"High-Impedance Fault Detection" Revisited: Why the Term Has Lost Its Meaning and Should Be Abandoned

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***Abstract*—"High-impedance fault" is a commonly used term in power system literature with a decades-long history. While the term may be commonly used, it is not used consistently. This is especially true when one considers the disparity between usage in academic and industry contexts. In academic literature, the term is almost never defined, but appears to mean something like, "faults that are hard to detect." When the authors informally survey practitioners, a common answer to the question, "What is a high-impedance fault?" resembles, "It is a fault with a high impedance." While this is correct by way of tautology, it is unhelpful as a functional matter. Few practitioners or academics include multiple varieties of power system events that occur on operational circuits which might reasonably be called a high-impedance fault, nor do they consider distinct and often differing characteristics of such events. Said differently, "high-impedance fault" is not a homogeneous class of events which can be considered uniformly, but a diverse set of power system conditions which share some characteristics and diverge substantially in others.**

This paper draws on over 40 years of practical experience and research in electrical characterization of normal and abnormal power system transients performed at the Power System Automation Laboratory at Texas A&M University to argue that the term "high-impedance fault" itself has become an impediment to developing techniques and technologies for detecting and mitigating a wide class of power system events which do not reliably operate conventional overcurrent protection devices.

***Index Terms*— high impedance faults, downed conductors, vegetation faults, incipient faults**

I. Introduction

"For a *large* class of cases - though not for all - in which we employ the word 'meaning'", the Austrian philosopher Ludwig Wittgenstein famously stated, "it can be defined thus: the meaning of a word is its use in the language." [1]

The past decade has seen an explosion of research interest in high-impedance fault detection. Dozens of papers have been published on the topic, and the authors of this paper have reviewed dozens of additional papers which were rejected in the review process. There are varied reasons for this renewed interest, ranging from wildfire risk mitigation to improved public safety and operational awareness. While the methods these papers employ vary, a common theme among many high-impedance fault detection papers, both published and unpublished, is a lack of firm understanding of and definition for what it is, exactly, they are trying to detect. In other words, while the papers all claim to be about detecting high-impedance faults, it is often not clear which types of high-impedance faults an individual paper may be trying to detect.

This trend is unfortunately exacerbated by a self-referential subgenre of literature which uses simulated data based on decades-old arc models to produce supposed "high-impedance fault signatures" which look little to nothing like real world events. In some respect it is difficult to blame authors for using simulated data. Staged high-impedance fault data is uncommon, owing partially to the difficulty of faithfully recreating such complex events in a laboratory setting. Confirmed field recordings from naturally occurring high-impedance faults are rarer still. That said, arcing models do not adequately capture the nuanced behavior of many real-world events, even the ones they purport to simulate. Because of widespread publication of these papers, many misconceptions and outright errors have crept into conventional wisdom regarding the electrical characteristics of so-called "high-impedance faults," to such an extent that common beliefs associated with the term in academic literature now bear only accidental resemblance to signals recorded on operational circuits.

The Power System Automation Laboratory at Texas A&M University has worked for over 40 years investigating the electrical characteristics of faults and failure events on operational power systems with the goal of improving both public safety and power system reliability. The views in this paper draw on an extensive body of research and hundreds of field-documented cases of failure mechanisms, including many dozens of events which would traditionally be labeled high-impedance faults. This research program has produced significant insights into the ways actual apparatus fail on operational systems, much of which was unknown when the term "high-impedance fault" gained popularity in literature. Rather than individually justifying each assertion in this text through specific examples, readers are encouraged to peruse previous publications from this group which contain information not only about specific case studies and failure

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events, but also about the data collection process and methodology which produced this dataset. Key papers are provided in the references [2-8].

Our goal in this paper is not to produce a new definition for the term "high-impedance fault," or to suggest an alternate construction which better captures the electrical behavior of failure events. Instead, our suggestion is that researchers and practitioners alike should be more precise regarding the specific failure categories they have in mind, rather than using a term which has come to be used so imprecisely that it effectively means nothing at all.

II. What, if anything, is a high-impedance fault?

While it is possible to generate both theoretical and functional definitions for the term "high-impedance fault," all such definitions are ultimately artificial and incomplete. Indeed, when the initial idea for this paper was proposed internally, the authors immediately began a circuitous discussion about necessary exceptions and caveats one would need to place on any given definition – in a roundabout way proving why the term ought to be avoided. That said, some definitions are better – which is to say, more useful – than others. As such, a short discussion of common understandings of the term "high-impedance fault" is warranted to demonstrate their various shortcomings.

