

High-Impedance Faults in Power Distribution Systems: A Narrative of the Field's Developments

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Abstract

High-impedance faults in power distribution system is a lasting problem with decades of steady investigation. Due to the complexity of the problem, the field can also be challenging to navigate. Although there exist surveys of the field in the literature, it is not easy to find a comprehensive contextualization of how and when the field developments unfolded. This paper presents the historical narrative of the progress and developments based on the most cited papers since the inception of the field. The accounts are not limited to archaic and obsolete works. They are all contextualized from the seminal papers to contemporary methods and related technology. Quantitative figures on the survey of the methods and relevant knowledge gaps are also discussed at the closing of the paper.

Keywords: High-impedance faults, literature, power distribution, review, survey.

1 Introduction

Before the seminal works that highlighted it as a problem worth addressing individually, High-Impedance Faults (HIFs) were just a part of the research field investigating earth faults in power distribution systems. At the time, HIFs were mainly described by the concerning scenario where a broken conductor falls to the ground, hence their equivalence with earth faults. Power engineers had to therefore rely on ground overcurrent protection to address such faults. It was quickly realized, however, that the sensitivity of ground overcurrent relays, which had to tolerate some load unbalancing, was not high enough to adequately address the problem. One early work [1], based on technical reports by the Pennsylvania Power & Light Company, drew attention to the underestimation of undetected broken conductor faults. Conducted in 1974-75, this work found that overcurrent devices failed to operate in 32% of the 390 staged faults. When faults were staged 2-3 miles from the substation, only one of the twenty cases was cleared. They also conducted surveys with many utility personnel about the clearance of such faults. From the 83 surveys, 61% said they had experience with broken conductors problems.

Despite not representing a threat to power equipment, HIFs are still dangerous disturbances due to their elusive behaviour. They became critical disturbances in power distribution systems when their potential to create safety risks and fire hazards was fully realised. For example, a HIF given by an energised conductor that breaks and falls to the ground can be sustained for an extended period as it goes undetected by protection devices. An interesting work [2] attested this fact by describing interviews with power line crews. They stated that around one-third of broken conductor faults were still energised when the crews reached the fault location. Such an alarming figure, however, only considers broken conductor occurrences that often leads to service discontinuity and consequent reports from costumers. For HIFs resulting from contact with vegetation, service discontinuity may never happen as they can form without conductor breakage, thus likely never being noticed.

Accessible work dates back to the late 70s, where the field was pretty much dominated by papers from Texas A&M University [3, 1] and Pennsylvania Power & Light Company [4, 5]. They were the first to propose practical solutions to the problem, but the field turned into a global

discussion by the early 90s. Since then, hundreds of papers have been published on the subject. The field has matured and the HIF term is now used to describe a more wide set of problems, encompassing all the faults that are not detected by overcurrent protection. Examples include leaning trees making contact to power lines [6, 7], tree branches that falls between conductors [8], pole and insulation failure [9], and more. Detection and clearance of such faults remains a subject up to this date, but the field soon started to encompass other problems like modelling [10, 11], understanding the fault behaviour [12, 13], proposing signal representation techniques [14, 15, 16], and HIF location [17, 18].

This paper presents a narrative for how the field advancements unfolded through time, contextualizing the novel ideas of the most influential papers. The inspiration comes primarily from the fact that one might find the field to be a convoluted and challenging landscape to explore. Since many claim to be presenting a definite solution for the problem, identifying the contribution to knowledge between similar works in the vast literature can be problematic. One can find comprehensive reviews in the literature [19, 20], which describe the existing HIF solutions and methods. However, defining techniques of the methods do not necessary gives the reader the sense of how the core ideas and advancements unfolded through time. This paper therefore aims at guiding the reader from the pioneering efforts on the field to the contemporary strategies and commercial solutions. The discussion of significant recent innovations and disruptive technology is also a potential contribution to the interested reader, which may be unfamiliar or newcomer to the field.

The following narrative describes the field progress through decades, with respective highlights in the end of each section, followed by quantitative figures and commentary to illustrate a coarse view of the field. The adopted methodology for filtering the papers was purposely direct and simple. It was performed by searching for the term “High-Impedance Fault” on databases like the *IEEEExplore*, filtering the publications by decade, sorting them by number of citations. If a significant contribution to the field was identified after reading and analysing a particular paper, the work was integrated and contextualized in the narrative arc proposed here. For the commentary section, quantitative descriptors such as popularity, signal representation, and decision methods compared and discussed. These descriptors include popularity, signal representation, and decision methods of the surveyed works. Punctual and brief comments on the possible knowledge gaps still present in the field are also presented.

The authors hope that the narrative present here can serve as a historical guide for students, engineers, and managers interested in the developments of the field. The pioneering efforts and the beginnings of the field in the 70s and 80s are described in the next section. As the field popularity and interest grew, the 90s and 00s have dedicated individual sections. Most core sub-fields like decision systems and modelling started in the 90s while the 00s were responsible for signal representation and specialization developments. Their description is followed by a section discussing contemporary methods (10s) where most recent solutions are discussed, including novel technology. The quantitative figures and commentary on the field are presented in the final section before conclusions.

2 The 70s and 80s — Genesis of the field

Pioneer researchers at Texas A&M University [3, 1] (TAMU), Pennsylvania Power & Light Company [4, 5, 21] and Amicus Engineering Company [22, 23] laid the path for following researchers with innovative approaches to HIF detection. Their ideas still profoundly inspire the works in the recent literature, such as the use of frequency components higher than the fundamental [1], power frequency of harmonics and voltage sequences [23], and the ratio between sequence currents [4, 5]. The work presented by researchers at the National Chen Kung University in Taiwan can also be cited as early work done at concurrent time [24].

The Pennsylvania Power & Light Company (PP&L) and Westinghouse Electric [21] presented the first electromechanical relay for fallen conductor detection. The electromechanical relay was an induction disc unit with torque proportional to the ratio between the zero-sequence and the positive-sequence currents. It required a substantial imbalance for it to be activated, but the authors were confident that it would detect more than 80% of fallen-conductor faults. A few

years later, the researchers at PP&L presented another electro-mechanical ground relay with the modelling of a 12.47-kV, four-wire, multi-grounded system. The activation method consisted of measuring the ratio between the phase positive-sequence current and the three-phase zero-sequence current. Such a protection philosophy was based on the premise that the ratio of these currents remains relatively constant for a given feeder in the absence of a HIF. Further work from PP&L presented [5] a digital computer implementation to compare the proposed ground ratio relay with the existing protection schemes. This approach was further validated and proven [24] to be effective when detecting currents higher than 15 A in a well-balanced system.

The researchers at TAMU proposed the first digital hardware prototype to detect staged HIFs [1]. The device comprised a method utilizing the frequency components from 2-10 kHz as HIF features. It was also the first to investigate higher frequencies in HIF detection. The authors felt that frequency components higher than ones close to the fundamental frequency represented an appropriate approach for detecting “ground arcing faults” from broken conductors. However, the authors raised caution for networks containing grounded wye capacitor banks which could increase the attenuation of these frequency components. The method was implemented in a computer capable of detecting some of the staged faults, attesting for the sophistication of the adopted approach. They were the first to conceptualize a top-down approach using data from staged faults to conceptualize a HIF detection method.

It may be useful to note that there is a parallel field of research which addresses a subset of HIFs named *ground arcing faults* [25, 26, 27, 28]. As pointed by authors early in this field [1], the return path of the current is often not fully established in a broken conductor that falls into a solid surface such as asphalt. The air gap between surfaces usually results in arcs created when the voltage reaches a *breakdown value*. Therefore, due to the sinusoidal nature of the voltage waveform, a burst of current conduction can happen near zero-crossings where the voltage crosses this reigniting-arc breakdown value. Some works also may use the terms “ground arcing faults” and “high-impedance faults” interchangeably.

By the late 80s, TAMU had more than a decade in broken conductor research. This experience gave them the insight which is often missing in contemporary works: HIF is too complex to depend on one single detection method. In their work [29, 27], the authors discussed a detection approach where many different algorithms calculated distinct *features* from the electric signals. They were later fed to a class of primal learning algorithms called *expert systems*. It intended to leverage the existence of observational data to emulate the decision-making of a human expert. It is not surprising that the authors opted for such an approach since the use of expert systems exploded in popularity in the 80s [30]. Due to its intention, i.e. replication of human intelligence to some extent, expert systems were considered to be the first successful Artificial Intelligence agent *expert systems*.

The 70s and 80s found many valuable findings and insights on HIF behaviour. The most relevant insights can be summarized:

- Due to the impulsive nature of the fault current, HIFs can increase the energy of a wide band of harmonic, and non-harmonic, frequency components [1, 31].
- HIF current magnitude can vary greatly in between cycles having an intrinsic *random* nature [1, 31, 29].
- Arcing often happens in broken conductor faults due to the air gaps between the conductor and high-impedance surface [23, 1].
- The high-frequency bursts in the fault current often happens near zero-crossings of the voltage due to arc reignition phenomenon called *voltage breakdown* effect [1, 31].

3 The 90s — Experts systems, commercial HIF detection, and modelling

Research at TAMU continued as one of the main leaders the HIF field in the 90s, despite the appearance of new players from other universities and countries such as South Korea [32], Canada

[33], Singapore [14], and Brazil [34]. At the beginning of the decade, TAMU researchers had fully embraced the idea that no single method could cover all HIFs. They started first to publish their ideas on how to address this fact, discussing how environmental parameters such as system unbalance, feeder configuration, load type, and surface conditions could affect the fault behaviour [35]. Based on the assumption that each technique will have strengths and weakness giving different conditions, they proposed a heuristic to select a detection method based on different environmental parameters [35].

The heuristics path by TAMU would become more evident in a further revealing paper [36] where they disclose a product resulted from a collaboration with General Electric (GE) company. The paper described the first substation equipment having HIF detection as its primary goal, embodied in a case that fitted the panel cut-off for a GE overcurrent relay. Following what was previously mentioned as a possibility, this work presented an expert system approach consisting of many independent algorithms to detect HIFs. These algorithms dealt with numerous signal's features: energies on the frequency spectrum, randomness, arcing (24 algorithms), load analysis and event, and burst patterns. The expert system heuristic consisted of receiving the algorithm's outputs which were then weighted to arbitrary values and aggregated in a detection result. An undertaking so sophisticated at the time that GE had initiated an advisory committee of experts to facilitate the device acceptance in the market [36]. As yet another significant aspect of this work, researchers validated their method using tests staged in a dedicated location called the *downed conductor test facility*, constructed and designed by TAMU for the sake of the experiments.

