

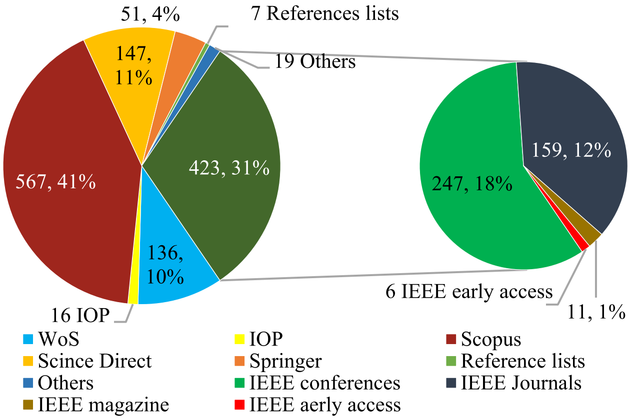

FIGURE 7. Sources of the articles reviewed.

B. ELIGIBLE STUDIES CHARACTERISTICS

Ninety-seven eligible studies were published between 1990 and 2021, comprising 103 journal articles and 18 conference papers. The keywords of the included studies were analysed and plotted in word-cloud software as shown in Figure 10. Table 4 demonstrates the number of conference papers and journal publications by year of publication. The number of publications has increased dramatically since 2010. Of note, the number of review papers about pollution flashover of outdoor insulators appeared little throughout the last decade. Although there have been many studies on pollution flashover, comprehensive reviews of insulator pollution flashover have not been done.

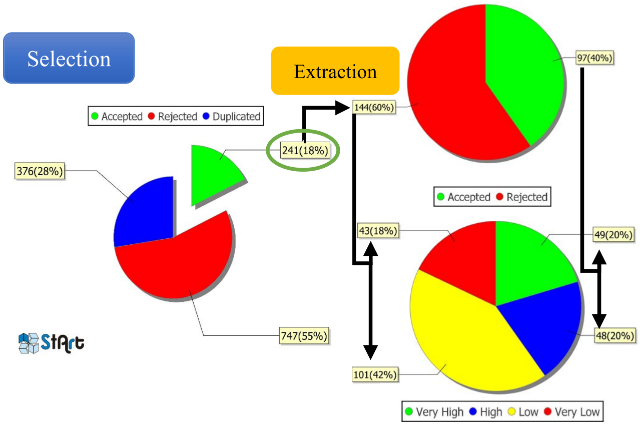

FIGURE 8. Selection and extraction details using StArt software.

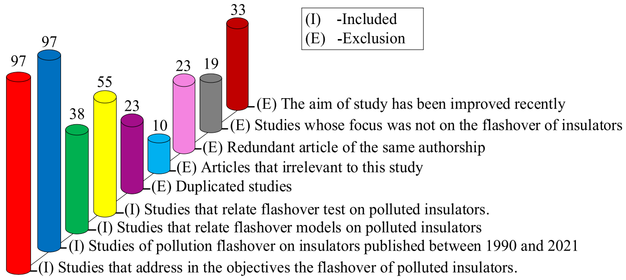

FIGURE 9. Numbers of the accepted and rejected papers based on inclusion and exclusion criteria.

FIGURE 10. Word-cloud of the included studies keywords.

Figure 11 shows the share of journals publishing papers on pollution flashover of high voltage insulators. From Figure 11, majority of the paper were published in IEEE Transactions on Dielectrics and Electrical Insulation (TDEI) (40 articles, 31.7%), Electric Power Systems Research (15 papers, 12%), International Journal of Electrical Power and Energy Systems (9 articles, 10.7%), and IEEE Transactions on Power Delivery (8 articles, 7%). The rest of the journals published less than 5 articles per journal.

The number of countries contributing to publishing papers on the flashover of polluted insulators were also taken into consideration. According to the affiliation of the first author on the noted papers, the published articles were classified as illustrated in Figure 12. Majority of the selected papers have

TABLE 4. Temporal view of studies included in the review by the year of publication.

Published year	Journals papers	Conferences papers
1990	1	0
1993	1	0
1994	0	0
1995	1	0
1996	0	0
1997	1	0
1999	0	0
2001	1	0
2002	1	0
2003	1	0
2004	2	0
2005	1	0
2006	0	2
2007	2	0
2009	1	1
2010	1	1
2011	4	1
2012	3	1
2013	6	0
2014	9	1
2015	4	2
2016	6	1
2017	3	1
2018	7	0
2019	8	1
2020	12	2
2021	7	0

been contributed by the researchers from China (32 papers, 32.9%), Algeria (14 papers, 14.4%), India (8 papers, 8.2%), and UK (6 papers, 6.1%). The papers published by other countries were less than 6 papers for each country. According to the classification suggested by [16] based on research type, the included publications were sorted as follows:

1) Evaluation Research (ER) (9/97 paper) [32]–[38], [142]–[154]
2) Validation Research (VR) (58/121 paper) [42] – [100]
3) Solution Proposal (SP) (30/121 paper) [101]–[129]

The majority of the research articles were Validation Research type with 59.7% (58 papers) followed by Solution Proposal with 30.9% (30 papers), and Evaluation Research with 9.2% (9 papers). None of the selected papers belong to opinion studies category of research types. To address the adopted methodology suggested in the selected studies on the flashover voltage on polluted insulators, 97 eligible studies were categorized into three new categories, namely, Experimental studies only (ES), Experimental studies supported by proposed model and ((ES)-(PMS)), and Experimental studies supported by prediction method ((ES)-(PS)). The new classification of selected studies was tabulated in Table 5. It is clear from Table 5 that most of the papers introduced experimental studies only. The above research questions are intended to present the techniques or approach utilized, the main parameters, and the contamination conditions for each experimental study, as well as the structure and type of the selected insulator. As seen from Table 5, the experimental study alone was used to test the contaminated insulators in 51 studies and to verify the model used in 36 studies. In addition, the experimental method was used to endorse prediction studies in 10 articles. The answer to the above question through the selected experimental studies was summarized in Table 6.

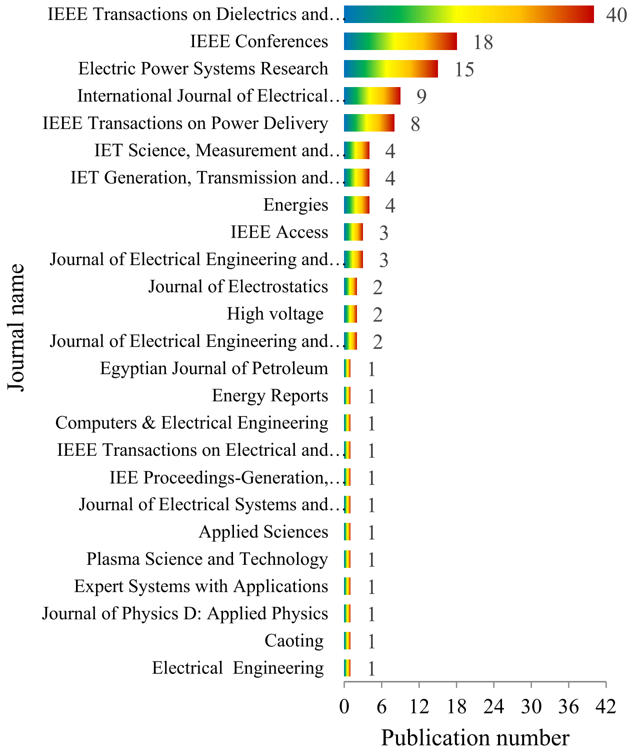

FIGURE 11. The share of journals publishing papers on the flashover of polluted insulators.

C. DESCRIPTION AND KEY FINDINGS

In this section, the fundamental information and the key findings of pollution flashover voltage of high voltage insulators are discussed. The pollution flashover of contaminated insulators was investigated using several parameters. According to data in Table 6, majority of the selected studies investigated pollution flashover based on the factor of equivalent salt deposit density (SDD), followed by non-soluble salt deposit density (NSDD), pollution distribution, humidity, dry band, coating, pressure, aging, polarity, wetting rate, and insulator shape, respectively. The impact and results of these parameters are discussed in this section. Flashover voltage, as one of the most important indicators of polluted insulator tests, has been studied frequently in 94 papers. Most researchers performed their experimental studies only on the flashover

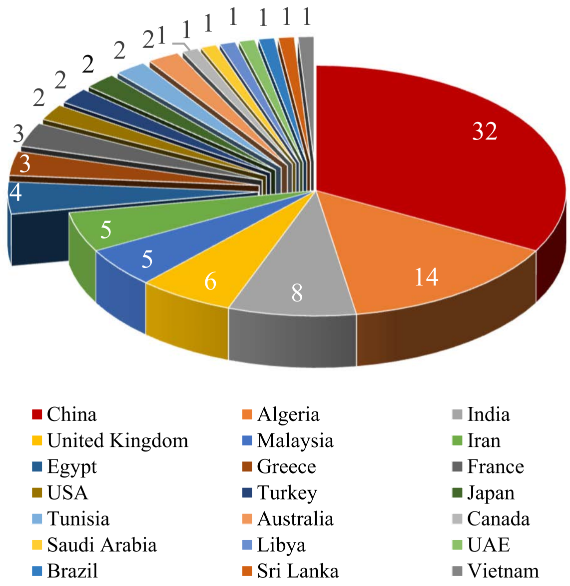

FIGURE 12. The share of countries on publishing papers based on the first author affiliation.

TABLE 5. Methodology classification of the selected studies.