From a purely linguistic analysis, what many or most papers seem to mean by the term "high-impedance fault" is something like an energized conductor on the ground, or possibly the initial current that flows when a vegetation contact spans two conductors. While these conditions may indeed produce unintentional low-magnitude current flows that might reasonably be described as high-impedance, they represent only a small subset of events which may result in such characteristics. An energized conductor resting on a crossarm, for example, can produce charring and tracking over a long period of time which may go undetected until it sets a pole on fire [9]. This is certainly a "high-impedance fault" by most reasonable definitions, at least in its early stages, but it does not fall into the conception of what most papers seem to mean when they use the term.

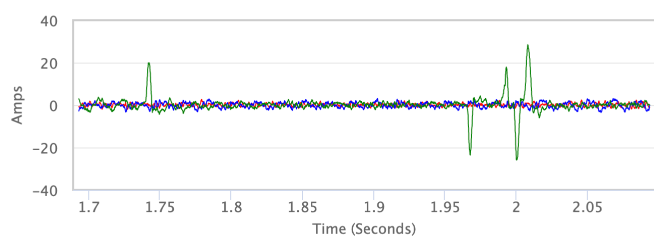

Fig. 1: What is the impedance of this fault?

When asking many engineers, an automatic answer to the question, "What is a high-impedance fault?" often sounds very much like, "A fault with high impedance." When pressed, however, this definition shows significant flaws. An immediate follow up question would be, "What level of impedance is 'high'?" At this point some engineers shrug and suggest a specific impedance value (e.g., 1,000-ohms), or alternatively say "Any fault that is not bolted." Each of these responses shows a certain flaw with using absolute impedance values to distinguish between "bolted," "high," and "low" impedance faults.

While it might be tempting to treat any fault which differs from its theoretical bolted value as a high-impedance fault, this definition falls apart quickly because all real-world faults have *some* fault impedance. Indeed, *many* – maybe even *most* – real-world faults exhibit some change in their impedance over the fault period, if the fault is not cleared within a few cycles. While textbooks treat all conventional faults as though they are zero impedance, 60Hz (or 50Hz) phenomena, on operational systems these faults are the exception rather than the rule. Furthermore, on very long rural circuits (e.g., where the farthest end of the circuit may be 50 electrical kilometers or more from the substation) some bolted faults may produce fault currents which are smaller than load transients (e.g., large three-phase motors) which are located closer to the substation. It is not uncommon in rural settings to have bolted fault current availability on the order of 250 amperes near the end of the circuit.

Choosing an arbitrary value of fault impedance to serve as a demarcation between high and low-impedance faults is also problematic. For many classes of events which are commonly understood to be "high-impedance faults," there is no single or even stable fault impedance. Many classes of "high-impedance faults" exhibit random or chaotic behavior where the fault may strike or restrike – or not – on a sub-cycle basis. Figure 1 shows current measured at a substation where the pre-fault load current has been estimated and removed, leaving only the fault current. Current bursts produced by such pulses may vary widely (e.g., 5x or more between pulses, in some cases) from one burst to the next, or they may not. In physical terms, this is because the primary governing impedance for these events is specific to local conditions at the fault point. An energized conductor on the ground, for example, has an impedance dominated by the contact impedance between the conductor and earth, potentially at multiple points. The specific geometry and electrical characteristics of the contact point(s) on a micro level are impossible to model and produce what is in effect a random but bounded impedance. As such, attempting to restrict the term "high-impedance fault" only to events which have a fault impedance of more than, for example, 100-ohms, is a category error. A similar statement could be made about any other arbitrary impedance value.

A functional definition, preferred by the authors, is that a high-impedance fault is one which will not reliably operate conventional overcurrent protection devices. [10] This definition is more useful than the previous definitions in that it at least gets at what protection engineers are most frequently interested in: de-energizing an unintended flow of current, ideally as quickly as possible, ideally as close to the fault point as possible. Such a definition is not without its own problems, however. For example, some international observers have rightly noted that what is "conventional" varies from region to region. While it is true that conventions vary, they do exist, and under any prevailing conventions some faults will fail to clear.

A stronger objection that could be made is that for this definition, the term "high-impedance fault" becomes dependent on system topology and the protective devices protecting the fault point – even within a particular notion of "conventional" protection. Consider the hypothetical case of a stable fault with a constant fault impedance such that the fault sources 250 amperes of fault current indefinitely on a radial circuit. In this case, such a fault on a single-phase lateral protected by a 15-amp fuse would likely operate protection both quickly and reliably. If the exact same fault with the exact same electrical characteristics were on the main three-phase trunk just outside the substation fence, however, it would likely remain indefinitely and never operate system protection.