The announced product by GE and TAMU [36] was not a relay but a *Digital Feeder Monitor* with broken and arcing conductor detection function. The distinction between relay and monitor represents an important point here. The authors firmly held the opinion that one should not trip a whole feeder for all HIF positive detections. They were aware that the device was not capable of correctly detecting all HIFs occurrences without producing false-positives, meaning that there was a trade-off between *dependability* and *security* to be considered. The 90s was the starting point for discussions around these two critical concepts. Dependability refers to the frequency of true positives when testing a classifier; it expresses how good the classifier is at detecting faults. In the HIF detection field, it is represented by the ratio between the number of fault observations correctly labelled, to the total amount of fault observations tested. Security, on the other hand, refers to the frequency of true negatives when testing a classifier; it expresses how good the classifier is at not detecting faults when they are not occurring. It can be calculated by the number of non-fault observations correctly labelled as non-fault, divided by the total number of non-fault observations. With the increasing proposal of different detection methods, the consequent question of addressing imperfect security and what to do with the detection result had to be addressed. The authors thus made use of the product disclosure to discuss possible liabilities assigned to utilities which decide not to install such equipment in regards to damages created by undetected HIFs [36]. Comments on how such a method could be used in different regions were also made. The authors sensibly argued that tripping a relay in arid areas where a downed conductor could ignite wildfires in vegetation would make more sense than in a city environment.

Researches at TAMU continued to build on their work by proposing a detection method based on current RMS fractal analysis [37] and publishing on practical experiences gained from the use of their device in real feeders [28]. The authors focused on the security discussion defending that service continuity of clients is far too valuable to be sacrificed for a 'trigger happy' algorithm. The paper [28] analysed the equivalent of forty-seven unit-months of device operation in five feeders where additional faults were also staged. It showed an optimistic view of the device application by stating that faults that were not cleared by overcurrent devices were mostly all detected by the feeder monitor (88% of staged faults). Furthermore, two more similar papers were published discussing the device implementation [38] and its practicality [39]. In the first, many issues arising from the use of such technology were discussed. From legal to emotional issues, the paper included a framework for testing and evaluating a HIF detection method, the result of surveys, and expert opinions. However, none of those subjects was discussed in too broad detail but rather in brief discussions. The second paper [39] disclosed details on the IP licensing of the technology to GE, the balancing of dependability and security for service continuity, and the functionality of the device.

The research undertaken throughout more than a decade at TAMU has evolved and culminated

on the present GE's *Multilin F60 Feeder Protection System* [40] which, to present day, still apparently uses expert systems to detect HIFs. Given current knowledge about learning systems, and how expert systems were superseded by machine learning techniques, there could be an argument for substantial improvement. This claim can be made based solely on the fact that the features' weights used in the expert system method are based on *a priori* knowledge from human experts, in contrary to a top-down empirical approach.

Other researchers in 1990 realized possible issues with arbitrary decision boundaries when proposing the first application of neural networks to detect HIFs [41]. The proposed method calculated large amounts of signal features such as the peak of transient current, RMS value, the magnitude of positive sequence, energy of harmonics, and used to learn a multi-layer perceptron feed-forward neural network. It was one of the first methods to use simulated HIFs in their validation (an ubiquitous practice in the following decades), instead of real, staged fault signals. Despite being novel, there were many noticeable issues with this approach. The neural network had a large number of inputs and nodes compared with the amount of generated data (possibility of *overfitting*). There were no validated HIFs models at the time, making it an excessive unrealistic simulation, and features were still hand-engineered. By "hand-engineered features" is meant that the predictors are created from human knowledge, calculated from signal representation techniques; the converse would be the features created in the process of applying deep learning, which captures layers of features from the data latent space. Further work with neural networks (1992) [33] addressed some of these problems. The methodology, instead of using hand-engineered features as inputs, consisted of feeding a fundamental frequency cycle of raw current samples to a feed-forward neural network. It was the first full top-down, supervised learning approach, used to learn patterns in the current time-domain signals.

Although powerful, top-down approaches still present the apparent constraint of requiring data from real, staged faults. Such experiments can be onerous and expensive, only to be performed by prominent universities and large companies. Consequently, due to the commercial value of the resulting IP, organizations performing such experiments had many incentives to keep the data private. This restriction led researchers to invest efforts in creating HIF models to be used in simulations, circumventing the problem of requiring experimental data. The complexity of the HIF phenomena and non-converging opinions in the literature clearly make such an attempt ambitious and highly challenging.

Historically, the first relevant and influential HIF model was proposed in 1990 [42]. The authors represented a HIF as a fault impedance in series with an anti-parallel diode and DC voltage sources branch, as illustrated in Fig. 1. The anti-parallel branch helped to model the previously explained breakdown voltage where conduction only started after it was high enough to break the dielectric nature of the high-impedance surface. Its main parameters were the fault impedance, which dictated most of the fault current amplitude, and the DC voltage sources values. The DC sources could assume different values to account for the asymmetric nature of HIFs, which can have different breakdown values for positive and negative half-cycles. Notwithstanding, one should mention that this work attempted to model the HIF behaviour of a broken conductor falling to sandy soil. The authors had the main goal of analysing to what extent frequencies from 120 to 180 Hz could be used to detect such HIFs. Any strong claims present in further papers directly influenced by this work which choose to ignore or dismiss these environmental conditions should be prefaced as hypotheses, speculations, or are just fallacies.

The urge for finding better HIF features, together with developments in the signal and image processing fields [43], was responsible for the introduction of a technique that revolutionized signal representation techniques: wavelets. Although promising, the application of top-down approaches like neural networks do not provide a phenomena understanding or casual framework that bottom-up approaches do. When used to decompose signals, the Wavelet Transform (WT) serves as an efficient time-frequency signal representation with fair time localization [44]. Different from the dominant and prevalent Fourier Transform (FT), the WT's decomposition basis functions are dilated and translated versions of finite oscillations with constant shape. This difference makes the transformation outputs to be well localized in time, conversely to the stationary sinusoid basis functions from the FT. The oscillations used in the decomposition are allowed to have arbitrary shapes, although one would prefer differentiable, compact, zero-mean, and square-integrable func-

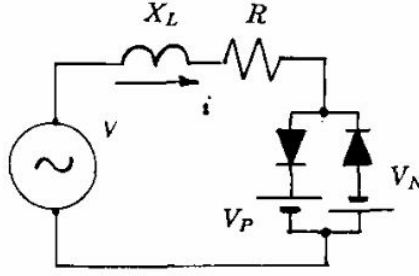


Figure 1: Emanuel's et al. HIF Model (1990).
Adapted from [42]

tions for practical reasons. Examples of commonly used wavelets with a specific shape, named ‘wavelet families’, are illustrated in Fig. 2. In general, wavelets are more efficient at representing signals’ discontinuities and transients since they have more *sparse* representations in the wavelet domain with consequent localized energy. This effect becomes especially evident if the mother-wavelet used in the decomposition resembles the shape of the represented discontinuity. An FT of the same signal, contrarily, will result in a wideband representation in the frequency domain with “spreaded” energy.

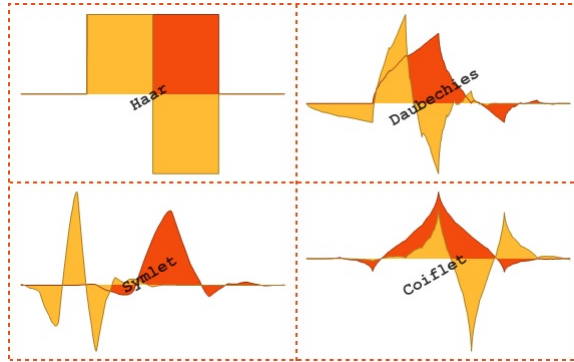


Figure 2: Examples of commonly used wavelet families.
Adapted from [45]

The use of wavelets for HIF feature extraction started at the end of the decade. The first influential work [14] used wavelets to detect the transients generated by the faults, followed by a heuristic to differentiate them from other disturbances. It was not only novel in its wavelet application but also built on the previously mentioned model [42] to propose a more intricate HIF model based on arc theory. Claiming that its predecessor did not represent the universal behaviour of HIFs, the authors proposed a model that was supposedly better at representing the non-linearity of a HIF impedance. A snapshot of the proposed model [14] is illustrated in Fig. 3. Differently from the inspired work, the voltage sources in the anti-parallel branch are time-varying, not restricted to DC values. Switch 3 is connected to a Transient Analysis Control System (TACS) model, which is set to represent the arc reignition and extinction. The TACS model inputs are the arc re-ignition voltage, peak value of the applied voltage, and arc voltage. The variable resistance is mainly responsible for the value of the fault current magnitude, which was in the order of tens of amps in the paper [14]. It was also one of the first papers to present a full simulation-based methodology instead of relying on experimental data. A second wavelet-based influential work [46] soon followed it by proposing the use of a different wavelet family as its only main contribution. As yet a novel idea, wavelet-based works became widely popular in the next decades, fiercely

competing with Fourier-based approaches.