Method of study	Studies	Count	%
Experimental studies (ES)	[24], [25], [31], [33], [36], [40], [42], [45- 47], [49], [51], [53], [58], [59], [61], [62], [66], [68 – 72], [74], [76-79], [84 – 87], [90-92], [96], [98], [100], [116], [141 -155]	51	52.5
Proposed Model and experimental studies ((PMS)-(ES))	[26], [29], [33], [37], [41], [44], [47], [54-56], [63], [65], [67], [73], [81], [82], [88], [89], [94], [95], [99], [101], [102], [118-130]	36	37.1
Prediction study and experimental studies ((PS)-(ES))	[27], [42], [60], [75], [83], [97], [131-133]	10	10.3

voltage and flashover voltage gradient of the polluted insulator. Meanwhile, some researchers used experimental tests to validate their proposed models. Accordingly, a good model would result in less error in predicting the flashover voltage [24], [33], [47], [56], [88], [121], [124], [129], [130]. The flashover voltage has therefore been the main parameter used to determine factors affecting insulation flashover. Figure 13 shows factors affecting the flashover voltage of insulators and the number of published studies for each factor.

1) SDD IMPACT ON FLASHOVER VOLTAGE

Based on Figure 13, SDD is the most influential factor in effecting insulation flashover voltage. This is based on the review of 47 papers [24]–[29], [31], [33], [34], [36], [37], [39], [40], [42], [43], [45], [46], [48]–[51], [54]–[56], [58]–[60], [63], [64], [66], [67], [69]–[73], [78]–[81], [86], [89]–[92], [96], [97], [99], [100], [120], [122], [126], [128], [130], [131], [132], [142]. Of note, SDD has often been studied in combination with other factors such as NSDD, wetting rate, and pollution distribution. Based on the experimental results for majority of the selected papers [41], [59], the relationship between the flashover voltage U_f and SDD follows a negative exponential function, expressed as:

$$U_f = A \times (SDD)^{-a} \tag{1}$$

where A is a constant related to the insulator profile and materials and a is the contamination characteristic index of the insulator.

Dong *et al.* [26] presented the effect of SDD on the flashover voltage of three types of insulators under various fog water conductivities. According to the results, there was a nonlinear decrease of flashover voltage with increasing SDD and fog water conductivities. A reduction in the flashover voltage ranging from 2.6–18.9 kV for silicone rubber composite insulator, 2.3–21.5 kV for porcelain insulator, and 2.3–28.3 kV for glass insulator was recorded with an increase of fog water conductivity from 0 to 3 mS/cm under a specific value of SDD. By increasing both the SDD and fog water conductivity simultaneously, a significant decrease of the flashover voltage was observed.

Similarly, [31] studied the effect of SDD and fog-water conductivity on the contamination flashover voltage of three different types of insulators under non-uniform pollution. From the experiment data, the relationship between the flashover voltage, SDD, and fog water γ was established as [31]:

$$U_f = f(SDD, \gamma) = A \times (SDD)^{-a} \times e^{-b.\gamma} \tag{2}$$

where b is a factor implying the rate of fog water on the flashover voltage and e is a constant equals to 2.718.

In [66], an experiment was carried out on three separate insulators (porcelain, glass, and polymer) to investigate the effect of contamination variations under salt fog (additional salt deposit density ASDD) on the flashover voltage. From [66], the relationship between ASDD in fog water and the pollution level SDD was represented as:

$$ASDD = k \times \gamma \times SDD \tag{3}$$

where k denotes the coefficient describing the effect of SDD and fog water conductivity on ASDD, determined experimentally as 0.179, 0.191, and 0.230 for porcelain, glass, and composite insulators, respectively. Then, the flashover voltage was expressed as [66]:

$$U_f = A \times (SDD + ASDD)^{-a} \tag{4}$$

where the negative of characteristic exponent (-a) indicates the flashover voltage stress decreases with an increase in both ASDD and SDD.

The authors in [58] tested the characteristics of the flashover voltage of polluted polymeric insulators under

TABLE 6. **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

Study	Aim of experiment	Measurement Technique	Source Type	Condition / location	Style pollution	Insulators
[24] [28]	To investigate the flashover voltage -current behaviors	Direct measurement using voltmeter between pin and 3mm electrode in the rib of insulator	AC	- Artificial pollution (ESDD) - Humidity / Test chamber in laboratory	uniform	- Single Porcelain (Cap-and -pin)
[25]	To collect data to predict risk of flashover on towers using ANN and FL	Optical and satellite sensors installed on transmission towers used to measure risk per day (wireless)	AC	- Normal conditions / Field real transmission towers (sugarcane fields)	uniform	- String Porcelain insulator (Cap-and -pin)
[26]	To analyze insulator performance under fog -salt treatments	Direct measurement using capacitor divider (10000:1)	DC	- Artificial pollution (ESDD) / Test chamber in laboratory	uniform	- Silicone rubber composite insulator FXBW-35/70 - Seven-disk porcelain insulators (XP-160) - Seven-disk glass insulators (LXY-160)
[29]	To assess the risk of non-uniform polluted insulator based on a new leakage current index measured experimentally	Monitoring system (Divider -DAQ-LabVIEW interface)	AC	- Artificial pollution (ESDD) - Wetting rate / Test chamber in laboratory	Uniform Non-uniform	String 3-units Glass insulator (LXP-70)
[29]	To predict flashover performance on polluted insulator based on field experience and laboratory test and short historical of chemical components	Direct measurement using a shunt resistor.	DC	- Artificial pollution (ESDD) / Test chamber in laboratory	Uniform	- Long rod porcelain insulator - Cylindrical porcelain insulator - Flat glass insulator
[31]	To investigate the effect of SDD and fog-water conductivity on the AC contamination flashover voltage of insulators under cold foggy conditions	Capacitive voltage divider (SGB-200 A, with ratio (10000: 1)	AC	- Artificial pollution (SDD) - Cold fog and Steam fog / Test chamber in laboratory	Uniform	- SIR (FXBW4-35/70) - Porcelain (XP-160) - Glass (LXY4-160)
[33]	To develop the mathematical model of critical parameters on polluted insulators based on experimental findings.	Capacitor divider	AC	- Artificial pollution (Salinity) - Humidity / Test chamber in lab	Uniform	- 3 single different porcelain insulators - 3 different glass insulators

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[32]	To test pollution flashover performance under low air pressure conditions and study the relationship between the results of artificial experiment and field experiment	Capacitor divider and resistance divider	AC	- Artificial pollution (SDD) - Fog - Low Air pressure (P/P0) / Field experiment (height of altitude 4484 m and 2820 m) Multifunction artificial climate chamber	Uniform	- 21 units string Porcelain ▪ XP-160 ▪ XWP-160 - 21 units string Glass ▪ LXY-160 ▪ LXHY-160 - SIR ▪ FXBW-10/70 ▪ FXBW-110/70 ▪ FXBW-750/A ▪ FXBW-750/B
[36]	To investigate the effects of contamination distribution, temperature, and dry band position on insulator flashover characteristics under different scenarios	Monitoring system (Divider (10000:1)-DAQ-LabVIEW interface)	DC	- Artificial pollution (SDD) - Humidity / Test chamber in lab	Uniform pollution In 5 different scenarios distribution	- Single glass LXY-70
[37]	To determine how insulator geometry affects the flashover voltage based on leakage current.	Shunt resistors, Rm,	AC	Artificial pollution / Test chamber in lab	Uniform Non-uniform	- 5 different porcelain insulators - 1 control cylindrical insulator
[39]	To investigate the effect of the contamination configuration, the voltage polarity and the pollutant resistivity on the leakage current and the flashover voltage.	Shunt resistors	Impulse	- Artificial pollution - SDD - Pollution distribution / Test chamber in lab	Uniform Non-uniform	- Flat glass insulator
[40], [43]	To test AC flashover pollution for various types of insulator strings under fan-shipped non-uniform pollution.	- Current sampling resistor r 1(Ω) - Capacitor divider	AC	- Artificial pollution SDD - Pollution distribution - Aging pollution / Multifunction artificial climate chamber	Uniform Non-uniform Fan -shaped	- 3 different types of porcelain insulator string - 2 different types of glass insulator string - 4-type SIR composite insulators
[41]	To investigate the performance of composite insulator under dry and rain conditions comparing with switching Impulse (SI) superimposed	Capacitor divider	DC	- Conductivity - Switching impulse parameters - Wetting rate Insulator orientations / Test chamber in lab	Uniform	- SIR composite insulator
[42]	To test arc path for lightning protection composite insulator under different pollution	Capacitor divider	Impulse and AC	- ESDD - NSDD / Test chamber in lab	Uniform	- SIR Lightning protection composite insulator
[44]	To quantify the effect of different types of water drops on flashover voltage	Capacitor divider	AC	- Water drops	Water drops	- Flat silicon rubber