A further problem with the definition is that the ability to detect many "high-impedance" faults differs substantially depending on whether the system in question is operated as three-wire or four-wire. Most so-called high-impedance faults are phase-to-ground/earth/neutral events. Because three-wire systems do not have a carried neutral, and thus do not connect loads phase-to-neutral, $3I_0$ is a much more sensitive parameter than it would be on four-wire circuits. A well-controlled three-wire circuit would be expected to have generally less than 5 amperes of standing $3I_0$ current, and non-earth-fault related transient conditions generally do not produce more than low-tens-of-amperes of $3I_0$ peaks, particularly on feeders which primarily serve low-voltage networks (e.g., in European style systems). By contrast, it is common for four-wire systems to have many tens of amperes of $3I_0$ current, and single-phase connected loads may produce startup transients of tens of amperes as well. As a result, three-wire circuits tend to have earth fault protection that is orders of magnitude more sensitive than four-wire circuits, impacting the level at which earth faults can be detected and cleared.

Another potential shortcoming of this definition is that events with similar macro-characteristics in the same location on a circuit may produce different outcomes based on their micro-level behavior. For many years the authors operated a test facility on an operational circuit for the purpose of performing staged tests on various electrical phenomena, including downed conductors. Researchers conducted hundreds of tests using varied conductors and soil types. Most downed conductor tests at this facility were protected with a standard 30K fuse. Researchers observed that for certain classes of downed conductor events (e.g., a 4/0 ACSR cable on grass), the fuse would generally either trip relatively quickly (i.e., in a few seconds), or the fault would remain energized for an arbitrarily long time. The point of this example is to note that even "the same" fault (physically, but not electrically) in the same location on a feeder may behave differently – and hence may or may not operate conventional protection – based on micro-level fault characteristics that are impossible to model or predict.

Finally, defining whether a fault is "high-impedance" or not based on protection system operations on medium and low voltage systems is complicated by the reality that most protection on these systems, particularly in North America, is based on inverse time-overcurrent, which is inherently two-dimensional. In other words, a fault may fail to clear protection because its magnitude is not sufficient (which is what many traditional conceptions of "high-impedance fault" focus on), *or* it may fail to clear protection because it is highly time-limited (e.g., an incipient cable failure that may draw 4,000 amperes for a quarter of a cycle). While both signatures may fail to reliably operate conventional inverse time-overcurrent protection, the reasons (and the signatures) are drastically different. As an added wrinkle, some utilities are deploying adaptive protection settings using definite time-overcurrent for the purpose of wildfire risk mitigation. The authors documented one case where an ongoing cable termination failure (a "high-impedance fault" event) caused 79 self-clearing pulses over a period of 200 days. Seventy-six of these pulses self-cleared without operating system protection. Three of them, however, occurred during times when the utility had deployed extra sensitive, fast-tripping settings to downstream reclosers. The sensitive settings caused the reclosers to operate several cycles after the fault had already cleared [11].

The preceding examples should illustrate the danger of trying to demarcate an essential definition for "high-impedance faults" based either on actual impedance or the subjectivities of system protection operations.

III. Real-world "high-impedance faults"

A. System considerations

Before addressing specific classes of events, it is important to briefly discuss relevant differences between the two predominant types of medium voltage systems deployed around the world. For the sake of convenience, we will refer to these as the NA-style system, common across much of North America, and the EU system, which is deployed in much of the rest of the world. While there are of course exceptions and deviations from the generalities we lay out here, these are two useful models for thinking about medium voltage systems.

Most medium voltage systems in the United States and elsewhere in North America are operated as radial distribution systems. In this model, medium voltage lines (typically 15, 25, or 35-kV class, though some 4kV class still exists) are brought directly to customers' locations, and then relatively smaller transformers (i.e., 15, 25, 37.5, 50 kVA) are located on site to serve one to a few customers, typically with a center-tapped 240V single-phase secondary for residential and light commercial load. Loads larger than 150 kVA are typically served three-phase at 120/208V or 277/480V. Larger buildings or complexes of buildings (e.g. apartments, underground URD loops) may be served with a correspondingly larger transformer (100-2,500kva) but in effect all customers on a NA radial system are served at medium voltage, in the sense that there is a step-down transformer at or within sight of the customer's location. By contrast, most EU-style systems operate their medium voltage systems (typically 11, 22, and 33kV) more in the style of a North American subtransmission network. EU-style medium voltage feeders often form a network, especially at higher voltage levels. At multiple points along the feeder, relatively larger transformers (e.g., 350 kVA, 600 kVA) are used to step voltage down to low voltage (commonly 230/400V or 240/415V) for radial distribution at a neighborhood level via area substations. This distinction is critical because there is substantially more medium voltage apparatus in NA systems compared to an equivalent EU system, and substantially more low voltage apparatus in an EU system compared to a NA one. EU-style systems in rural areas do more closely resemble NA-style systems with comparable customer density, but even still EU-style medium voltage circuits tend to be shorter and less branched than their NA-style counterparts.