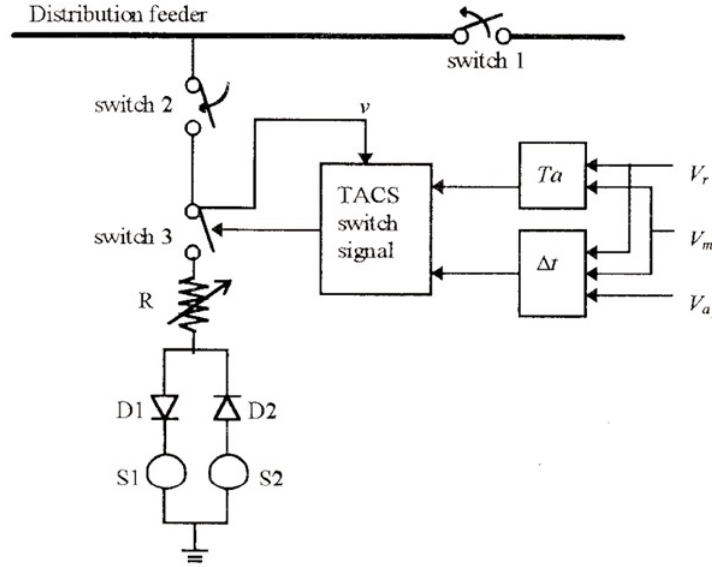


Figure 3: David and Xia's HIF Model (1998).
Adapted from [14]

Nevertheless, Fourier/Harmonic analysis was still the prevalent feature extraction method in the majority of detection methodologies. Most methods were based on findings made in the 80s around the HIFs effects on the harmonic signature of phase and neutral currents. One pioneering work [47] presented a Kalman filtering approach as an on-line recursive estimator of harmonics that accounted for time-varying nature of the signals. The advantage of this approach was that it did not need to assume the signal to be stationary (like the conventional FT). The method was centred on calculating a randomness value from estimated harmonics, in four to six fundamental cycles, and detecting a fault if it increased higher than normally observed values. A following work [48] argued for the unique harmonic characteristics of HIFs. It stated that such faults would have high third harmonic components with characteristic phase shifts that could be used for detection. Similarly, a creative approach using the ratio of odd and even harmonics to detect HIF occurrences was proposed [32]. It was based on the hypotheses that HIFs have a particular harmonic signature due to their half-cycle asymmetry, which could introduce even harmonics to the system. The unbalanced current and energy of harmonics were also used to conceptualize another method [49] that was validated with staged tests. Such an approach seemed to work reasonably well for fault currents higher than 5 A.

These cited works have the advantage of being validated with data from real, staged tests, usually in multi-grounded systems, mimicking a downed conductor scenario. Their weakness, however, relates to the consensus that harmonic content alone is not a reliable parameter to attest for a fault occurrences [34, 15, 50, 51, 52, 53, 54]. It is often stated that similar harmonic conditions could appear in normal operation states of the system, mostly from switching events and the contemporary diversity of non-linear loads. A significant number of VHIFs do not produce harmonics in the first seconds of conduction at the fault location, meaning that they would be even more attenuated for measurements far away from the fault point. Nonetheless, it was not a widely shared opinion at the time these methods were proposed but it changed particularly due to the ever-increasing penetration of non-linear loads and novel signal representation tools.

Two other influential and valuable works from this decade are also worth commenting. The first is the highly innovative method [34] presenting the first active method to detect HIFs. It consisted of injecting periodical impulses to the network and measuring its response, which would presumably change in the presence of a fault. The methodology was tailored to Brazilian networks, which have many single- and two-phases branches, thus being heavily unbalanced. Its most substantial

constraints were the need for network data, full knowledge of its topology, and high-speed data acquisition systems. After injection, the electric signals were sampled, processed via FFT, and used as inputs in a fuzzy reasoning system. The fuzzy rules, as in other approaches in this era, also used *a priori* knowledge and rules of thumb from human experts. In the second work, a paper by a GE engineer [55] reviewed and discussed some of the current technologies to detect HIF. This paper was the first influential work in the literature to discuss mechanical methods to detect HIFs. The author explains that such a device would be mounted, in a cross arm or pole, under each phase wire and connected to the ground. In this manner, a conductor breakage would realize contact between phase and device, creating a ground fault that could be easily detected by existing overcurrent devices. He also then quickly dismisses the usage of such a method claiming that installation and maintenance costs would be too high to be feasible. Nevertheless, the author still recommended its installation close to critical areas such as churches, schools, or hospitals. The rest of the paper could be seen as a call to action to utilities install the previously mentioned feeder monitor conceptualized by TAMU. Comments on the use of the detection result and the need for HIF detection devices were made based on the possible million-dollar liabilities companies could face for damages created by HIFs.

One can see the 90s as the golden era of HIF detection engagement and innovation, where the most influential ideas were proposed. The core of insights and innovations of the decade can be summarized:

- First commercial protection device targeting HIFs [36].
- First full top-down application of neural networks in HIF detection [33].
- First HIF model to circumvent the need for experimental data [42].
- First use of wavelets in HIF detection [14].
- First active detection method based on the network impulse response [34].
- Emphasis on HIF detection based on the harmonic content of current signals [49, 48, 32, 47].
- Deeper discussions on the trade-off between dependability and security given by possible actions to a HIF detection and utility liabilities [36, 28, 38, 39, 55].
- Despite exceptions, methods still heavily relied on *a priori* human expert knowledge.

4 The 00s — Wavelets, machine learning, and specializations

Although falling short in terms of ground-breaking innovations, the 00s were responsible for important incremental contributions to previously proposed techniques and sub-field specializations. Many feature extraction variations were proposed as novel contributions, forming a competitive scenario in signal representation approaches such as wavelet and Fourier. Being mostly hand-engineered and relying on *a priori* knowledge, the new proposed features can be mainly classified as bottom-up approaches to HIF representation. Detection methods using such features, however, started to increasingly have their decision boundaries defined by machine learning techniques (*a posteriori*), instead of arbitrary thresholds. For the most part, most of the contribution value from this era probably came from sub-field specializations such as in specific conduction surface, network grounding types, and sensor-based sampling technologies.

Wavelet-based methods surged in numbers and popularity with many feature extraction variations proposed as novel contributions. One of the first works of this decade [56] is an example of such an approach. It proposes a different WT decomposition where the frequency bands are linearly spaced in the frequency domain, named wavelet Packet Analysis (WPA). In addition to being the first to apply WPA to HIF detection, the authors also took into consideration the wavelet components phase distribution w.r.t. the current fundamental cycle. Such phase distribution becomes relevant when considering the previously mentioned voltage “breakdown value”, which will

lead to more discontinuities near zero crossings of the fundamental voltage signals. Its downside, not surprisingly, is that not all HIFs present evident breakdown phenomena (further explained).

A feature variation on the coefficients of the WT, now in its traditional Multi-Resolution Analysis (MRA), is also presented in [57]. The work calculates the RMS conversion on the detail coefficients extracted from current signals as features and uses it to establish decision boundaries for fault detection. The features are fed to the classical machine learning technique named Nearest Neighbours Rule (NNR). In a similar way to its more known version, K-Nearest Neighbors (KNN), this technique is a simple non-parametric classification method that established decision boundaries based on votes from the nearest data points in the feature space. This work's [57] specialization factor, however, comes from its consideration of distributed generation in the power system simulations. As in many other works further discussed, its solely modelling approach is somewhat simplistic in regards to the complexity of the phenomena, which makes it hard to defend as a conclusive finding.

Further papers [58, 59] proposed a different heuristic for classification and an important specialization consideration: network neutral earthing type. The feature extraction is performed by the application of the WT on the neutral/residual voltage and current signals. The detection is done by a heuristic on a measure of phase displacement between current and voltage coefficients [58] and a perceptron-based classifier [59]. In its purely simulation-based analysis, the authors conclude that the most challenging faults to be detected were the ones simulated in a compensated network (resonant grounding type) due to the significantly reduced ground fault current.

Still in wavelets, some authors such as [60, 61] proposed variations on the transform application in two similar papers. Both use WT for feature extraction but different approaches in fault detection: (1) Genetic algorithm for feature selection and a Naive Bayes classifier for classification, and (2) Principal Component Analysis (PCA) for feature selection and ANN for classification. The works are relevant due to their use of real, staged tests, intricate machine learning algorithms, and optimization methods. However, the relatively small number of HIF staged tests opens the work for criticism when ANN is applied for classification. The complexity of the method in relation to the number of used features makes the approach prone to *overfit* the dataset, and possibly less generalizable to new HIF data. Adding this to the fact that non-fault examples came from simulations makes it hard to evaluate the real effectiveness of the approach, even with the application of intricate, powerful tools. Other worthwhile mentioning works presenting wavelet variations are papers proposing adaptive neural fuzzy inference [62] and Support Vector Machines (SVM) [63] as classifiers. In the first [62], the authors used six features: four derived from the wavelet coefficients energies from current signals and two from third harmonic and signal mean value. In the second [63], the energy of the details was extracted as features, having their dimension reduced by PCA, and then fed to an SVM classifier.

Various Fourier-based approaches shared the theme of feature extraction variation and specialization. Early in the decade, a paper [50] describing the use of harmonics energies from residual currents and voltages was presented. As some of the recently cited papers, its strength was mainly correlated to being a specialization approach. In this case, it was related to a hardware prototype implementation of an ANN-based classifier, which was indeed novel for the time. A following interesting approach [64] using harmonics and its phases to draw 'Harmonic Patterns/Phase Portraits' was soon after introduced. By making use of the third and fifth harmonic, phase portraits were drawn and used as patterns that could discriminate a fault occurrence from nominal system operation. Although interesting, it was a convoluted heuristic that did not get much attention after proposed. Later, a simple and effective approach using FT [65] and learning algorithms became very influential. It consisted of merely doing the FT of the current signals and using the components to learn a machine learning algorithm, named 'Decision Trees' (DT). As yet another purely simulation-based work, the authors granted in their conclusions that wavelets could have helped enhance the performance of the classification results. If encompassed in the classification of Fourier-based approaches, proposed Kalman filtering techniques [66, 67] for features extraction should also be mentioned. The authors of these two similar papers studied the use of the estimated harmonics with an ANN [66] and an SVM classifier [67].

After discussing some of the most influential wavelets- and Fourier-based works, a couple of important remarks regarding their adoption and HIF modelling should be made. The first concerns

the increasing use of wavelets to represent fault signals. Since the first impactful work in 1998 [14], wavelet-based methods went from a fringe idea to a prevalent approach in the surveyed works. One could argue that such an effect, and the ever-present use of wavelets, is evidence of its superiority in representing HIF signals over Fourier-based approaches. The second remark concerns the overwhelming number of proposed methods based solely on HIF model simulations. All the Fourier-based methods mentioned in this section exclusively rely on models rather than data from real experiments. From wavelet-based methods, more than half rely on models when conceptualizing their approach. On the one hand, this practice is not surprising given the fact that experiments are so onerous and simulations are so accessible. On the other hand, it is also not surprising that commercial methods do not use most of these variations, and they are not regarded as robust and defensible evidence. This assertion is especially true if one accepts the presupposition that HIF behaviours are not fully represented in current HIF models.