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[45] [49] [76] [141] [143] [144] [152]	To test effect of longitudinal and fan-shaped non-uniform pollutions on flashover voltage of SIR composite insulators	Capacitor divider	AC	- SDD - Fog / Test chamber in lab	Non-uniform Longitudinal Fan-shaped non-uniform pollution	- 4-type SIR composite insulators - Porcelain Glass
[46] [84] [85]	To test effect the insulator profiles and wetting rate on the mean flashover voltage	DAQ card	AC	- SDD - wetting rate / Test chamber in lab	Uniform pollution	- SIR ▪ conventional insulator ▪ textured insulator
[47]	To examine effect of desert conditions such as, fillers and ultra-violet on the flashover voltage of insulators	Capacitor divider	AC	- Ultra violet - Mechanical stress - Thermal - Three types of filler - ATH - H3BO3 - Mg (OH)2 / Test chamber in lab	Uniform pollution	- Cylindrical polyester composite
[48]	To assess the reliability of insulator using Pollution Existence PFD, a Log-Normal Distribution function To test effect of pollution and humidity on SiR insulators in different aging times	Capacitor divider	AC	- ESDD - Aging pollution - Humidity - Ultra violet / Test chamber in lab	Uniform pollution	- 4type SIR composite insulators
[50]	To predict the failure probability of the studied nano-RTV-coated, RTV-coated porcelain insulators in the presence of different levels of contamination.	Capacitor divider	AC	- SDD - Nano-RTV coatings for - RTV coating / Test chamber in lab	Uniform pollution and coating	Single porcelain insulator
[51]	To study the effect RTV coating on glass insulators under different natural pollution	Capacitor divider	AC	- ESDD - RTV silicone-coated - Aging - Superhydrophobic nano-coated / Site test	Uniform pollution and coating	- String 10-unit glass insulators
[52]	To analyze leakage current and flashover voltage with different fog-haze parameters	Capacitor divider	AC	- Fog conductivity - Fog-haze duration / Test chamber in lab	Uniform pollution	- 2-unit polymer insulator
[54]	To obtain the relationship between flashover voltage and electric field measured laboratory using fiber optic.	Leakage current sensor and DAQ Capacitor divider Fiber optic probe	AC	- ESDD - Humidity / Test chamber in lab	Uniform pollution	- Composite Long Rod - Ceramic Pin Type - 3 different types of Ceramic line post
[53]	To compare the experimental results of current and critical voltage with the results that obtained using mathematical model under different pollution conditions and humidity.	Capacitor divider (100, 25,000 pf)	AC	- Salinity Sa - Different Humidity - Different applied voltage / Test chamber in lab	Uniform pollution	- Cap and pin ▪ 3 types glass insulators ▪ 3 types porcelain insulators

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[56]	To validate the dynamic model of flashover voltages under uneven pollution between windward and leeward sides on insulator	Capacitor divider	DC	- SDD / Test chamber in laboratory	Non-uniform -windward and leeward pollution - top and bottom	- Long rod porcelain insulator
[58]	To test flashover voltage gradient performance of insulator strings under eight kinds of soluble constituents	Capacitive voltage divider (10,000:1)	AC	- ESDD with different salts: NaCl, NaNO3, KNO3, NH4NO3, $Mg(NO3)_2$, $Ca(NO3)_2$, $MgSO_4$, $CaSO_4$ / Test chamber in lab	Uniform pollution and	- Strings: ▪ Porcelain: XP4-160 ▪ glass: LXY4-160 ▪ SIR A: FXBW-35/100, FXBW-35/70
[59]	To investigate the high voltage insulator performance under natural contamination deposit environment, and distributed from different pollution severity areas	Leakage current sensor CT	AC 110 kV 220 KV	ESDD NSDD / Test chamber in lab	Natural pollution - Uniform pollution - Non-Uniform pollution	- Strings 3 units porcelain insulator
[60] [132]	To test flashover voltage and current characteristics of glass insulator covered by pollutant (sand)	Capacitive voltage divider for voltage Resistor for leakage current	AC 220 KV	Sand Quantity NSDD ESDD Applied voltage Dry band length and location / Test chamber in lab	Uniform and Non-uniform Pollution - with dry band - without dry band	A glass plan model
[62]	To study effect of dry band and distribution of pollution on insulator performance under impulse voltage	Capacitive voltage divider for voltage and Resistor for leakage current	Impulse	Resistivity positive and negative polarities Arc length Number of arcs / Test chamber in lab	Uniform pollution -with 2 dry band - with 3 dry band - without dry band	A plan model
[63] [142]	AC contamination flashover of 4 types insulator with ring-shaped non-uniform pollution were test	Direct measurement using capacitive voltage divider 10000:1 for voltage Resistor for leakage current	AC	SDD / Test chamber in lab	Non-uniform Pollution Ring-shaped	Cap and pin - 3 different type porcelain insulators - 1 glass
[64]	Seven kinds of nitrates were prepared as the soluble contamination, and the ac flashover performance of 4 types of insulators under various nitrates were investigated	Direct measurement using capacitive voltage divider 10000:1	AC 110 kV	ESDD NSDD ESDD x NSDD Different salts NaCl NaNO3 KNO3 NH4NO3 Mg(NO3)2 Ca(NO3)2 MgSO4 / Test chamber in lab	Uniform pollution and	- SIR composite - 2 different insulators Cap and pin ▪ 1 glass insulator ▪ 1 porcelain

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[65] [88] [98]	To validate the critical current and voltage calculated using electro-thermal and dynamic models of flashover polluted insulators	Direct measurement using capacitive voltage divider	AC	Pollution resistance NSDD polarity 12 different electrolytes / Test chamber in lab	Uniform pollution	Plant model
[66]	Flashover voltage and current were tested under additional salt deposit density (ADD) and water salt-fog for three different insulators.	The leakage current signals were captured by NI USB-6215 data acquisition card (NI) and voltage using capacity divider	AC 110 kV	- ESDD - ASDD - Clean and salt fog water / Test chamber in lab	Uniform pollution	- Porcelain XP-160 - Glass LXY4-160 - Composite
[67]	The differences on the flashover voltage of contaminated SIR insulators using three wetting methods.	Direct measurement using capacitive voltage divider	AC	- SDD with - Wetting methods: ▪ Brushing Method ▪ Dipping Method ▪ Spraying Method / Test chamber in lab	Uniform pollution	4 different configurations of polymer insulators SIR
[67] [146 -149]	To test flashover performance on glass insulator under RTV and Nano-filler coating for cap and pin metal and insulator	Direct measurement using capacitive voltage divider	DC	RTV coating cap and pin insulator Nano-filler coating / Test chamber in lab	Uniform coating	Cap and pin glass insulator Plate
[69]	To investigate the insulators performance under different Non-uniform pollution	Direct measurement using capacitive voltage divider for voltage and Resistor for leakage current	AC	- SDD ▪ top and bottom ▪ Fan-shaped ▪ Ring-shaped / Multifunction artificial chamber in lab	- Uniform pollution - Non-Uniform pollution	String Porcelain insulator
[70] [71]	To test the flashover performance on a wet pollution layer by monitoring the flashover development using infrared image	FLIR A325 camera DAQ card Capacitive voltage divider	AC	- SDD - Fog - Dry band / Multifunction artificial chamber in lab	Uniform	Silicon rubber insulator 11kV
[72]	To investigate DC pollution flashover propagation under low air pressure	USB-6215 DAQ VI Logger Lite Capacitive voltage divider 100000:1	DC	- SDD - Low Pressure / Multifunction artificial chamber in lab	Uniform	String 7 unit XP-160 porcelain insulator
[73]	To test characteristics of AC arc on the contaminated insulation surface using CCD spectrometer and temperature monitoring	Red Lake® ultra-high-speed camera Spectrometer Rogowski coil	AC	- SDD - Pressure - Temperature / Multifunction artificial chamber in lab	Non-Uniform pollution	Glass triangle plate sample
[74]	To study the development parallel discharges of polluted insulator sample under different geometric for electrodes	Fast camera Capacitive voltage divider	AC	- Polarity - Shape electrodes / Lab	Non-Uniform pollution with dry band	- Rectangular plate of glass with different electrode geometric ▪Plane-plane ▪Rod-rod ▪Rod-plane ▪Multi rods-rod

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[75]	To monitor activity of discharges through arcing discharges pattern recognition using a combination of efficient image processing and classification algorithms	SONY DCR-SR video camera	AC 220kV	- Conductivity - Applied voltage / Test chamber in lab	Uniform	- Rectangular plate of glass
[77] [101] [102]	To test polluted insulators performance under fog and dew condition	Capacitive voltage divider	AC 220 kV	- Surface conductivity - fog and dew - Time - Dry band / Test chamber in lab	Uniform	Porcelain cap and pin, Open model for cap and pin glass insulator,
[78]	To investigate the relationship between flashover voltage and string insulator strength under pollution condition	AC capacitive divider	AC	- SDD - NSDD - String length / Test chamber in laboratory	Uniform	String LXHY3-160 glass insulator
[79]	To test the effect of the angles of V strings on flashover characteristics of polluted insulators	High-speed camera	DC	- ESDD - V strings angle / Test chamber in lab	Uniform	Two types of string porcelain insulators
[80]	To examine the performance of flashover for contaminated insulator string in natural fog.	High-speed camera Capacitive voltage divider	AC	- SDD - NSDD - Wind velocity - Natural fog / Test chamber in lab	Uniform	Cap and pin 3 units of glass insulator string
[81]	To determine the arc constant for different insulator profile To test effect of insulator shape on flashover voltage.	High-speed camera Capacitive voltage divider	AC	- SDD - Insulator profile / Test chamber in lab	Uniform	Triangular glass plate, "Π" type glass model,
[82]	To study influence of pollution distribution and insulator shape on flashover parameters	Capacitive voltage divider	AC	- ρmin - ρmax - Insulator shape - Arc length	Uniform Increase Decrease Practical	Rectangular plate
[86]	To investigate wetting status effect on electrical performance for polluted insulators	Capacitive voltage divider for voltage Resistor for leakage current	AC	- Wetting rate - Wetting time - SDD - Temperature - Insulator type / Test chamber in lab	- Uniform pollution - Uniform wetting	- 2 different type cap and pin porcelain insulators, - 2 different types Cap and pin glass insulators - SIR composite insulator,
[87]	To examine the flashover characteristics of polluted insulators under different polarity	capacitive voltage divider	Impulse	- Salt density - Polarity - Time / Test chamber in lab	Uniform pollution	5 different types 6.6 KV solid core insulators
[87]	To test the stage boundaries of the leakage currents during the entire contamination flashover process	Capacitance voltage divider (SGB-200A) Current sensor and amplifier	AC	- ESDD / Test chamber in laboratory	Uniform pollution	- Cap and pin glass insulator, - Antifog porcelain insulator,