Another important distinction between the two types of systems is grounding or earthing. NA-style medium-voltage systems are most typically operated as four-wire, multi-grounded wye systems where a neutral conductor is carried along the entire length of a circuit and firmly grounded at every transformer, or at least once every 400 meters. This produces a system with generally high available fault current which is designed, in part, to avoid conditions where low fault currents fail to trip system protection. EU-style systems, on the other hand, tend to be operated as three-wire systems, which may be either earthed or unearthed at the substation. Earthing, if present, may be solidly earthed, earthed through a resistance designed to limit earth fault current (e.g., a neutral earthing resistor), or earthed through a tuned inductor (i.e., a Peterson coil). A full overview of these practices is outside the scope of this paper, but interested readers should consult [12, 13]. The upshot is that because EU style have no phase-to-neutral connected loads, no neutral conductor that an energized phase conductor can contact for a solid return path, and consequently have much lower $3I_0$ current levels, any observed $3I_0$ current above the typically low levels (<5 amperes) produced by capacitive charging effects is likely to be an earth fault. NA systems are more likely to produce high fault currents capable of reliably clearing protection based on their much stronger earthing system, but low-magnitude faults to earth or system neutral are much more difficult to detect both because of steady-state system imbalances, which can frequently produce close to 100 amperes of steady state $3I_0$ current at peak load, as well as loads which are intentionally connected phase-to-neutral.

We acknowledge that the discussion in this section is highly simplified and generalized. National and regional variations exist, and some countries, in particular countries presently or historically associated with the British Commonwealth, operate systems which could reasonably be described as a hybrid of the two systems. The larger point is that one cannot simply assume fault characteristics or solutions without knowing the topology and type of system under discussion, and especially the system grounding configuration.

B. Categories of low-magnitude faults

1) Downed conductors

The most common event which is typically classified as a "high-impedance fault," and indeed the first type of event to broadly receive the name is the case of a conductor which remains energized while in contact with earth. Two of the authors of this paper (Russell, Benner), conducted substantial fundamental research on the behavior and characteristics of downed conductors, and developed the first downed conductor detection algorithms to be patented and sold commercially [14-17].

Like "high-impedance fault," the term "downed conductor" is often used too broadly, with the reality being that substantial differences in behavior exist depending on the exact local configurations at the fault point. A conductor that lands on reinforced concrete behaves very differently from one which lands on dry sand. Attempting to detect or classify both using the same approach and algorithms will not be successful.

Fig. 2: Flashover produced by vegetation contact.

2) Vegetation contact

The authors of this paper have conducted multiple staged experiments on operational circuits to explore the progression of vegetation related faults [18, 19]. A full exploration of results are outside the scope of this paper, but the most important finding for the purposes of this discussion is that at a variety of medium voltage gradients, the initial stages of vegetation contact between two conductors draws relatively little current, often for minutes or tens of minutes, then quickly transitions to a near-bolted state. This finding has been independently confirmed by other research groups in the United States, including tests at the Electric Power Research Institute's Lenox test facility and Pacific Gas and Electric's ATS facility [20-22].

While it may seem obvious, the fact many papers group vegetation contacts with downed conductors makes it necessary to explicitly state that the progression and electrical characteristics of these two fault categories are substantially different.

A further note regarding vegetation contacts: as with other categories of events, many publications group use the term "vegetation fault" ambiguously to refer to multiple classes of events with distinct electrical characteristics. In general there are four separate fault mechanisms which are commonly conflated as "vegetation faults": 1) Vegetation teardown or burndown of conductors, which in effect is a downed conductor caused by vegetation; 2) Vegetation pushing two conductors together, which is in effect a conductor-slap event initiated by vegetation; 3) Vegetation of sufficient diameter spanning two conductors while making sustained or prolonged contact; 4) The initial stages of vegetation growing into lines, which often results in self-pruning. The electrical signatures produced by each of these categories vary substantially. Care should be taken when evaluating utility outage tickets, because all these scenarios are typically grouped together under a common cause code, but they are not identical.