Despite the challenging nature of the problem, essential works regarding HIF modelling were presented in this period. The authors of the first paper [68] argued that the models previously presented did not represent important HIF behaviours such as *Build-up* and *Shoulder*. Build-up is defined by the period where fault current grows to its maximum local value, which last approximately tens of cycles, according to the authors. The shoulder is the period where the build-up temporarily cease for a few cycles until it starts growing again towards its maximum global value. The authors intended to propose a simpler and more realistic model incorporating such features that did not have as many components as previous ones. It was conceptualized by just two series time-varying resistances controlled by TACS in Electromagnetic Transients Program (EMTP). Illustrated in Fig. 4, this model was inspired by thirty-two tests performed by a Korean power company, sampled at 10 kHz. It attempted to account for the proposed features by modelling one of the time-varying resistances with periodical changes (shoulder), while the other monotonically decreases from its large initial value (build-up). Despite impactful, it is not hard to find issues with this approach. Some examples are the number of tests used, the absence of information around the fault surface, and more importantly, how it was validated. The authors seemed satisfied with the fact that the current curves from simulated and real data closely overlapped visually and had close harmonic content. A further work [69] also used the same two-resistor scheme to propose a HIF model based on arc theory. The authors attempted to propose, in a full bottom-up approach, a model that would mimic surveyed HIF features described in the literature and their arc-like characteristics. Notwithstanding, it is hard to defend such a methodology since there was no verification with real data.

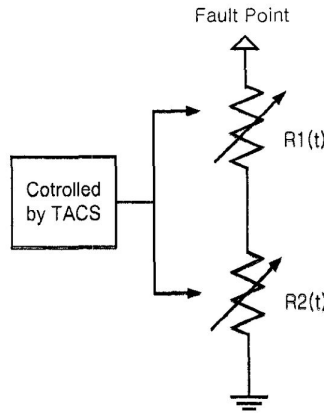


Figure 4: Nam et al. HIF Model (2001).
Adapted from [68]

An important contribution proposed in works from this decade was the specialization on different types of neutral grounding. In multi-grounded or solidly grounded systems, a ground-fault current is limited by the series line impedance. In an ‘Ungrounded’ system, the limiting factor is the stray system capacitance. The difference in the circuit diagrams is illustrated in Fig. 5. As

these capacitances are the only current return paths in ground faults, they are solely responsible for the existence of fault currents in ungrounded systems. This fact makes such a configuration to have major benefits: lower ground-fault current, better personnel safety, and more reliable service [70]. The latter is achieved by the fact that a ground fault will not alter voltage between phases; two- and three-phase loads can then simply ride through them. Any significant fault impedance on such a system would result in current levels similar to HIFs in grounded systems. It does make faults less dangerous but does not solve all the problems. Single-digit fault currents, which can ignite fire in surfaces like vegetation, are still not easily identified. Moreover, another considerable downside is the increased voltage level in the other two phases created by the shift of the neutral point in an occurrence of a fault. The practical application of neutral grounding types in real systems is, nevertheless, not so polarizing. A Neutral Earth Resistance (NER) can be placed between the neutral and earth, making it a high-impedance neutral earthing system. Even more sophisticated, alternatively, a variable high-impedance reactor connected to the neutral point can be adjusted to compensate the stray system capacitance. Such a reactor, illustrated in Fig. 6, is known as Peterson Coil, arc-suppression coil, or ground-fault neutralizer. Three-phase networks with this type of grounding are often referred to as resonant-grounded or compensated systems. Ground fault currents in this type of systems can be reduced to about 3 to 10 per cent of that for an ungrounded system. They can be found in Northern and Eastern Europe, especially in Nordic countries [71, 17], China [72], and Israel [73]. In Australia, legislation has been enforcing and mandating utilities to install resonant grounding with Rapid Earth Fault Current Limiters (REFCLs) [74] due to past severe wildfires ignited by powerlines in the country. If interested, the reader can find more information on ground fault protection methods for different neutral grounding systems in a detailed and professional description by *Schweitzer Engineering Laboratories* (SEL) [73].

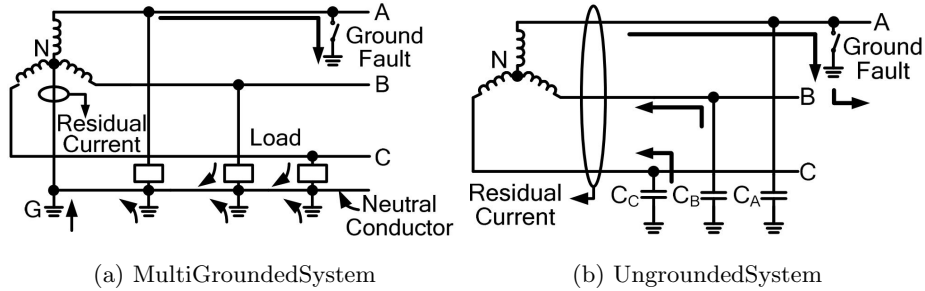


Figure 5: Types of neutral earthing.
Adapted from [51]

One of the advantages of having the high-impedance connected between the neutral and ground point of a three-phase system is the resulting smaller earth-fault current. The operation of the system benefits from the fact that, since the loads have all to be connected between phases, zero-sequence measurements are *free* to be used for earth fault detection. The REFCL, labelled ‘Ground fault neutralizer’ [75] by its pioneering company, *Swedish neutral*, presents itself as an enhanced suppression coil. Its main advantage lies on speed, being able to compensate neutral residual currents in under three power cycles (150 ms). Such capabilities make REFCLs an effective solution for earth faults in terms of fire safety. However, as most engineering solutions, there are trade-offs and limitations in their application. The first REFCL applicability constraint is the fact that it can only be implemented in resonant-grounded systems. As their functionality is primarily dependent on the residual earth current, REFCLs are not suitable to systems that intentionally rely on the earth path for their standard operation like most Australian networks. This incompatibility represents a considerable constraint since, in places like Victoria, Australia, SWER lines are 28,000 of the 88,000 km of the distribution overhead power lines [76].

The installation of REFCLs can be expensive and have exceptional added costs. These costs emerge from the intrinsic behaviour of ungrounded systems in fault occurrences. As in all other configurations, if a conductor comes in contact with the earth, they both assume the same electrical potential. However, phase-to-phase voltages magnitudes will not change in ungrounded systems.

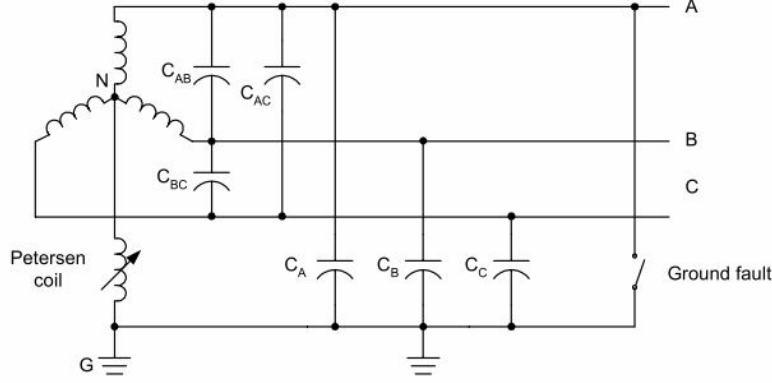


Figure 6: Diagram of a compensated system.
Adapted from [73]

Instead, a shifting of the neutral point happens, changing its value to a point where all the voltages between phases remain the same as before the fault. This intrinsic characteristic of ungrounded systems gives it the ability to ride-through earth faults without any service disruptions (loads are all connected between phases). However, if the fault happens in the phase C, for example, the voltages of phase A and B to ground will increase to values higher than nominal, assuming previous phase-to-phase values. This overvoltage event on the remaining phases is one of the sides from the trade-off associated with the adoption of ungrounded systems; it adds more stress to power equipment insulation. Therefore, power companies have to take precautions with vulnerable equipment in the network before installing such equipment.

Discussions of HIF detection in non-effectively grounded systems in the literature started in the middle of the decade with the aforementioned wavelet-based detection work [58]. The authors propose a detection method on the phase displacement between the zero-sequence voltage and current, arguing that it would be more challenging to detect HIFs in such systems due to their smaller fault currents. However, a later analysis [70] by a SEL engineer argued the case that, in such systems, HIF could be more deterministic and accurate by just having highly-sensitive measurements on the ground residual current (see Fig. 5b for residual current representation). With detailed circuit theory, the authors proposed faulted feeder and faulted phase identification with residual voltage and current phasor analysis. Nevertheless, researches from Finland and Egypt were convinced that current resonant systems' technology to detect tree-related HIFs needed improvement.

Given that fires can be ignited by faults with single-digit amperes in vegetation [8], it is not surprising that the important specialization regarding tree/vegetation faults came from works discussing non-effectively grounded systems. The discussion started in a series of three publications [71, 7, 77], where authors focus on this particular type of fault. In their first paper [71], laboratory experiments were set-up to conceptualize a leaning-tree HIF model. The outcomes included an arc theory-based model and a wavelet-based HIF detection method. Features were extracted from residual voltage and current signals, and HIF occurrence was detected by a simple wavelet-coefficient summation. The authors were satisfied with the resulted model, which closely approximated the V-I characteristic curve of a small number of experiments. The method scheme, with validating simulations, was further presented in their second paper [7]. One of their conclusion was that the fault behaviour was also dependent on the network characteristics, making the transients used in the detection less sensible for faults distant from the measuring point. Therefore, they also had to include and advocate for wireless sensors that would be distributed throughout the network. Such wide-area monitoring through sensors was one of the innovative ideas that got traction in the 00s; it was also presented in their third paper [77], which used new data from a few tree HIF tests staged on a real feeder to validate their previously proposed method. Despite different from the methodology proposed in [70], both authors pointed to the consensus of using residual current and voltages to detect HIFs in non-effectively grounded systems. A pioneering

work focusing on the electrical characterisation of vegetation faults [13] is also worth-mentioning. It presented important evidence to the importance of dealing with these specific types of faults such as the linearity of the fault current in the first cycles of conduction.