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[90]	To study flashover characteristics on polluted insulator under natural pollution and fog- haze	Capacitive voltage divider	AC	- ESDD u/l - NSDD - Fog -haze - Natural pollution / Test chamber in lab	- Uniform pollution - Non-uniform pollution	- Porcelain XWP2-70 ME160KN, - Glass U160T145W - Polymer FXBZ-220/300,
[91]	To investigate effect of ESDD and NSDD on flashover voltage of insulators	Data acquisition (DAQ)	AC	- ESDD, NSDD - Insulator shape - Creepage Distances / Test chamber in lab	Uniform pollution	- Porcelain ▪ XP-160 ▪ XWP2-160 ▪ XWP4-160 - Glass ▪ LXY4-160 ▪ LXHY3-160 - Polymer FXBW3-110/100
[92]	To study flashover voltages across gaps on insulator top surfaces and gaps between sheds.	AC	AC	ESDD / Test chamber in lab	Uniform pollution	- single and a 3-unit glass insulator string
[93]	To study of insulators performance under discontinuous pollution layers	AC	AC	- Layer conductivity - Applied voltage - Arc length - Pollution layer length - Transferred voltage / Test chamber in lab	Uniform Discontinuous pollution	- Glass plate of 500x250 mm
[94]	To investigate interfacial breakdown on electrolytic surfaces of insulator	Capacitive voltage divider	AC	- Pollution resistance - Electrolyte NaCl, CaCI2, Ca(NO3)2, MgSO4 - Arc length / Test chamber in lab	Uniform pollution	Plate insulator
[94]	To investigate the effect of the insulator hydrophilic fraction on the pollution flashover performance.	Resistor and Capacitive voltage divider	AC	- Hydrophilic fraction - Saturated wetting time - SDD - NSDD / Test chamber in lab	Uniform and Non-uniform hydrophobicity	SIR FXBW-1000/210
[97],	To obtain the relationship between flashover voltage, pollution level and hydrophobicity degree for insulators	Data-acquisition (DAQ) system Capacitive voltage divider	AC	- SDD - hydrophobicity / Test chamber in lab	Uniform pollution and hydrophobicity	SIR FXBW4-35/70
[99] [100]	To test the performance of 10-kV post insulator with concentric externally gapped line arrester (EGLA) under pollution condition	Capacitive voltage divider Camera	AC	- ESDD / Test chamber in laboratory	Uniform pollution	- SIR 10- kV Post Insulator with concentric externally gapped line arrester (EGLA) - 11kv composite insulator

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[115]	To examine the influence of the electrolyte on the phase shift of dry-band discharges	- Monochromator - Photomultiplier	AC	- Two types of electrolytes (NaCl and MgCl2) / Test chamber in laboratory	Uniform	Ceramic plate
[116]	A new measurement technique was proposed to classification leakage current under different pollution	- Remote sensor with antenna - Shunt resistance	AC	- Lab. Polluted-low salinity - Polluted- high salinity - Field Polluted - Voltage level - Insulator profile / Test chamber in lab	Uniform	- 3 SIR Composite insulators - Cap and pin ▪ 2 porcelains ▪ 1 glass
[119]	To describes the different physical criteria controlling arc propagation, over electrolytic surfaces under ac voltage application	Capacitive voltage divider	AC	- Resistance pollution - Multiple arcs - Discharge length / Lab	Uniform	Flat plate with electrolyte
[118]	To evaluate the influence of arc-levitating on the DC flashover voltage of contaminated insulators and to measure the insulators' DC flashover voltages with and without the air-gap arc influence.	- Capacitive voltage divider - Shunt resistance	DC	- SDD - Low air pressure - Surface arc - Gap arc / Lab	Uniform	Porcelain XZP-210 string insulator (5 units)
[121]	To validate the proposed critical parameters of polluted insulator based on dynamic model.	- Current sensor - Capacitor divider	Impulse	- Resistance pollution - Thickness pollution layer / Lab	Non - uniform	Rectangular plate glass insulator
[122]	To test flashover performance in polluted insulator strings (Suspension And T-type)	- Capacitive voltage divider - Shunt resistance	AC	ρESDD / Lab	Uniform	- Strings ▪ Glass LXY4-160 ▪ 9 unit suspension (7+2) T-Type ▪ 6 units suspension (3+3) T-Type
[123]	To measurement Partial Discharge (PD) signal for CNN training.	Coupling devices	AC	Pollution configurations / Lab	Non-uniform	11 kV polymer insulators
[124]	To validate model of the time to flashover of polluted insulators.	- Capacitive voltage divider - Shunt resistance	Impulse	- Pollution surface conductivities - Critical voltage	Uniform	Single cap-and-pin glass insulator
[126]	To explore the flashover characteristics of polymer insulator under Inorganic and Bio contaminants	Current Sensor module (M_sen) DAS	AC	Inorganic pollutions - SDD - NSDD - Bio-contaminants algae - Radial growth ratios tme / Lab	Discontinuous uniform pollution Continuous uniform pollution	Triangular plate silicon rubber insulator

TABLE 6. ***(Continued.)*** **Purpose, techniques, parameters, conditions and insulators samples of flashover voltage tested.**

[127]	To extract the data from flashover videos taken on a plan glass insulator model of uniform contamination.	Capacitive divider A video camera (Full HD_20 Megapixels)	AC	- Five conductivities of Saline solution - 4 amounts of Sand and distilled water - Applied voltage / Lab	Uniform	Glass insulator plan model
[128]	To analyze the flashover properties of a two-unit glass suspension string under various conditions.	Capacitive divider Camera	AC Impulse	- ESDD - NSDD - Phase angle / Lab	Uniform	String 2 units LXY1-70 glass insulator
[129]	To validate of the proposed dynamic flashover model of string polluted insulators.	Capacitive divider Coaxial shunt	AC	Salinity / Lab	- Non-uniform in different Position of polluted discs	String 6 units cap and pin porcelain insulator
[130]	To validate of the proposed arc root flashover model of different polluted insulators.	Capacitive divider 1 Ω non-inductive resistance	AC	- ESDD - NSDD - Insulator shape / Lab	- Uniform	Glass flat plate single XP1-160 glass insulator
[131]	To forecast the occurrence and likelihood of flashover in SIR composite insulators using the leakage current harmonic components.	Capacitive voltage divider VBA macro	AC	- ESDD - NSDD - Insulator length - Humidity	Uniform	5 SIR composite insulators with different length
[132]	To represent characteristics of leakage current for tracking complex surface discharges to flashover on polymer insulator in serious fog-polluted conditions using self-normalizing multivariate (SNM) analysis approach.	10-Ω shunt resistor in connection with an analog to digital (A/D) converter	AC	Relative humidity (RH) Conductance of surface	Uniform	single -shed silicone rubber insulators

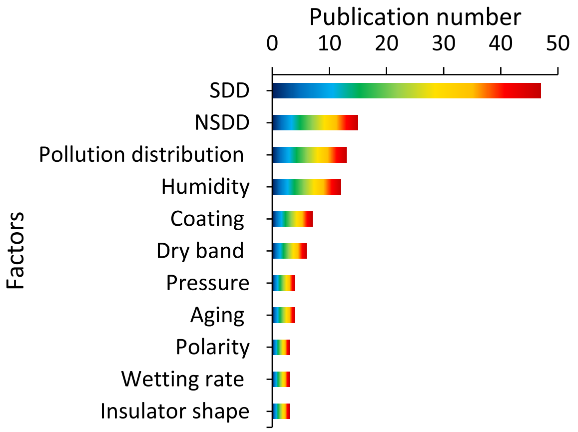

FIGURE 13. **Publication number on factors affecting pollution flashover voltage.**

three different polluting methods, namely, Brushing Method (BM), Dipping Method (DM), and Spraying Method (SM). The study reported some variations in contamination flashover parameters, and that their effects on the flashover voltage were different. The relationship between the flashover voltage and pollution severity under these three methods of polluting was calculated using equation (1). The different pollution methods was noticeable with changes in coefficient A, but negligible in the characteristic exponent a. Meanwhile, [79] extracted the relationship between the flashover voltage and SDD with the changing numbers N of insulator units in an insulator string, as seen in Figure 14.

2) POLLUTION DISTRIBUTION IMPACT ON FLASHOVER VOLTAGE

The flashover voltage under non-uniform pollution was tested in references [40], [43], [45], [49], [56], [63], [69], [76], [129] and [141]–[144]. Non-uniform pollution distributions were formatted into five shapes: top and bottom (T/B), ring-shaped (I/O), longitudinal (H/M), fan-shaped (leeward and windward sides) (L/W), and mixed longitudinal and fan-shaped non-uniform pollutions, as shown in Figure 15. For DC flashover voltage under top to bottom non-uniform pollution, the Electric Power Research Institute (EPRI) [140] developed a formula $K = 1 - C \times log(T/B)$ as the correction factor, where C is a constant representing the non-uniform pollution coefficient. Based on this correction factor, the authors

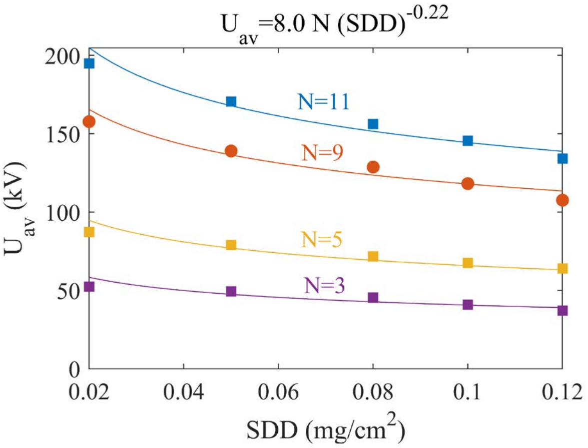

FIGURE 14. Relationship between the flashover voltage U_{av} and SDD for different numbers of insulators in a string.

of [49] calculated the relationship between the flashover voltage and SDD under fan-shaped (L/W), top to bottom (T/B), and longitudinal (H/M) non-uniform pollution conditions for composite polymer insulator as follows [49]:

$$U_{50} = \begin{cases} 9.24(SDD)^{-0.351}\left[1-0.0995\log\left(L/W\right)\right], & k=10\% \\ 9.24(SDD)^{-0.351}\left[1-0.1127\log\left(L/W\right)\right], & k=20\% \\ 9.24(SDD)^{-0.351}\left[1-0.1218\log\left(L/W\right)\right], & k=30\% \\ 9.24(SDD)^{-0.351}\left[1-0.1506\log\left(T/B\right)\right] \\ 9.24(SDD)^{-0.351}\left[1-0.1894\log\left(H/M\right)\right] \end{cases} \tag{5}$$

where k represents the ratio of polluted surface area to the total surface area.