3) Series arcing

Series arcing is included in this list, even though it is arguably not a "fault" in the traditional definition. Classically, a "fault" has been understood as an unintended current flow to ground or another conductor [23]. Series arcing, on the other hand, is an unintended interruption of an intended current flow.

Fig. 3: Arcing clamp detected and repaired before catastrophic failure

Series arcing develops as a hot spot or imperfection in a load carrying path. It is most commonly associated with switches and clamps but has also been observed in bushings and transformer windings. Series arcing produces signatures distinct from more traditional "shunt" arcing. While shunt arcing currents are frequently governed by system and contact impedance, series arcing currents are governed by the amount of connected capacity downstream of the failing device. Series arcing failures can, perhaps counterintuitively, result in protection operations both upstream and downstream of the failing device. While the phenomenon itself is poorly understood scientifically, ongoing research is increasingly effective at detecting and locating series arcing events before they cause a catastrophic failure.

4) Capacitor arcing / restrike

Series arcing in the path of a capacitor switch is a special case of the phenomenon which has particular importance because of the severe power quality problems it creates, and its tendency to destroy equipment both on the same circuit, as well as other circuits attached to the same bus. Capacitor arcing is especially problematic because it can cause the failure of MOV lightning arresters, which are documented to cause fires. A separate but related form of capacitor failure, restrike, occurs when a switch operates normally to switch a capacitor OFF, but current begins conducting again, usually with arcing, some cycles later. Both phenomena can produce substantial high frequency activity on the affected phase voltages, as well as large but time-limited current spikes. Neither event is likely to operate system protection, even fusing at the point of the capacitor.

5) Voltage regulator contact failures

Another category of low-magnitude incipient failure is a particular failure mechanism associated with voltage regulator contact failures. Regulators use a make-before-break scheme when changing taps, and the mechanical contacts necessary for those changes wear over time and eventually stop functioning as intended. When a regulator develops an internal failure it creates low magnitude arcing that carbonizes insulating oil and could lead to an explosion. At some point in time, the developing failure can cause substantial power quality issues, both annoying customers and damaging sensitive equipment. These failures have been documented to manifest months before an eventual catastrophic failure. The early stages of these failures may produce current signatures that are the same order of magnitude as large inrush transients or motor start events. Figure 4 shows an RMS trace of one such incipient failure condition. Because the signature is on the same order of magnitude as that of a large inrush transient or motor, conventional protection systems cannot be sized to prevent such failures, and indeed a utility would almost certainly not want to operate on such an incipient event but rather be notified of it so the regulator could be replaced in a controlled manner.

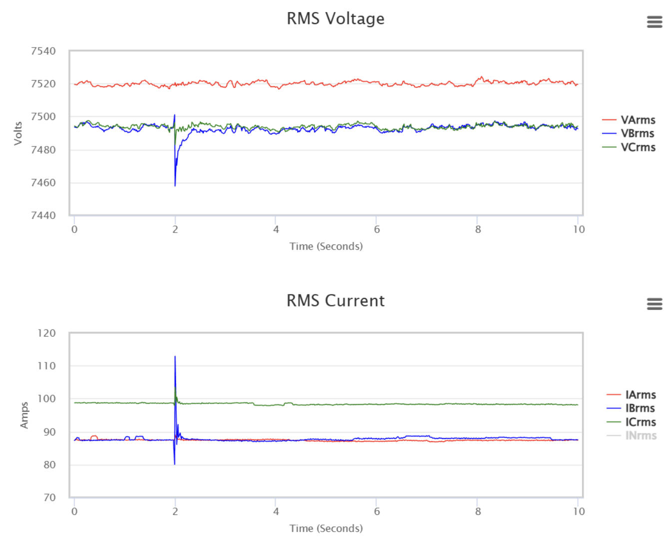

Fig. 4: RMS signals from incipient failure of voltage regulator contacts.

6) Bolted low-voltage faults observed from the medium voltage system

A major class of events observed from the medium voltage system which (intentionally) do not operate system protection are bolted or near-bolted faults on the low voltage side of a transformer. In these cases, the primary impedance limiting of the fault is the transformer itself and cabling on the secondary. As an example, a bolted fault in a customer's open wire secondary might produce thousands of amperes on the secondary side, which in turn would produce only tens of amperes on the primary. Secondary faults at larger facilities (e.g., industrial facilities served by a 1,000 or 2,000kva transformer) have been documented to produce hundreds of amperes of fault current on the primary side. If secondary protection fails and these faults persist long enough, primary protection at the transformer can operate. In many cases, however, these faults will "self-clear" from the perspective of the primary, medium voltage system.