Regarding the use of wireless sampling technologies, an increasing number of works started to propose and discuss the idea of using distributed sensors to aid in HIF detection. In one of the first influential works from this decade, researchers from Brazil [78] proposed an innovative sensor-based approach. It described a sensor to be placed in power poles such that it would be sensitized by the electric fields produced by the conductors on the primary feeder. With strategic placement, this single sensor was able to detect three-phase voltages unbalances that would indicate the occurrence of a broken conductor. In addition to the presentation of the detecting device, the authors also suggested a methodology based on powerline carrier communication for signal transmission. The cost could be pointed out as a constraining aspect of the presented scheme. The authors explained that although the rest of the device was relatively low-cost, the capacitor used in the transmitter coupling costed around thirty-five thousand dollars. Moreover, a different sensor approach targeting covered conductors in Finland’s systems was proposed [9]. The sensor based on the *Rogowski coil* — an air-cored coil around the feeder conductor separated by polyethylene isolation — was set to measure leaning-tree fault Partial discharges (PD) pulses. The authors argued that such coils have the advantage of possessing a high signal to noise ratio in wideband frequency response. Hence, they would be effective at detecting short and high-frequency PDs generated by leaning trees. Its strengths are the certain possibility of being a less expensive coupling and non-invasive installation. Its possible main disadvantage, however, is the consequent need for communication methods and data processing. Invested on the approach, nonetheless, the authors continued to publish on the use of the device in a further review [79] and in an attempt of validated their method [80]. It is important to note that, these publications mainly targeted the PD detection research field. The devices were not described as a HIF but as a PD detector. Nevertheless, in a non-effectively grounded system, a leaning tree that touches a faulty covered conductor is most probably a HIF. Therefore, this work can be seen as representing a novel literature intersection of the PD and HIF detection fields. A further work proposing PD sensing in overhead distribution lines [81] using frequencies as high as 25 MHz with Rogowski coils can also be cited as an example of such an intersection. Ultimately, it is hard to deny the possible benefits and accessibility that such sensor-based approaches could bring. They probably represent the most likely candidates for future HIF sensing and detection. Recent works and patents granted with very similar ideas [82, 83] can also be counted as evidence for the interest in sensor-based sampling technologies.

On the commercial field, development and discussions of solutions from key industry players continued to evolve. Competitor companies such as *ABB* and *SEL* felt the need to propose their HIF solutions following the pioneering efforts of *GE*. In 2004, *ABB* published an announcement of its HIF detection philosophy to be included in their feeder protection devices [84]. Sampling signals in 32 samples per cycle (1.6 kHz at 50 Hz fundamental), the method comprised of a combination of wavelet analysis and ANN. High order statistics were applied to the wavelet coefficients while a two-layer network was fed five cycles of raw current samples. Although mentioned in the document as a ‘voting system’, the decision logic on the wavelet features and ANN outputs was unclear. Such a methodology, however, attested for the interest of the company in using trending and modern bottom-up and top-down approaches. The same could not be said for the algorithms proposed by *SEL* [52]. In the paper, the author argued that a deterministic methodology using traditional relay logic would be easier to understand and simpler to implement. In a somewhat contradictory stance, favouring deterministic approaches and dismissing “black-box methods” such as neural networks to detect the faults, the author proposed a method consisting of a heuristic applied to the current signals. It starts with the extraction of its single main feature: a running average of a quantity named “Sum of Difference Current” (SDI). Defined as a one-cycle differentiator set to represent all the cumulative effect of non-harmonic frequencies, the SDI can allegedly assert the occurrence of arcing HIFs. The feature is compared to a trend, which could be adaptively tuned for different environmental conditions, and sent to the decision logic algorithm. The classification label is then given by a counter responsible for tracking how many times the SDI exceeded the threshold within the previous seconds. Validated in apparently four tests in the disclosing paper, this methodology would then evolve to the current commercial *Arc Sense™ Technology* present in many feeder

protection devices by SEL [85]. The same author also published a paper reviewing HIF detection in systems with different grounding types and describing the performance of the algorithm in staged faults [51]. In this analysis, strong arguments were presented for the specialization hypothesis by criticizing methods that claim specific detection rates without specifying distinct conducting surfaces. From GE and TAMU, however, only one paper describing the field experience with their previously proposed HIF detection algorithms was published [2]. The discussion revolved around a power company’s experiences from installing relays with HIF detection in 280 feeders over a period of two years. Being the first to do it on such a widespread basis, interesting findings were presented. For example, interviews with line crews indicated that around one-third of downed conductors were still energized when they got to the pointed location. In the company’s log, forty-eight out of the seventy-one confirmed faults had data available. Forty-six of them armed the relay (96%) but only twenty-eight were detected as downed conductors (58%). The authors explain such difference was due to the bias towards security purposely programmed in the algorithms to have the smallest number of false-positive as possible. Overall, the commercial works from these key industry players asserted, with their individual and competing solutions, the relevancy and importance of HIF detection problem.

Lastly, brief comments on novel approaches regarding HIF location are worth making. Its relevancy becomes apparent when considering tripping a long and branched faulted feeder where finding such a HIF by visual inspection may take a considerable amount of time. This decision will also depend on the importance of the supplied loads and environmental conditions. Quickly locating HIFs would thus be always advantageous, possibly increasing service continuity and chances of preventing damaging fires. Such an important idea was discussed in a simple but influential work [86]. In a fully simulation-based approach, the authors learned an ANN with sequence currents and their harmonics to estimate the fault location. It is not hard to find many issues with this methodology, despite its novel idea. It neglects the fact that the current amplitude, network topology and harmonic content created by the load can significantly vary. It used an apparently small amount of data when training the network and made stretching considerations when validating its results.

Overall, most noticeable developments and contributing ideas from the 00s can be summarized:

- Wavelet transform as a signal representation technique surging in popularity, equating to Fourier-based transforms [7, 58, 60, 56, 62, 57, 63].
- The ubiquitous use of HIF models, leading to an overwhelming amount of simulation-based works [50, 58, 68, 87, 62, 7, 66, 57, 65, 63].
- Consideration of different types of neutral grounding as a HIF detection specialization [71, 58, 70, 71, 7, 77].
- Discussion on the use of sensor-based approaches as a possible non-invasive, low-cost, sampling technique [78, 9, 79, 80, 81].
- Presentation of commercial solutions from other key industry players [84, 52, 85].

5 Contemporary literature — More specializations, sensors, and fault location

The research published after the 10s, considered herein as contemporary literature, represents the largest number of publications when compared with other decades. It is not clear that the same could be said in terms of innovation in the field. Most contributions probably came from more specializations in the HIFs surface types, continuing investigations on wireless-based sampling approaches, and more in-depth discussions on HIF location. The latter showed a slight change in field direction, suggesting some transcendence on the problem of detection. It is possible that some researchers were satisfied or saturated with the large number of approaches targeting fault detection and wanted to progress the field to more significant challenges. Such possibility becomes

more evident if one investigates the number of replication works, i.e. works that do not present more contributions but instead apply a slight variation of an already proposed technique, published in this period. Notwithstanding, discussions and findings presented in specialization works assert the fact that much still needs to be understood about the HIF phenomenon behaviour.

Unsatisfied with the current state of HIF modelling, researchers continued to propose new ideas for improving phenomena representation. A model proposed at the beginning of this decade [88] aimed at building on the first described model [42] to increase the represented frequency band to components up to 12 kHz. By using 40 tests staged on many types of surfaces such as asphalt, cement, soil, and tree, the proposed model consists of six branches of the previous model (see Fig. 1) in parallel. When fitting the model parameters, the authors used FFT for extracting features from the current signals, PCA for dimension reduction, and an iterative minimization on the Bonferroni interval as cost function. The work tried to fit different types of HIFs in a single model, which would make it deficient if high-variance between surface types is indeed present. A further work [11] addressed this hypothesis and presented some evidence in its model proposition. The authors, decided to build on another previously discussed work [68], proposed a model with the same characteristics (see Fig. 4) but with parameters individually fitted for each surface. On their results, one can see a significant variance in the impedance parameters and current waveforms for each of the studied surfaces. With approximately ten tests each, a variety of surface types were considered: grass, cobblestones, gravel, asphalt, sand, and local soil.

A recent modelling approach [10] presents itself as the one of the most innovative model specialization: tree-related HIFs. This type of faults are especially crucial due to their implications in HIF-related fire ignition and that they can have significant, particular characteristics. Two different behaviours described in the paper, from the initial phases of conduction (that can last for several seconds), are significant insights: (1) the fault current is smaller than other surface types, in the range of milliamperes; (2) its impedance behaves closely to a linear resistor, meaning that there is no arcing and no significant levels of harmonic injection. Results from other vegetation-related HIF works [54, 89, 13] corroborate these robust findings, attesting for the recurrent mA-range fault currents and smoother conduction near zero-crossings. Researchers will need to take these vegetation-specific characteristics into account when developing detection methods if they have the goal of fire mitigation. According to recent evidence, the only chance of doing so is to act on the first few seconds of the fault [8]. The data used to conceptualize the model [10], despite being collected from a small number of real, staged tests, was collected with the non-traditional sampling rate of 1 MSa/s. Such sampling rate is much higher than the vast majority of works discussed herein and allows for a better representation of the fault HF components. Its parameters were calculated using the Hammerstein-Wiener model to fit low-frequency components of the fault impedance, while the high-frequencies were approximated by a sum of sinusoids determined via the least-squares method. Moreover, in the same paper, the authors also proposed an approach for detecting the faults based on the innovative idea of using the Magnetic Field (MF) strength instead of voltage or current signals.