The authors of [63] also extracted the relationship between the flashover voltage and SDD under ring-shaped nonuniform pollution for porcelain insulator as follows [63]:

$$U_{50} = \begin{cases} 30.0(SDD)^{-0.350}\left[1-0.151log\left(O/I\right)\right], & r:R=0.5 \\ 30.0(SDD)^{-0.350}\left[1-0.220log\left(O/I\right)\right], & r:R=0.7 \\ 30.0(SDD)^{-0.350}\left[1-0.172log\left(O/I\right)\right], & r:R=0.9 \end{cases} \tag{6}$$

where O and I are the outer and inner of the insulator surface area, respectively. Meanwhile, $r : R$ represents the ratio of pollution diameter on the insulator surface to the whole insulator diameter.

When comparing fan-shaped non-uniform pollution with fan-shaped uniform pollution, the flashover voltage dropped with fan-shaped pollution. The increase of the degree of fan-shaped non-uniformity pollution (L/W) resulted in a decrease in the flashover voltage, as shown in Figure 16 (c). For ring-shaped non-uniform pollution, the flashover voltage increased References [45], [49], [143] and [153] reported that, compared to uniform contamination, the flashover voltage increased with longitudinal non-uniform contamination.

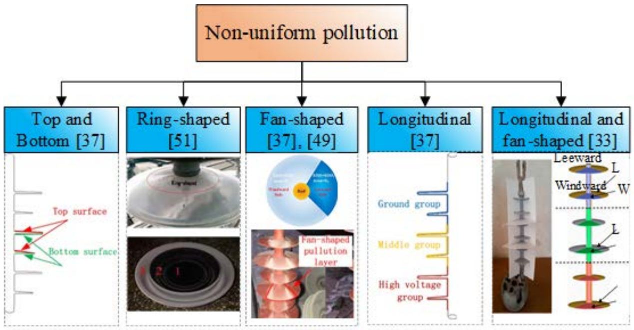

FIGURE 15. Non-uniform pollution classification.

Furthermore, the flashover voltage U_{50} increased as the longitudinal non-uniformity level (H/M or L/M) increased for all types of investigated insulators, as shown in Figure 16 (a). As shown in Figure 16 (b), with smaller mean value of the electrical conductivity of contamination on the insulator surface and higher surface of the insulator in (Top/bottom)-shaped, the flashover voltage as the level of I/O increased, and under some situations, it increased by approximately 36% compared to a uniform pollution condition, as shown in Figure 16 (d). Meanwhile, the flashover voltage would initially increase and subsequently decrease as the radius (r) of extremely contaminated areas increased [63], [142].

3) AIR PRESSURE DISTRIBUTION IMPACT ON FLASHOVER VOLTAGE

The effect of air pressure on the flashover voltage were investigated by the references [34], [72], [73], and [120]. The results in [34] showed that the AC flashover voltage on polluted insulators decreased with the reduction of air pressure under a specific value of SDD. For example, for the cap-and-pin type glass insulator with SDD of 0.03 mg/cm^2, the flashover voltage decreased from 238.5 kV to 191.0 kV due to a decrease in air pressure from 98.6 kPa to 70.1 kPa. In addition, the results showed that the distinctive exponent n in equation (7) describing the effect of air pressure on contamination flashover voltage U_f, which has an impact on the flashover voltage of contaminated insulators, is variable, and n value is related to the contamination degree and geometric structure of the insulator.

$$U_f = U_0(P/P_0)^n \tag{7}$$

where U_0 is the flashover voltage at the normal air pressure P_0, P is the experimental air pressure, and n is the exponent describing the effect of air pressure on U_f.

In the study of [72], the data of a polluted porcelain insulator string composed of 7 units of insulators indicated that the flashover voltage decreased remarkably reduced air pressure. As arc radius dropped from 89.9 kPa to 61.7 kPa, the flashover voltage decreased by 13.1 %. In addition, the arc radius of flashover under the effect of air pressure was considered. The results indicated that the arc radius was 1.5 mm and 3.5 mm corresponding to air pressure of 89.9 kPa and 61.6 kPa, respectively [72]. The electron density n_e of

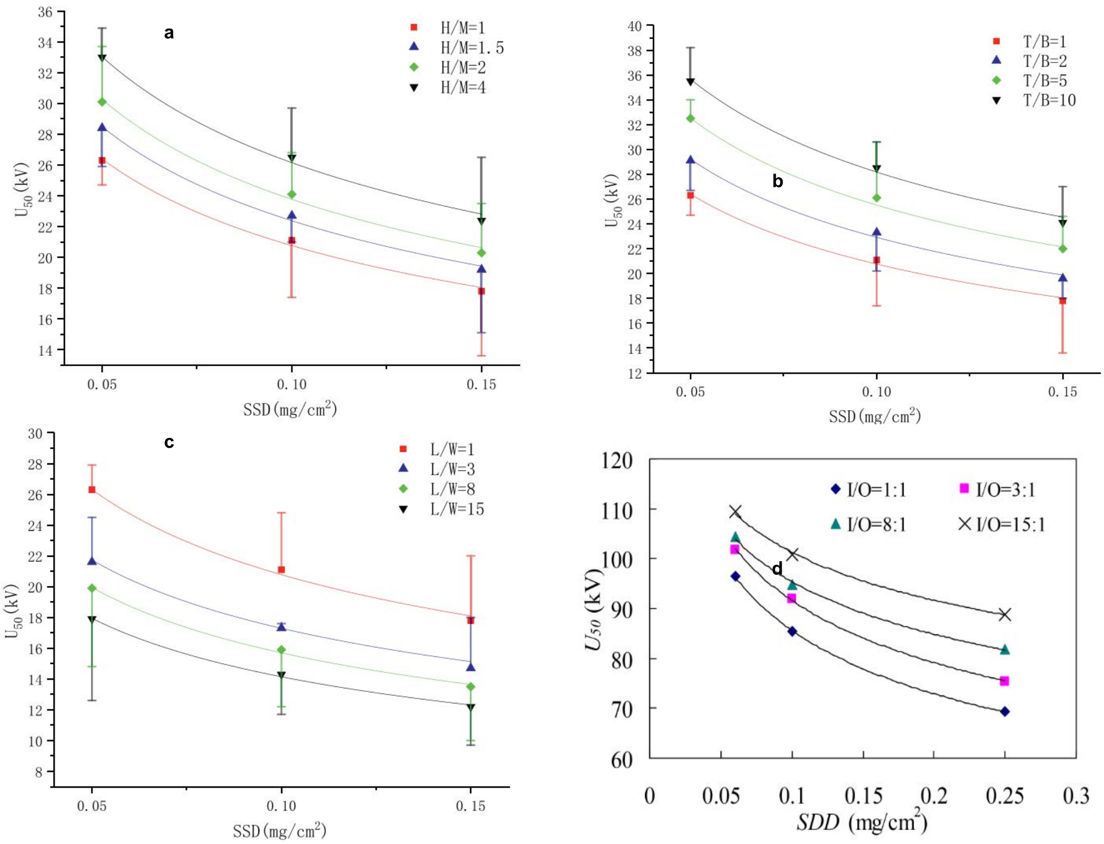

FIGURE 16. Flashover voltage under different non-uniform pollution: (a) Longitudinal [49], (b) Top-Bottom [49]; (c) Fan-shaped [47]; (d) Ring-shaped [142]. (Permission from Elsevier)

the flashover arc channel at low pressure was also investigated experimentally by [73]. The results reported that, with increasing pressure, the electron density of the arc channel increased based on equation (8):

$$n_e/n_0 = P^{\alpha} \tag{8}$$

where α is the index determined using the least-square method to be 0.58 and n_o is electron density in atmospheric pressure. The effect of the flashover phenomenon of polluted porcelain insulators under low air pressure on arc levitation was also studied in [120]. According to the findings, higher contamination and lower air pressure resulted in more serious arc levitation.

4) DRY BAND IMPACT ON FLASHOVER VOLTAGE

The flashover voltage under the influence of dry band was discussed in references [36], [62], [70], [71], [74], [112], [132]. The flashover voltage of glass insulators under dry bands with five scenarios of pollution distribution were tested in [36]. The results showed that dry bands had a significant effect on the flashover voltage, in which the flashover voltage increased with a decrease in the dry band area [36]. Authors in [62] investigated the effect of the number of dry bands formed on the contaminated plate insulator surface on voltage distribution. It was discovered that increasing the number of dry bands resulted in less discontinuity in the voltage distribution along the insulator, which improved the voltage grading and had a significant impact on the insulator's withstand capability.