Documentation of such events is challenging because the overwhelming majority occur without any notice to the utility company. Based on substantial field experience with multiple utilities, however, it is the authors' belief that the majority of so-called "high-impedance faults" – at least in the United States where loads can be connected phase-to-neutral – fall into this category. On three-wire systems such faults are observed to be phase-to-phase (because single phase loads are connected between two phases, rather than phase-to-neutral).

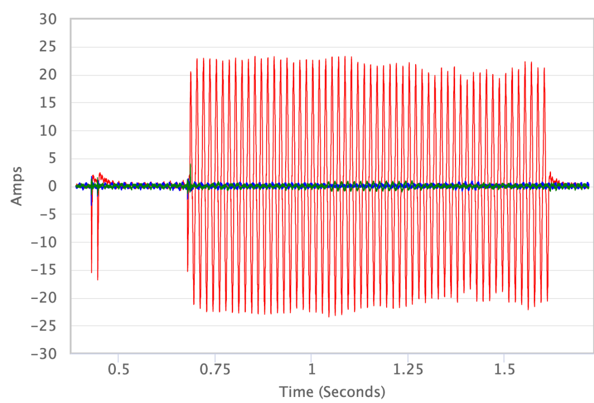

Fig. 5: A "high-impedance" fault believed to be a bolted event on the secondary side of a customer transformer.

Likewise, in EU-style systems which serve low-voltage networks, faults on the low-voltage secondary are frequently visible from the medium-voltage system. One example of this is seen in Figure 6, which was recorded from a medium-voltage circuit serving a 230/400Y low-voltage network through a Dy transformer. As with the case in Figure 5, the dominant impedance in this particular case is the transformer itself.

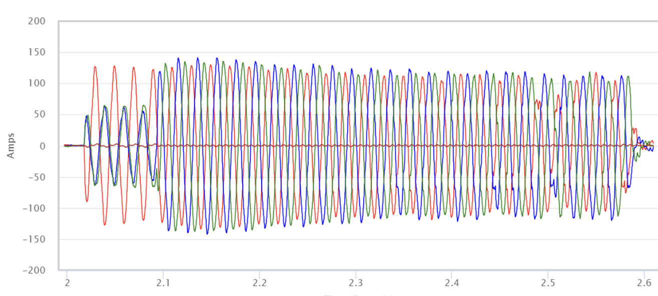

Fig. 6: Low-voltage (230/400Y) fault recorded from the medium voltage system

7) *"Fault-like" loads*

Some loads on power systems themselves exhibit arc-like characteristics. Take as an example Figure 7. This signature in many respects shares important characteristics with certain downed conductors both in terms of its random and impedance limited nature and its cycle-to-cycle variability. The fact this signature occurs every 45-60 seconds during weekday work hours indicates that it is not a downed conductor, but rather an arc welder within an industrial facility served by an unusually large single-phase transformer. Indeed, researchers were able to visit the site with utility personnel and were able to confirm the timing of the recorded electrical signatures corresponded with arc welder activity within the facility. The point is that many loads on distribution systems – particularly on NA-style systems – are intentional "high-impedance faults."

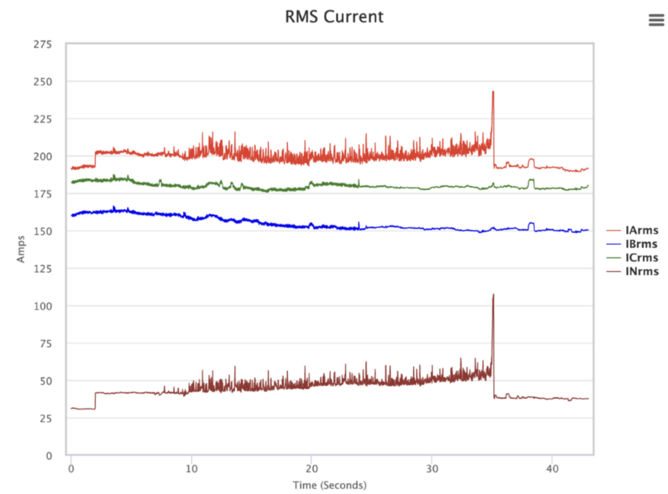

Fig. 7: Is this signature a downed conductor or an arc welder?

8) *Fires on secondary services*

Researchers have observed multiple cases of fires on secondary services resulting in signatures that resemble primary "high-impedance" faults. As with the previous two categories, the primary impedance limiting factor is the impedance of the transformer itself, rather than the fault point. Figure 8 shows twenty seconds of data captured from a 15kV medium voltage primary circuit that resulted from a fire in a customer's secondary service. The electrical activity eventually resulted in the CSP transformer clearing the fault, but only after 30 minutes of intermittent fault behavior.