Recent tree/vegetation HIF specialization works highlight the relevance of particularly addressing these faults. The authors of the model [10] published two more works on tree-related HIFs features and detection [90, 91]. One used the empirical mode decomposition to extract features and the linear regression slope on resulted components quantiles to classify the faults [90]. The other [91] presented the same idea but discussing the use of the magnetic field strength as the domain of the extracted features. The authors argued that using MF sensors would be a more accessible way of sampling the signals and that the MF strength signal is independent of the sensor location on the feeder. The latter, if true, would mean that one sensor would be enough to monitor the whole feeder. However, the authors did not present compelling evidence for this strong claim besides presenting finite element model simulations from part of the studied system. Further questions can then be raised given that no modelling details on the system stray capacitance were detailed, which will attenuate the small fault current (magneto-motive force) in considerable distances. The authors of the present paper would like to be transparent to the fact of their bias towards the importance of this subject (vegetation-related HIFs) since it was the focus in their past publications [54, 92, 93, 12]. The first presents a study on the vegetation HIFs most perceivable characteristics [54], while the second proposes a HIF detection method based on fault's high-frequency features

[92]. The other two works [93, 12] are evidence gathering studies where the importance of the high-frequency components are discussed and fault signatures are extracted and illustrated in the time domain.

Magnetic field sensing is one of the novel ideas discussed in contemporary literature. An innovative work [94] discussed such an approach to replace the three current sensors mounted under each phase with one MF strength sensor. In its feature extraction part, the additional novel idea of *mathematical morphology* for signal representation is used. A SVM classifier performs the classification with feature selection done by a genetic algorithm. The results proposed, in a partly simulation-based approach, show considerable detection accuracy with a fresh, attractive, solution. Similarly, a following recent work [95] proposed another non-invasive MF strength sensor as a continuation of a previous detection method [96]. With the goal of presenting a low-cost method, a coil-shaped sensor to be mounted under (not around) the primary feeder conductors was proposed. The classification of the faults was based on the inter-harmonic current level, as previous work [96], estimated by an accessible Arduino microprocessor. Despite being undoubtedly novel, it is hard to assess the real effectiveness of these methods in the field. They are partially or fully simulation-based methods that still aimed at detecting all HIFs types with a single approach. Nevertheless, they are indeed evidence for the direction of preference in using non-invasive, sensor-based, approaches to sample signals able to indicate HIF occurrences.

Wavelet-based feature extractors maintained their popularity, but other possible signal representation candidates were also discussed. With the assertion of the field relevancy, accessible HIF models, and popularity surge, the idea of using wavelets to extract features was quickly explored in the past decade. This saturation led to an increasing number of papers presenting replicated methodologies with very few novel aspects. A fraction of the surveyed works herein was selected to be discussed in this section. From the chosen ones, none presented the use of wavelet as its main contribution, with a few using it as support for their primary specialization.

Mathematical Morphology (MM), used to analyse spatial structures in the field of image processing, was one of the novel signal representation ideas introduced. It uses a structuring element and two important concepts, *Dilation* and *Erosion*, to encode information regarding the form, shape, and size of structures. The application in HIF detection is mainly made by using it to represent the particular irregular shapes of HIF-generated waveforms [15, 94, 97]. Such application, however, was based on two assumptions with thin evidence: (1) the arbitrarily chosen structuring element will be adequate to represent the transients created by the fault, and (2) the consequent representation will exclusively represent HIFs. In the first paper [15], the authors used a variation of MM to propose a feature named multi-resolution morphological gradient. It was used in an ANN-based classifier learned from a data set composed of a mixture of a small number of real, staged tests and a large data set from simulations. In their results, the authors argued that the experiments showed MM to be more effective than WT and Fourier-based transforms at representing HIFs. The previously discussed MM-based work [94] is a translation of this approach to the domain of MF strength signals. In the following years, another fully simulation-based work [97] also made a case for using MM to represent HIF signals with just a change in the structuring element and a threshold-based heuristic.

Other two relevant works using different signal representation are also worth discussing. The first relates a work, quickly recognized in the literature, that used a time-frequency analysis based on the Choi-Williams distribution [98] to represent signals. Intending to propose a simple and effective method, staged tests with tree branches, grass, and concrete were performed in a laboratory as part of the methodology. Its feature extraction, going in a different direction as most works in the field, was performed by time-frequency decomposition followed by a joint time-frequency moment calculation. After the application of PCA for dimensionality reduction, the results from learning a SVM classifier showed perfect dependability but deficient security. Its relevant influence on the field was not only resultant from its consistent methodology but also due to its discussion on establishing evaluation criteria for future proposed methods such as cost, objectivity, speed, and completeness. These criteria, despite previously discussed in past methods, are not always present in method-proposing works. They are usually discussed individually when the proposed method wants to highlight a particular advantage in related criteria. In this critical discussion, the authors also drew attention to the need for a systematic presentation of future methods. These

standards would include reporting concepts inspired by the machine learning literature: confusion matrix, accuracy, dependability, security, safety, and sensibility. The authors soon followed this work with an important analysis [99] where a similar detection method performance was compared considering data sets with different origins: simulations (using a HIF model) and real data. The expressive results were a proxy of the effectiveness of simulation-based works at representing real-world scenarios. The method's security reduced from 100% in the simulations to 38.4% in the real data scenario, while dependability went from 100% to 88.2%. The second work addressing signal representation presented an innovative mathematical method for analysing the fault signals [16]. The authors proposed a whole novel orthogonal decomposition where the basis functions were derived from the actual fault signals sampled in staged tests. The main advantage of this approach is the non-reliance on a predefined set of basis functions like the ones present in the Fourier and wavelet transforms. The authors argued that such decomposition was highly effective due to its sensitivity to phase unbalances present in a HIF occurrence (phase-to-ground fault). Moreover, they tried to make a case that the resulted components highly correlate with the fault distance and thus could be used to guide fault location. The method was validated with the use of real data, and promising results were presented for relatively moderate current amplitudes (± 20 A).

5.1 HIF location

Altogether, no subject in the HIF literature presented more innovation than fault location. Most fault location methods categorized as *exact* approaches can be divided in *travelling wave* or *parameter estimation* technologies. Other proposed techniques can be categorized as *fault location estimators*, as they are used as support in search of the fault location, usually reducing the fault search space.

From travelling wave-based methods, a work presented in a series of three papers [100, 101, 102] targeting HIF location can be regarded as one of the most influential. It was conceptualized to detect and locate a HIF using Power Line Communication (PLC) devices. The detection was performed by a PLC device that continually monitors the feeder impedance and detects the fault when an abrupt change in the HF impedance is asserted. After detection, one PLC device (transmitter) starts to inject impulses into the network, which are to be received by another PLC device (receiver). Based on the travelling wave phenomena, the received impulse by the receiver, and the reflected impulse on the transmitter, the exact fault location can be theoretically calculated. In this manner, the fault location always occurs between two successive communication devices. The methodology, first conceptualized for rural single-phase rural networks with earth return [100, 101], was further generalized to multi-phase systems [102]. The results presented in their simulation analysis for fault location are promising but also raise questions to severe constraints. For example, it requires knowledge of the topology, impedance, and resonant frequencies of the system for the best narrow frequency range selection. Since the detection and location system merely indicates changes in the system topology (HIF as a small topology change), it has to consider such a topology to be stationary. The faults were simulated as constant impedance, as are the loads, far from the complex behaviour comprehensively described by other authors. Moreover, as it considers the end of the line as open-ended, band-stop filters may be required on the primary side of low-voltage transformers.

One of the most relevant parameters estimation-based works [103] also suffered from strict constraints. It proposed the calculation of the fault distance with a time differential filter on the feeder current. In the methodology, the time-domain subtraction on the current signals is performed from subsequent cycles observed in the feeder so the fault parameters can be estimated. If an abrupt change in the parameter calculation is asserted, a fault is detected. Then, the fault distance is given by a polynomial estimation of the parameters with Newton's gradient descent method. Another recently published work also uses a similar differential current approach but with parameter estimation done via ANN [18]. The authors claimed that such ANN would not need prior training as it was conceptualized to train on-line as it acquires data. The results were compared to the method previously discussed [103], resulting in less estimated distance error. Many issues could be pointed out with these works, but probably the most relevant one is the fact that both built their methods on the presupposition that the fault parameters and non-linearity are known.

The models used by the authors may reflect the non-linearity of certain HIF types but will, at best, closely represent a single type of fault. These methods, moreover, are conceptualized with currents much higher than HIFs can assume (from single-digit amperes), in the range of 60-100 A.

Other fault location search supports are also recently proposed. As the ones formerly discussed, they require full knowledge of the system topology, loads, and system accurate modelling. A work using wavelets in MRA [104] proposed HIF detection and location by comparing the values of signals coefficients with a pre-developed data set. Such data should come from system simulations for many faults in all the branches, so calculated values can be compared and ranked in regards to distance. Another work [105] that proposed HIF detection with the use of distributed measurements throughout the network described fault location estimation by how intensely these were sensitized. Thus, with a reasonable number of allocated monitors, the fault search space could be significantly reduced.

For the most part, HIF location solutions are still in the early stages and have many obstacles to deal with until attesting generalization. Some intrinsic characteristics of power distribution systems pose critical constraints to the effectiveness of these theoretical solutions. The conductors' size change between branches, making the impedance calculations non-linear. There is a possible existence of multiple feeder taps and laterals, phase imbalances, and inaccurate load representation/aggregation, which are challenging to model. But most importantly, one still needs to resolve the problem of the non-linear and non-effectively modelled HIF behaviour when relying only on simulations. In fairness, however, one should not expect that works from an emerging sub-field as HIF location to have all obstacles solved. Future development in this field is probably going to use different strategies to be more generalizable and have considerable potential to improve with better HIF models and sensor-based technologies.

5.2 Contemporary commercial solutions

Due to the intense history of catastrophic wildfires, Australia has been heavily involved in the application and development of contemporary solutions. After a series of fires that devastated the state of Victoria in 2009, there was an injection of government funding and pressure to mitigate potential powerline-ignited wildfires. It led to the funding in infrastructural changes, but also in vegetation HIF staged tests [8] and evaluation of potential solutions [106]. These projects influenced the further 'Electricity Safety (Bushfire Mitigation) Amendment Regulations 2016' [74], which made provision as requirements for power companies to increase safety standards of their operation. Between the requirements was the roll-out of 45 Rapid Earth Fault Current Limiters (REFCLs) by the following seven years [107] with possible penalties of 2 million AUD per substation that did not address the installation mandate [108]. As mentioned in the last section, REFCLs are not a exactly new technology, but Australia has been installing them in recent years, thus undergoing an interesting experiment. The choice for REFCLs could have been influenced by the urgency and pressure from the events. REFCLs are not particularly inexpensive, only work in three-phase feeders, and can't guarantee protection against HIF between phases. However, they are fast and sensitive enough to be applied was a direct protection system to mitigate potential fires.