The propagation of flashover on polluted porcelain post insulators under dry bands was investigated in [70], where the findings indicated that the discharge characteristics was affected by the formation of dry bands. In addition, the study compared the flashover voltage values between rain and fog factors. It was reported that the flashover voltage in rain was obviously higher than that in fog. An increase in the number of dry bands on the insulator surface would lead to a reduction in flashover activities and, as a result, an increase in the flashover voltage [71]. As suggested by [74], the effectiveness of insulation of polluted insulators increased with increased dry band length. Meanwhile, the effect of the dry band position on the performance of plate insulators was investigated by the authors in [112] (Figure 17). From the results, the flashover voltage with the dry band placed in the middle of the insulator was the highest; the flashover voltage with the dry band placed near electrodes of the insulator was lower than that with the dry band placed in the middle of the insulator.

5) NSDD IMPACT ON FLASHOVER VOLTAGE

The influence of NSDD on the flashover voltage of polluted insulators was investigated in [59], [60], [64], [91].

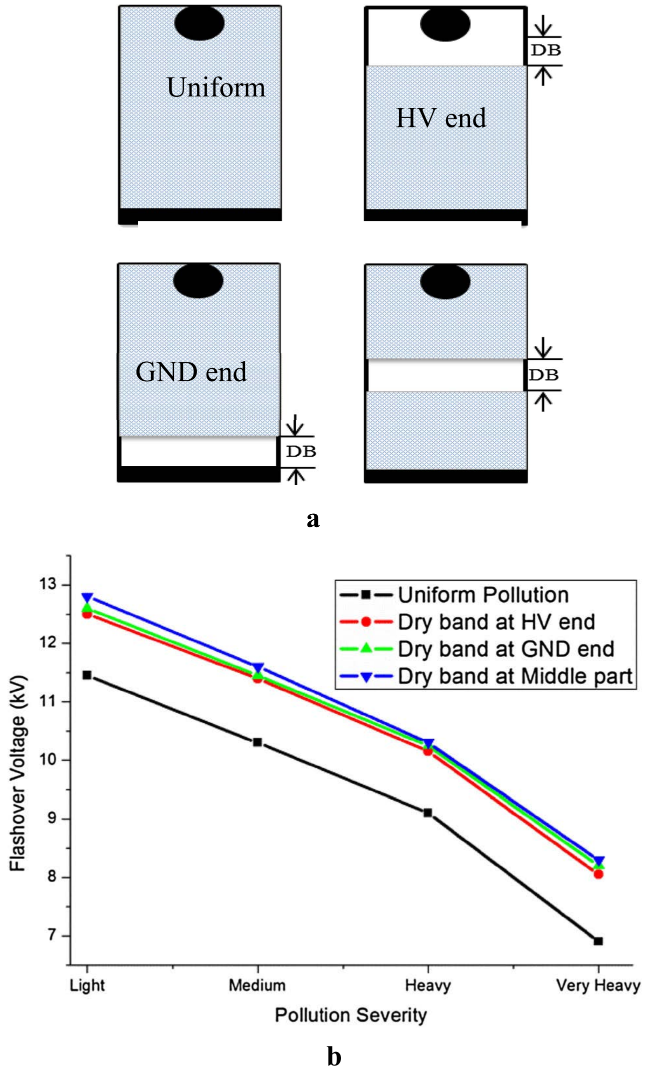

FIGURE 17. (a) Dry band location in the pollution; (b) Dry band effect on flashover voltage [112].

The critical voltage (before flashover) of porcelain insulators that contained heavy NSDD had significant distortions as shown in Figure 18 [59]. Furthermore, the greater the NSDD and/or contamination width, the lower the flashover voltage, and the more extreme and long-lasting the discharges are [60].

The influence of NSDD on the flashover voltage gradient of three different insulators was studied in [64]. The flashover voltage gradient E_L recorded from the experiment can be fitted to is fitted to equation (9) to determine the characteristic exponent c that characterizes the effect of NSDD on the flashover voltage [64] [91].

$$E_L = \frac{U_{50}}{L} = A \times SDD^{-a} \times NSDD^{-c} \tag{9}$$

where L represents the insulator length in cm.

According to the fitting results, the characteristic exponent c value for NSDD between 0.078 and 0.103 mg/cm^2 is within 0.12- 0.14 for glass and porcelain insulators, and within 0.13 – 0.16 for composite insulators [64]. According to the results in [91], the flashover voltage subsided as NSDD and ESDD (also known as SDD) increased. The effects of NSDD and ESDD on the flashover voltage are independent of one another, as seen in Figure 19, which depicts the combined effect of NSDD and ESDD on glass and porcelain insulators.

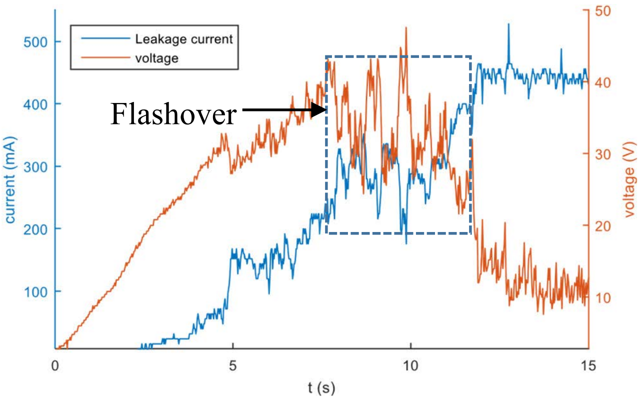

FIGURE 18. Voltage and current of porcelain insulator string with heavy NSSD [59].

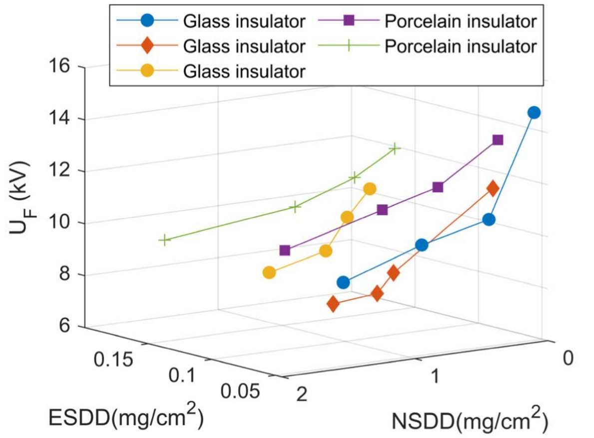

FIGURE 19. Relationship between the flashover voltage and non-soluble deposit density [91].

6) HUMIDITY IMPACT ON FLASHOVER VOLTAGE

Humidity has a significant influence on the flashover voltage. The influence of humidity on the flashover voltage of glass insulators under different contamination profiles were tested and reported in [36], [150], [152]. The results showed that increased humidity led to a decrease in the flashover voltage. For a heavy pollution case, for example, under 0.25 mg/cm^2 ESDD, increasing the humidity from 75% to 95% decreased the flashover voltage by 10 kV (32 % reduction) (Figure 20). [27], [84] tested the flashover voltages of contaminated composite silicone rubber insulators (conventional vs. textured) and glass insulator string (3 units) under variable wetting rates. The findings revealed that the flashover voltage of the conventional insulator decreased from 24.9 kV to 22.8 kV when the wetting rate increased from 3 l/h to 8 l/h, whereas the flashover voltage of the textured type insulator decreased 6.9 kV with the same increase in wetting rate [84]. According to [27], increasing the wetting rate of contaminated insulators caused a decrease in the flashover voltage gradient, jeopardizing the insulator's dielectric properties. For the glass insulator string, under medium contamination (0.12 mg/cm^2), the flashover voltage gradient reduced by 31.5 % and 47.69 %, respectively, due to increased wetting rate from 2.5 l/h to 5 l/h and 7.5 l/h. This implies that greater wetting rates has a major impact on electrical insulator efficacy and flashover risk [27]. In [152], the flashover voltage under DC and AC fields were compared under the effect of humidity. The results indicated that the flashover was more obvious under AC field especially if the humidity exceeded 80%. Figure 21 shows the surface flashover under DC and AC fields.

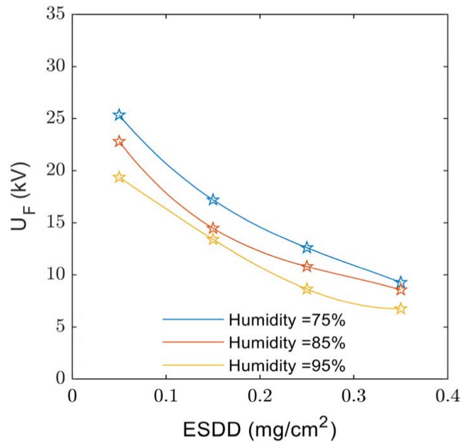

FIGURE 20. Flashover voltage vs. SDD under various humidity [36], [151].

7) INSULATOR SHAPE IMPACT ON FLASHOVER VOLTAGE

According to [37], [81] and [154], an important factor influencing the flashover voltage is the insulator shape. Boudissa *et al.* [37] provided the results of the test that enabled the influence of porcelain insulators' geometry on the flashover voltage to be quantified. Non-uniform contamination methods were used to quantify the effect of insulator shape on the flashover voltage, where non-uniform insulator surface contamination was reported to reduce the flashover voltage; greater non-uniformity resulted in lower flashover voltages. This voltage decrease was demonstrated by a change in the length of the insulator.

Li *et al.* [81] tested the flashover voltage of four different insulators with different structures, i.e., Π-type glass insulator, plate-type glass insulator, CA-590EZ porcelain insulator, and CA-878EY porcelain insulator. Based on the findings, a double-arc method for calculating contamination flashover was developed. The correlation analysis showed that calculating the flashover voltage based on different insulator types can be an effective method in determining insulation flashover.

8) POLARITY IMPACT ON FLASHOVER VOLTAGE

Some studies considered the effect of voltage polarities on the flashover voltage [39], [88], [98]. From these studies, it was concluded that the flashover voltage of plate insulator was different under positive and negative polarities. The average flashover voltage discrepancies for the single arc were obtained to be 21% and 28% for positive and negative polarities, respectively [39]. According to [88], the critical voltage was larger when the supply was in the positive polarity rather than the negative polarity.