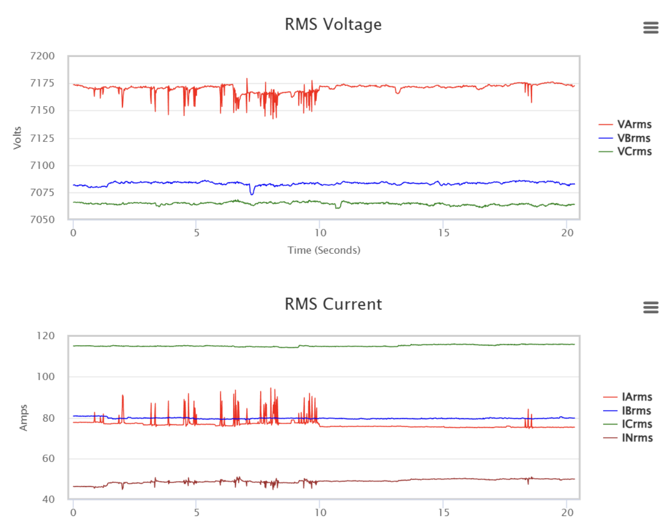

Fig. 8: Twenty seconds of RMS current resulting from a fire in customer's secondary service.

C. Categories of high-magnitude (potentially >1000A) time limited but not bolted faults.

1) Cable termination and splice failures

Cable termination and splice failures often manifest with extremely short duration (i.e., sub-cycle) current bursts that may recur over a period of hours to weeks. These bursts often have substantial magnitude such that if they persisted for any length of time protection would operate. For example, some termination and splice failures have been documented to produce half-cycle pulses with peak currents of over 3,000 amperes.

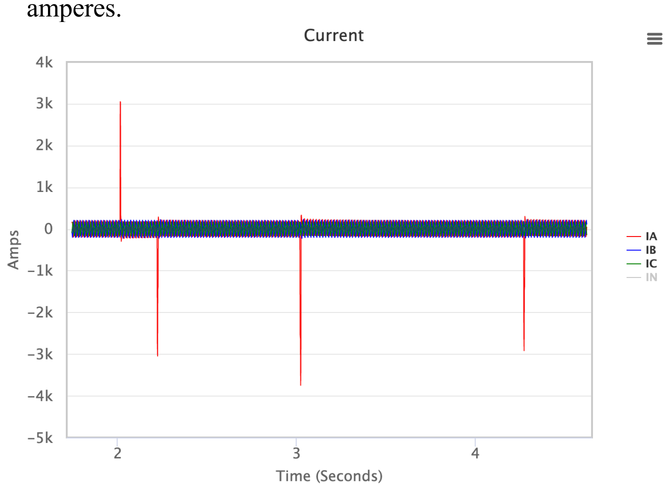

Figure 9: Four pulses from an incipient cable fitting failure.

Figure 9 shows a single instance of an incipient cable termination failure where four sub-cycle pulses are clearly visible. Two things are important to note about these pulses. First, even though the incipient failure event is occurring in the same physical spot on the power system, the fault current magnitudes differ for each pulse, which is frequently observed. In general, current magnitudes for short lived events like this can vary dramatically. It is not uncommon for events to show magnitudes that vary by 50% from one occurrence to the next. Consequently, conventional model-based predictions are not accurate to determine fault location for these cases. Models may bound the search area – for example, the case in Figure 9 is almost certainly located on a section of the circuit with at least 2,500 amperes of bolted available line-to-ground fault current. A second important observation about these events is that they fail to operate system protection even though the absolute fault magnitudes are quite high. Rather, these pulses self-clear and remain quiescent, often for days before recurring. This is important to note because there are cases where incipient termination failures *do* operate protection after self-clearing. In such cases, crews may be unable to find a problem associated with an outage because the underlying fault condition is dormant. Because these failures can produce hundreds of pulses spread across months, there is a significant potential for degraded reliability and power quality.

2) (Some) Arrester failures

In 2021, researchers at Texas A&M documented a failure associated with a lightning arrester on a 25kV distribution circuit in the United States. This failure began as a series of relatively low-magnitude, time-limited current pulses (e.g., less than 30 amperes), but rapidly escalated into much higher pulses, with the largest examples exceeding 3,000 amperes.