The wave of incentives to invest in HIF solutions in Australia also resulted in the development of new technology. The solution by *IND Technology* is not necessarily a HIF detection method but a Early Fault Detection (EFD) device [109]. It applies sensors in an wide-area monitoring system based on partial discharge concepts to monitor overhead power lines and detect incipient faults before the turn to a low-impedance fault. Based on the premise that insulator deterioration will release radio-frequency signals in the conductor, the device uses frequencies in the range of MHz to detect potential HIFs. According to one of the founders, in highly-branched networks, the device needs to be installed in 5-kilometres intervals [110]. The sensors are wireless and installed in under the primary conductors. The company reported that the device has shown sensitivity to detect plenty of events: lighting, live-line workers, switching events, assets warranting immediate replacement, and vegetation lying across conductors. It is unclear that the device could be used as protection device since the patterns found in the signals are sent to the cloud and further analysed. The equipment has been installed in Australia, USA, China, and is in continuing testing

and development.

TAMU also betted on the path of a predictive approach, rather than reactive (detection and responding). Their main solution was described in a paper revealing a development work of more than a decade with the Electric Power Research Institute (EPRI) [111]. Using a technology coined as *Distribution Fault Anticipation* (DAF), the device is allegedly capable of detection incipient apparatus and line failures, using the waveform of existing CTs and PTs at the substation bus. The device also has the capability of clustering patterns of disturbances that may be intermittent, appearing in the intervals up to several days. The clustering framework is presented in a more recent paper where the automate method to mine, cluster, and report is described [112]. Although initial field tests of the equipment were discussed in the presenting paper [111], a more comprehensive application was recently reported [113]. Funded by the Texas government, the device was tested in 11 distribution feeders of a local power utility. If successful, the device can work to monitor events on single-phase laterals, but precise values for the sensitivity of the equipment and speed for protection integration appears still to be reported.

As one of the most traditional players, Schweitzer Engineering Laboratories believes the solution for powerline-ignited fires will come from a holistic approach. The framework includes four strategies: (1) preventive maintenance, involving inspections and proactive vegetation management; (2) enhanced system protection, to produce more visibility and control of the system; (3) strategic operational practices for assessment of risk and forecasting; (4) and system hardening, which includes assets replacement such as poles and overhead conductors [114]. The company does not present any innovative technology for HIF signal classification. It relies on the previous discussed technology, which is based on the inter-harmonic signals in the load current, applied through traditional timer and counter logic. However, the company does present some interesting hardware that could allegedly detect broken conductor faults before the wire touches the ground [115]. Such a system relies on sensors distributed throughout the network called Fault and Load Transmitter and Receivers (FLT and FLR) that can wirelessly communicate SCADA when a loss of current or unbalancing is detected. The advantages of the hardware is that it can be installed up to 10 miles from the receiver point and up to 168 devices can use the same DNP3 mapping, as opposed to one for each device. The protection-level speed has been reported in a paper [115] where faults were staged in a collaboration with a utility company. Similarly to the TAMU approach, sensitivity is yet another gray concept for these devices, specially considering that the company defines HIF currents having amplitudes below 100 A in grounded systems [114].

A relatively new company from China, *SilverFern Power*, it is also bringing their sensor-based solution to the market [116]. As well as SEL, this company sensors are also mounted on the conductors, gathering data with sampling rates of 256 Sa/cycle. The communication, however, is done through 3G/4G networks. The company does necessarily focuses on HIF, but as most systems in China are non-effectively grounded, fault currents are usually much smaller. In public reports, the company states that with such a system can detect and locate any single-phase earth fault current more than 1 A [116]. It also states that tens of thousands of sensors have already been put in operation in more than 600 substations.

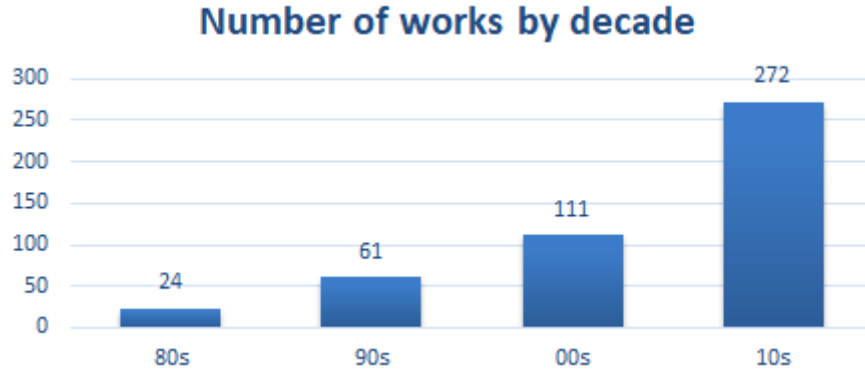
With the largest number of works proposed, contemporary literature was responsible for relevant contributions and many validations studies. The highlights from this research period can be summarized:

- Modelling and detection specialization of tree/vegetation HIFs [10, 89, 90, 91].
- Increasing number of sensor-based solutions, pointing to increasing interest and consensus on their advantages [82, 83, 94, 95].
- Magnetic field strength sensors as the sampling domain for HIF detection [94, 95].
- Deeper discussions on HIF location asserting it as a legitimate HIF sub-field of research [102, 103, 18, 104, 105].
- Contemporary solutions moving to a predictive monitoring approaches [110, 111].

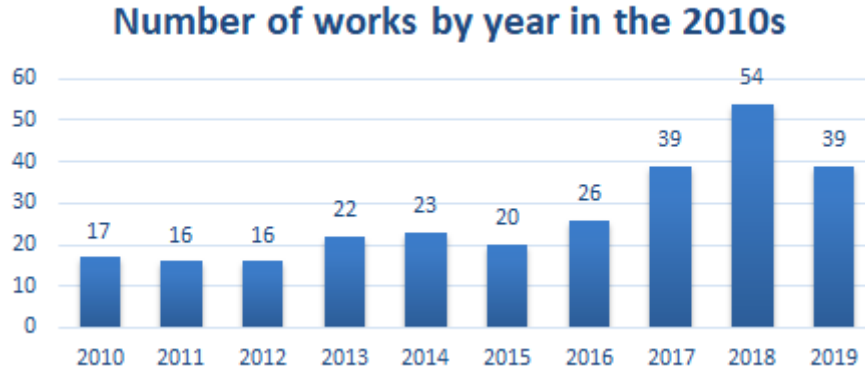
6 Discussions

To bring such a survey closer to a quantitative analysis, this section illustrates and discusses some statistical figures calculated from the analysed works. Before beginning such discussions, it is worth to note that there is a difference between the number of works previously described in detail and the total considered in the following quantitative evaluation. The total number of papers and technical documents analysed pertains to many classes: 131 total works, including 94 HIF detection papers, 9 HIF modelling methodologies, 7 HIF location papers, and 4 literature reviews. The remaining include method validation works, commercial papers, tutorials, related technology, and patents. Although being less than the total amount of papers published in the topic, it is still a representative sample of the direction and distribution of techniques used in the field.

The first quantitative figure presented is an illustration of historical growth of the field. The number of papers published by decade and by year in the IEEEExplore repository is illustrated in Fig. 7. As seen in Fig. 7a, the number of publications consistently increased throughout the decades. It more than doubled twice, and more papers were published in the 10s than all previous decades added together. In the 2010s, papers were consistently published every year with an overall positive trend from the beginning to the end of the decade, as shown by Fig. 7b. The number of papers published in 2018 was certainly a record and outlier. The exact reasons for this phenomenon is not known, but the hypothesis that it may be linked to the recurrency and intensity of the wildfires ignited by powerlines in the current and past decade might be an interesting subject of research. The number of works analysed in detail, mentioned in the last paragraph, is a set of the works presented in Fig. 7b as it includes all the papers listed in IEEEExplore with the words “high-impedance fault”.



(a) Papers published in IEEEExplore by decade.



(b) Papers published in IEEEExplore in the 2010s by year.

Figure 7: HIF field popularity and growth.

It is also useful to illustrate how the techniques to extract HIF features from fault signals are distributed in the previously presented methods. As repeatedly discussed in previous sections, signal representation and feature extraction techniques are often the primary contribution to knowledge attempted by HIF detection works. The pie chart shown in Fig. 8, produced from the papers evaluated in detail, shows the distribution of techniques used to extract the discriminative information from fault signals. In the figure, ‘MM’ represents Mathematical Morphology and ‘HH/EMD’ signifies the Hilbert-Huang transform or Empirical Mode Decomposition. ‘Wavelet’ and ‘Fourier’ represent methods based on their respective transforms while ‘Sequence’ depicts the analysed methods based on zero and negative sequence currents and voltages. The ‘Impedance’ works are a few of the papers found where the detection is based on the apparent impedance measured from sampled voltage and current signals. The ‘Others’ category include alternative time-frequency analysis techniques, impulse response and travelling wave-base methods, time series analysis, and mechanical methods. From all the mentioned techniques, it is remarkable that wavelet-based methods clearly dominate the practice considering it was only popularized in the 00s. It is easier to find wavelet-based methods than Fourier-based ones, even though the latter were introduced in the beginning of the field. Likewise, it is also remarkable that the ‘Other’ category is well represented, matching the same proportion as Fourier-based methods. One can hypothesise that this class have such a significant share due to the fact that feature extraction and signal representation techniques are often the main contribution to knowledge proposed in the papers. As authors need to introduce novelty in their work, many publish on experiments and use of not-previously tested techniques so they can have a claim of original work. These works are seldom replicated, ending up in single or double mentions, hence the ‘Other’ classification. Moreover, one last notable fact attested by Fig. 8 is that the majority of the works still use hand-engineered features. Hand-engineered features have the advantage of being closer to explaining causality but are also dependent on the human knowledge that creates them. One can induct two reasons for the dominance of these symbolic approaches: (1) researches are still not proficient with the use of techniques such as deep learning and encoding techniques, or (2) researchers do not believe that exploring such techniques are worth. The latter could be due to the lack of causality in the methods and their uncertainty, or by belief that such approaches will not be well received by the community.