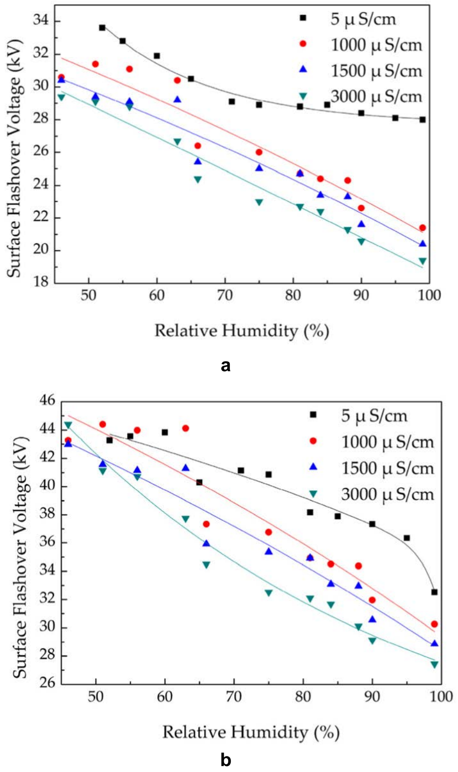

FIGURE 21. Flashover voltage vs. humidity under (a) DC, (b) AC.

9) WETTING RATE IMPACT ON FLASHOVER VOLTAGE

The effect of wetting rate on the flashover voltage was studied in [27], [36], [135]. In the work of [17], the authors determined the relationship between the flashover voltage gradient and the leakage current index R_{hi} extracted from experimental work. The results showed that the flashover voltage gradient decreased by 46.92% with increasing R_{hi} by 2.5 under a wetting rate of 2.5 ± 0.1 l/h for a glass insulator string with 3 units of glass insulators. For a porcelain insulator string with 3 units of porcelain insulators, the flashover voltage gradient decreased by 48.32% under the same change in R_{hi}. Meanwhile, the flashover voltage of the polymeric insulator under a high wetting rate is higher than that obtained under a low wetting rate [36]. The authors in [135] concluded that the relationship between the flashover voltage and wetting rate can be determined from equation (10):

$$U_f = W_r^{-\beta} \times C_p \tag{10}$$

where W_r is the wetting rate, C_p is a constant of pollution, and β accounts for the effect of the wetting rate on the flashover voltage at a constant SDD.

Figure 22 depicts the results from [135] in correlating the flashover voltage with the wetting rate of different insulators. For each insulator, the flashover voltage continued to decrease as the wetting rate increased, to the point where the flashover voltage was three times lower in cases of high wetting rates compared to low wetting rates [145]. Regarding insulators type, the flashover voltage was the lowest for the porcelain insulator.

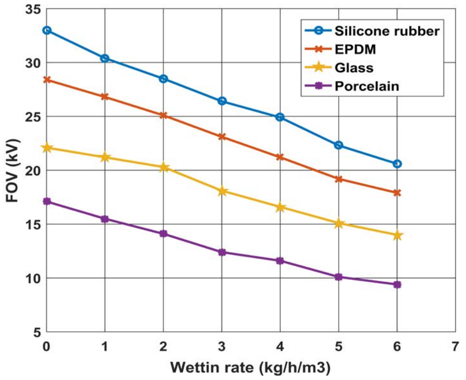

FIGURE 22. Flashover voltage vs. wetting rate at SDD (0.3 mg/cm2) [145].

10) COATING IMPACT ON FLASHOVER VOLTAGE

The flashover voltage performance of insulators under different coatings was investigated in [50], [67] [146]–[150]. In [50], the critical flashover voltage was measured to assess the reliability of room temperature vulcanizing (RTV)-coated porcelain insulators under different contamination levels. Figure 23 depicts the achieved flashover voltages for the porcelain specimens, without and with RTV coating, at various pollution levels. Compared to the uncoated specimen, the critical flashover voltage of the RTV-coated insulator increased noticeably. Moreover, the reduction in voltages was clearly proportional to the severity of contamination. It can be noted that the RTV-coated insulator had a better performance compared to the uncoated insulator at all levels of pollution, particularly under medium and light pollution levels [50]. Literatures [146], [147] investigated the flashover voltage of a porcelain insulator with varied coating damages. As shown in Figure 24, the flashover voltage was the lowest for insulators with fan-shaped damage. When the damaged region gets bigger, the critical leakage current increased whereas the flashover voltage reduced.

Reference [150] also tested the influence of the dimension and location of the coating damage on the flashover voltage of RTV-coated insulators. Different shapes of coating damage on a plate insulator were investigated. Generally, the flashover voltage reduced as the area of damage increased, either longitudinally or laterally, as illustrated in the Figure 25. When there are many damages, the contamination flashover voltage can calculated by the minimum "effective path" distance, defined as [150]:

$$U_f = 0.3744 + 0.2483(l_1 + l_3 + 1.666 \times l_2) \quad (11)$$

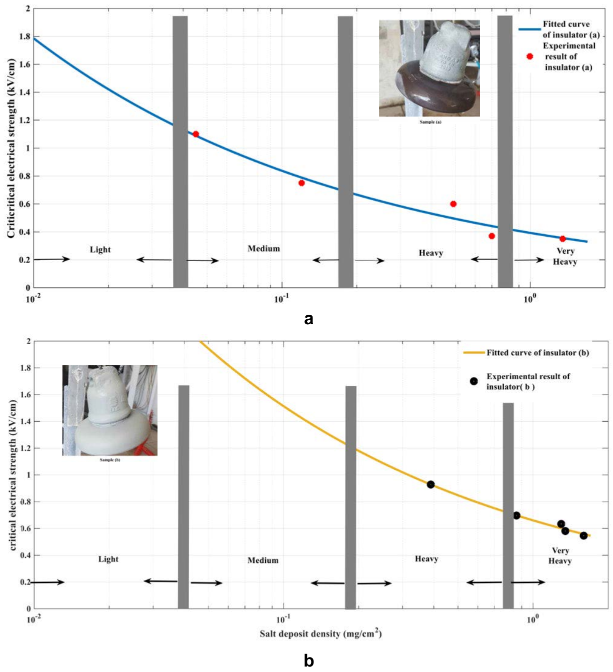

FIGURE 23. Critical voltage (before flashover) of porcelain insulator: (a) Without RTV coatin; (b) With RTV coating [50]. (Permission from Elsevier).

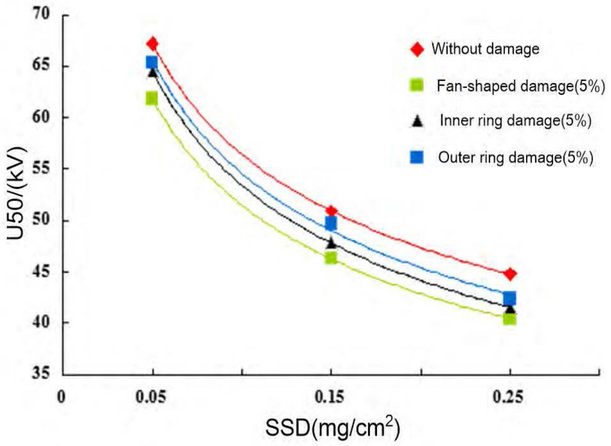

FIGURE 24. Flashover voltage of porcelain insulator under different coating distribution [146].

$$L_{ep123} = l_1 + l_3 + 1.666 \times l_2 \quad (12)$$

$$L_{ep14} = l_1 + 1.666 \times l_4 \quad (13)$$

$$L_{mep} = \min(L_{ep123}, L_{ep14}) \quad (14)$$

where L_{ep123} and L_{ep14} is the "effective path" distances along *l1-l2-l3* and *l1-l4* respectively while L_{mep} is the minimal "effective path" distance. According to the findings, the flashover voltage and the "effective path" distance had a linear relationship.

11) AGING IMPACT ON FLASHOVER VOLTAGE

The flashover voltage for four various types of unaged and aged polymeric insulators under AC voltage was discussed

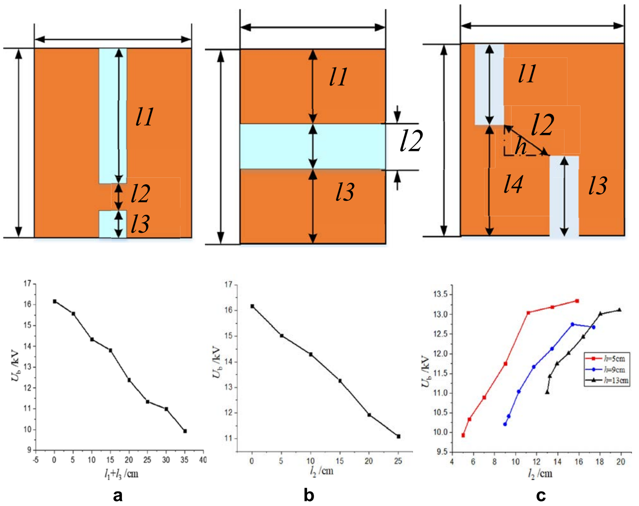

FIGURE 25. The impact of the position of damage on the contamination flashover voltage: (a) Horizonta; (b) Vertica; (c) Random (Permission from Elsevier) [150].

and studied in [19], [43] and [48]. Flashover voltage tests were performed in 0, 2, 4, and 6 weeks of aging duration. As shown in Figure 26, increasing the aging duration of the composite insulators reduced the flashover voltage and weakened the insulator's performance. According to Figure 26(c), with SDD equal to 0.05 mg/cm^2, the flashover voltage of the insulators aged for 4 and 6 weeks decreased by around 3.56 kV (28%) and 12.15 kV (95%), respectively, as compared to the unaged insulator. This implies that the hydrophobicity of the polymer surface decreases with increasing aging duration. Aging therefore has a substantial negative impact on the resistance and flashover voltage of insulators.