Figure 10 and Figure 11 show two waveforms recorded during the lightning arrester failure approximately 9 hours apart. The arrester in question was on the substation getaway cable, explaining the high available fault current. The high fault current eventually contributed to locating the fault, as the later failures approached bolted fault current levels, but importantly did not clear system protection (i.e., the substation breaker) before the fault self-extinguished. Again, it is worth noting that for much of the time (approximately 10 hours) between the initial electrical detection of the fault and the time when the underlying cause was discovered by the line crew, the fault was in a "high-impedance" state, at least in the sense that its fault current magnitude was far lower (i.e., its fault impedance was far higher) than a system model would predict for a fault in that location. In other words, there was a substantial, variable, fault impedance, even though many of the observed pulses produced several hundred or several thousand amperes of current.

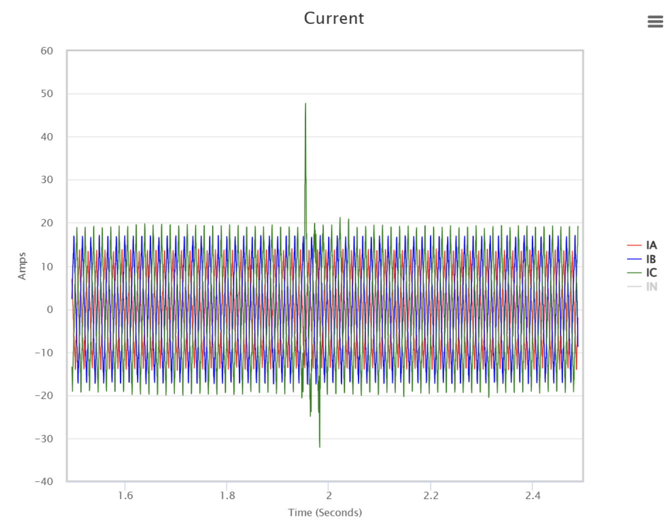

Fig. 10: Early-stage failure associated with lightning arrester

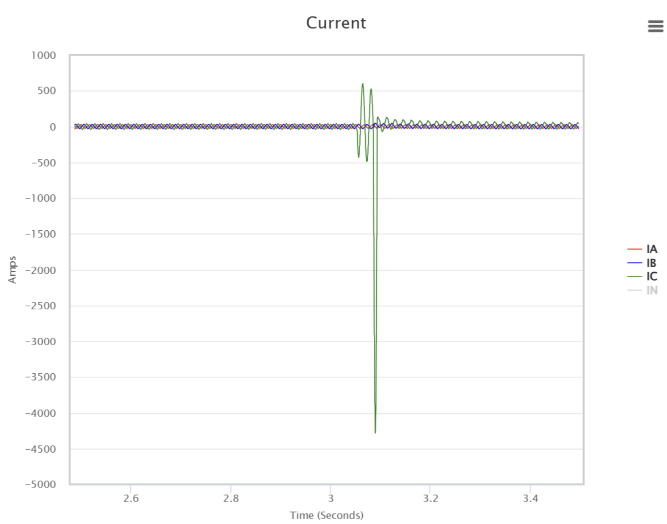

Fig. 11: Failure of the same lightning arrester (from Fig. 10) captured 9 hours later.

IV. Conclusion

We return at this point to statements made in the abstract and introduction: the term “high-impedance fault” – while commonly used – is used inconsistently and has increasingly become an impediment to producing solutions to a critical public safety issue. The examples used in this paper illustrate multiple cases that could reasonably be classified as a “high-impedance fault” which nonetheless have strikingly different characteristics and behavior. As stated in the introduction, our goal in this presentation is not to offer a new definition for the term. Rather, we would implore authors and practitioners to plainly state what they mean.

In practical terms, this might look like saying, “energized conductor on reinforced concrete,” or, “vegetation contact spanning two conductors.” So-called “high-impedance faults” not only have different current magnitudes but different characteristics. Approaches which group all such faults together without recognizing their distinctive character are doomed to failure.

The authors are under no illusion that this paper will eliminate the term high-impedance fault from broad usage. We hope, however, that it will give appropriate context and background so those who use the term can do so more precisely and effectively.

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VI. Biographies

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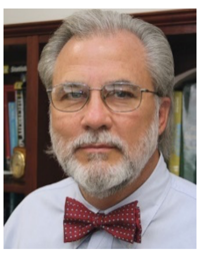

B. Don Russell (F'91) is a Distinguished Professor and Regents Professor in the Department of Electrical and Computer Engineering at Texas A&M University. He is director of the Power System Automation Laboratory and for over four decades has conducted research in the design, operation, and protection of electric distribution circuits. Dr. Russell Is past president of the Power and Energy Society of the Institute of Electrical and Electronic Engineers and is a member of the National Academy of Engineering. Dr. Russell is a fellow of five technical societies.

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