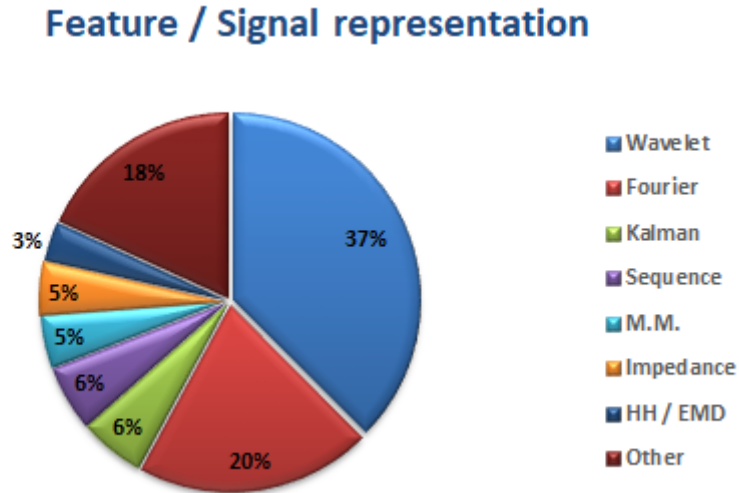


Figure 8: Signal representation techniques in HIF detection works.

Demonstrating the distribution of choices in the classification techniques is as important as illustrating feature extraction approaches. They are responsible for the crucial task of classifying the signals as originating from a fault or not, which takes place after the discriminative information has been extracted. The practice mainly consists of establishing decision boundaries which will

result in the classification of the observed data or feature. The technique used to classify the signals can take many forms and assume different levels of complexity; from a simple threshold value established on a calculated feature to complex decision boundaries defined by neural networks trained on labelled data. From the works analysed in detail, Fig. 9 shows the distribution of classification techniques labelled as ‘Deterministic’ and ‘Probabilistic’. The chart illustrates the interesting fact that probabilistic decision boundary techniques relying on observations are almost as represented as deterministic ones. The fact probabilistic techniques started to be adopted later than thresholds and arbitrary decision boundaries ones is the main reason for their representation being remarkable. This effect is present in the distribution of probabilistic techniques as well, also shown in Fig. 9. Artificial Neural Network-based approaches (ANN-based in the chart) surprisingly dominates the probabilistic techniques attesting for the high interest from the research community. Other machine learning techniques such as support vector machines, random forest, and k-nearest neighbours occupy 39% of probabilistic techniques.

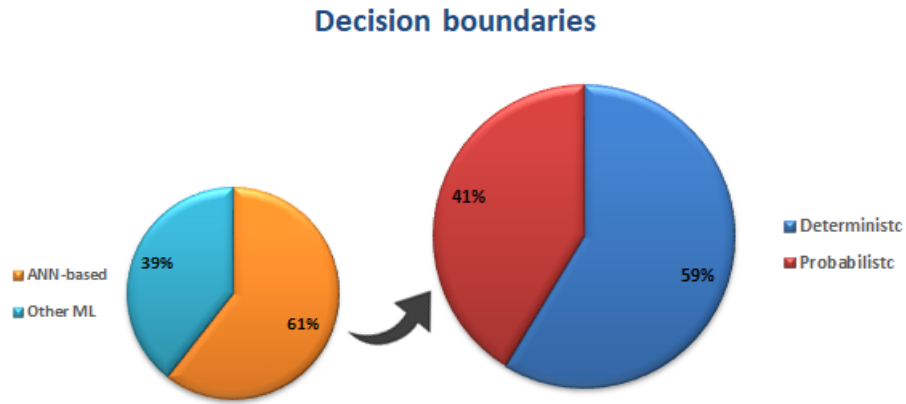


Figure 9: Techniques used to define decision boundaries in HIF works.

It is interesting to make a note on the sampling rates used by the HIF detection works. From the analysed detection papers, only 53 made their data acquisition sampling rate clear. Close to half of them (24) adopted sampling rates lower than 5 kSa/s while 22 adopted values between 5 and 50 kSa/s. Only 3 fitted the exception of sampling signals at rates higher than 50 kSa/s. Nevertheless, one of them was a purely simulation-based work while another was as active method based on travelling wave theory where a pulse gets injected into the line and its response is measured. The third was sampling signals at 64 kSa/s. The fact that higher sampling rates are not often adopted is not necessarily detrimental to the field. Having accurate detection with smaller sampling rates is desired since it is less demanding and closer to the sampling of existing digitizers allocated on the field. However, if one accepts that HIF detection is a lasting problem to be still definitely solved, investigating the effects of faults at higher sampling rates becomes a very interesting research problem, which may prove to be crucial.

The proportion of works that were purely simulation-based or specializing in different fault surface type are also two aspects worth commenting. The introduction of HIF modelling in the 90s, as an attempt to circumvent the need of real data by the use of simulations, was effective at becoming a common practice. From the 88 investigated papers, 42 presented pure simulation-based works that made use of previously proposed HIF models to make claims about accurate fault detection by their methods. Nevertheless, given the variance between fault types presented in the literature and here, one could argue that methods based purely on modelling are still to prove their capability of generalizing to real faults. There is no consensus, as seen from the present survey, on the best way to model HIFs or whether they can adequately represent all types of fault surfaces. In regards to works that focus on vegetation as the particular fault surface, conversely, one can confidently state that they are rare. From the analysed works, 8 include some type of vegetation on their tests, but only 4 focuses solely on it as fault surface. From the research that is

continuing, a few group of researchers presented original contribution regarding vegetation HIFs [90, 117, 10, 91, 6, 13, 54, 92, 93, 12].

Having gone through the description of the field, some perceived knowledge gaps can be also discussed. For example, between all the works discussed in this paper, few try to discriminate between fault conducting surfaces such as grass, tree branches, gravel, asphalt, and sand. Detection methods are often proposed with the alleged ability to detect all HIFs, despite the conducting surface. Nevertheless, since seminal works in this field, authors have already stated that it is unlikely that a single method would be able to detect all types on HIFs [118]. After analysing numerous publications from the field of HIF detection, one could argue that it is likely that the scarcity of HIF type specificity is one of the reasons for the lack of consensus regarding a definitive fault detection solution. If true, such assumption would mean that the aforementioned traditional definition — HIF as faults with current below protective devices sensitivity — is a condensed definition for a more intricate problem. Based on the consensus of fault variability, therefore, it is reasonable to say that HIFs should also be investigated in sub-classes given by parameters such as the type of the fault, contact surface, and network type.

Researches have recently started to publish more on tree/vegetation faults as a specific type of fault to be studied [119, 10, 89, 91, 13]. They have gathered evidence of essential and distinct HIFs characteristics that diverge from other investigated surfaces. One of these is the current magnitude in the first moments of the fault occurrence; initial values are often in the range of a few amperes [8, 13, 117]. This characteristic is conflictual to a large part of the works in the literature since, as discussed in this paper, most methods do not have their current sensitivity defined but are instead presented as a generic solution to the traditional definition of HIFs. The second interesting characteristic relates to the first in that, on those initial seconds of the fault, the current seems to have an almost linear relationship with the voltage [54, 117, 8]. That behaviour also represents a conflict with part of the methods in the literature since they heavily rely on the harmonic content of current signals as the predictive information. The relevance of these two particular characteristics — low current amplitude and low harmonic content — further increases when aspects like detection speed are considered. According to a work testing hundreds of vegetation species [8], VHIFs have to be detected and addressed in the first five seconds of fault inception if a considerable fire risk reduction is desired.

Few works perform experiments that were conceptualised with particular limitations to the fault currents. When proposing detection methods, most papers do not dedicate effort to establish thresholds or standards for the fault current. This fact is consequential because it is not possible to know how sensitive are the results if the current is not carefully limited. Limiting the fault current to relatively small values (from 0 to a few amps) can be further explored since they still can ignite fires in overhead systems. Having positive results in this niche current level also represents an unaddressed gap in the literature.

As mentioned in previous paragraphs, the vast majority of works do not cross the rates of 50 kSa/s when acquiring data from their experiments. Therefore, having signals sampled in such a large bandwidth represents a significant gap. The large bandwidth can also allow distinct experiments. For example, in which the bands are concentrated important predicting information content for fault detection. Having accurate representations of the HIF behaviour can add evidence and fill the gap of the phenomena understanding.

Part of reason for a definite solution is clearly the problem complexity, which is arguably higher than researchers initially thought. However, one can also argue that because it is not an immediate and asset-damaging problem, there are also not enough incentives to animate more elaborate solutions. There is a challenging aspect in creating such incentives since producing and staging the necessary experiments is an onerous and expensive activity. When other organizations end up doing real experiments, the fact that they are so burdensome results in negative incentives to sharing the experimental data. If the HIF phenomenon is indeed as high variant as seen here, one should expect that conclusive solutions for all types of conduction surfaces to only come from large data sets with a massive number of experiments. The lack of standard data sets results in convoluted literature where many solutions are presented for different sub-problems inside the HIF detection field. This confusion leads to the incapability of comparing different methods performances and leave much of the proposed knowledge without any specific use or application. Therefore, the author would

like to propose a call to action for future researchers to include the vegetation ignition data set in their method validation. Another goes to the companies to make their data publicly available so researchers can have proper assessments of their methods and so others can build an open-source data sets of HIFs. The authors believe that this will be the fastest way to solve the HIF detection problem and probably save the overall community from the massive amount of damages resulting from powerline-ignited fires.

7 Conclusions

This paper presented a historical narrative and commentary of the HIF field in power distribution systems. Descriptions were organized in decades, from the field seminal works and pioneering researchers to the contemporary methods and technologies. Key players and how the advancements unfolded were contextualized in the pool of most cited papers and technical documents. After analyzing the surveyed works, one can see that the HIF is a highly complex problem that resulted in a fruitful but convoluted field of discussions. It is essential to understand the historical arc where the developments took place to be able to analyze novel work critically. The authors hope that such description can be used by readers in many fields, making them more familiar with the efforts, struggles, and core ideas in the field. It is probable that the best scenario for convergence of knowledge now is to have open-source data sets with diverse conducting surfaces so methods can be properly compared and discussed. That are many lasting knowledge gaps, and further advancements can result in saving lives and mitigation of environmental damages.

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