IV. REMARKS AND RECOMMENDATIONS

From the review, SDD is the main parameter used to determine the flashover voltage of insulators. The advantage of determining the flashover voltage based on SDD is that it enables the pollution severity to be mapped with appropriate insulator selection criteria. The use of SDD, when coupled with the measurement of conductivity, allows the quantification of the amount of pollution deposited on insulators, thus representing both contamination accumulation and wetness.

However, the determination of the flashover voltage from SDD measurements suffers from the drawback that the flashover voltage values do not always reflect precisely the insulation pollution condition. This is because the composition of soluble salts in natural pollution is complicated. For example, soluble salts in most polluted locations are dominated by calcium sulfate ($CaSO_4$), a particularly difficult compound to dissolve in water. Since a huge amount of water is used in the SDD measurement approach, $CaSO_4$ dissolves and adds to the solution's conductivity. In reality, however, the amount of water on the surface of in-service insulators is little, typically equaling just around 1% of the water utilized during an SDD test. Very little $CaSO_4$ can therefore be dissolved in such a little amount of water. The presence of $CaSO_4$ does not, in practice, contribute to solution conductivity and hence the pollution flashover voltage.

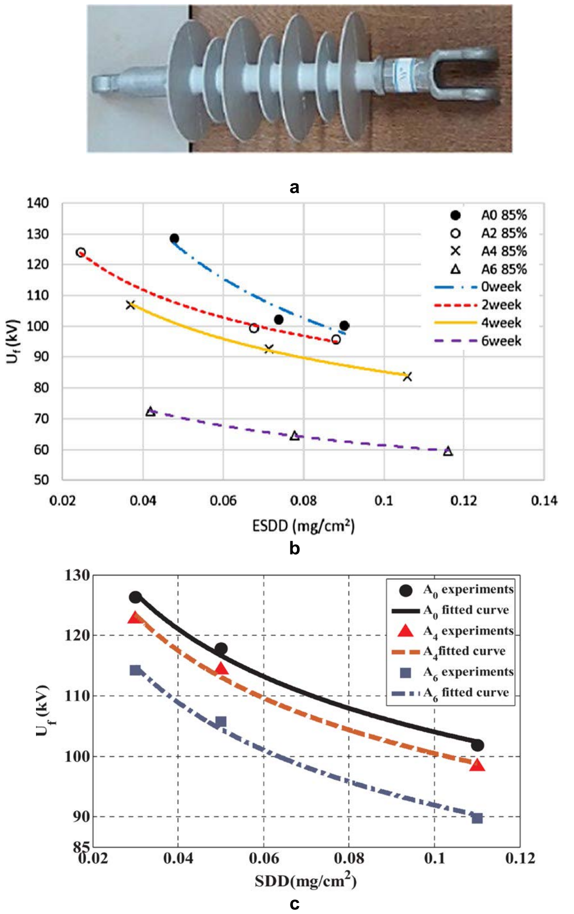

FIGURE 26. Flashover voltage of polymer insulator in 0, 2, 4, and 6 weeks of aging test (a) Insulator sample; (b) Flashover voltage with different SDD for each age level [48; (c) Flashover voltage with specific value of SDD for all age levels [43]. (Permission from Elsevier).

Since artificial contamination employs NaCl to imitate soluble salts, the pollution flashover voltage of a naturally contaminated insulator is frequently substantially greater than that of an artificially polluted test sample, even under the same SDD. Furthermore, because soluble salt contents vary greatly by area, the pollution flashover voltage testing of natural samples under the same SDD value might result in a wide range of findings. Of note, the most crucial criterion for determining the suitability of a parameter in indicating pollution severity is the ability of the parameter to correlate well with the pollution flashover voltage, and this is sadly lacking from the SDD correlation of the pollution flashover voltage.

To address some of the shortcomings in the SDD measurement approach, researchers examined the chemical composition of soluble salts found in natural pollution deposits. The SDD value obtained using the conventional method was then normalized based on the percentage of monovalent and bivalent salts in the soluble layer. These adjusted SDD values, also known as 'effective SDD,' have a better correlation with the flashover voltage. Nevertheless, chemical examination of soluble salt compounds of in-service insulators is expensive, time consuming, and energy intensive. Therefore, conducting chemical analysis for each SDD measurement is impractical.

From the review, the examination of pollution distribution can also provide a preliminary view of the behavior of insulators with regard to pollution deposition owing to wind and rain effects. This would assist in finding the distribution of pollution layers that further explains the natural state while analyzing the distribution of pollution experimentally. Of note, the humidity can be monitored during testing using sensors, and the humidity can be controlled to a desired level. Also, under the same test conditions, the influence of an insulator shape on flashover voltage may be determined by employing different insulators of the same material with varying diameters. Although the humidity and insulator shape parameters can also have an influence on the flashover voltage, their interpretation of the flashover voltage becomes meaningless in the absence of SDD data. Therefore, the use of the humidity and insulator shape parameters in addition to SDD would be preferable in obtaining better correlation of the parameters with the pollution flashover voltage.

While NSDD can have impact on the flashover voltage of insulators, most research employs kaolin as insoluble materials in determining NSSD. This may be one of the limitations in correlation the NSDD parameter with the flashover voltage, since majority of the non-soluble natural materials are sands and free carbon particles (soot). Therefore, the use of different compounds in NSDD formulation could lead to better correlations of NSDD with the flashover voltage. It should be noted that the rate of NSDD deposition is affected by various factors, including desert sandstorms.

Meanwhile, the investigation of the impact of coatings on insulators regardless of pollution level is one of the greatest studies that reflect the beneficial results of coatings in increasing insulator performance. This is due to the usage of the same coating material even in experimental research. However, these studies are not viable if the insulator's coating has been in place for more than 10 years, where exposure to sunlight and artificial lighting can have adverse effects on the useful life of insulator coatings.

V. POSITIVE AND NEGATIVE FACTORS INFLUENCING FLASHOVER VOLTAGE

Based on Figure 13, eleven parameters obtained from 94 papers were discussed in this review study. It was clear that five parameters (SDD, NSDD, aging, humidity, and insulator shape) had negative impacts on pollution flashover voltage while only two parameters (coating and pressure) have positive effects. Four other parameters (pollution distribution, dry band, polarity and wetting rate) can have positive or negative effects on the pollution flashover voltage depending on the condition of the insulator and the change of the parameter value. These parameters were extracted from eighty-one papers. The fact that some of the parameters have a negative impact on the flashover voltage indicates that increasing the value of the variables leads to a decrease in the flashover voltage on contaminated insulators [151]. On the contrary, with the value of parameters having positive impacts increases, the flashover voltage also increases. Figure 27 illustrates the type of influence for factors flashover voltage.

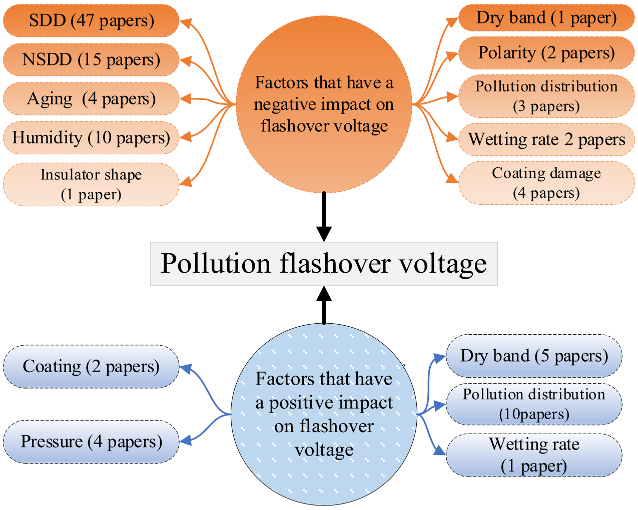

FIGURE 27. **Flashover voltage factors and their impact classification.**

VI. FUTURE RESEARCH DIRECTIONS RELATED TO FLASHOVER VOLTAGE OF POLLUTED INSULATORS

Although the systematic review method as recommended by [19] has been used in the current work, there is a need for additional comprehensive research on the flashover voltage characteristics of insulators to enable researchers to further explore parameters affecting the flashover voltage issues of insulators. Future research directions linked to the flashover voltage might include, but are not limited to, the following work:

1. Research studies of flashover voltage and other characteristics related to polluted insulators.
2. Critical review of studies pertaining to materials characteristics that can aid in the improvement of the performance of insulators.
3. Critical review of artificial intelligence-based optimization techniques in predicting the flashover voltage.
4. Investigation of the degradation of insulator surfaces on the flashover voltage.

VII. CONCLUSION

The current work has examined peer-reviewed publications focusing on pollution flashover voltage tests on high voltage insulators using a systematic methodology. This has offered value-added knowledge about pollution flashover voltage studies carried out by different researchers around the world. Critical parameters that affect the pollution flashover voltage have been discussed by reviewing the literature published between 1990 and 2021. The impact of eleven parameters, i.e., SDD, NSDD, aging, humidity, and insulator shape, coating, pressure, pollution distribution, dry band, polarity, and wetting rate, on the flashover voltage has been mainly discussed. The emphasis has been placed on the importance of knowing the pollution flashover voltage of insulators as a critical component for the evaluation and detection of the condition of the insulator on transmission lines. Nevertheless, research challenges remain especially on how one can properly monitor insulator pollution and propose techniques for analyzing insulator conditions prior to catastrophic failures. While several prototype devices have been proposed to monitor the condition of insulators using various ways, including those with infrared thermal imaging technology, much work is needed to ensure reliable monitoring and analysis of insulator conditions.

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