Does Anyone Know What a High-Impedance Fault Is?

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***Abstract*- Protection engineers have wrestled with the challenge of clearing earth faults for over one hundred years. On four-wire multi-grounded systems, like those used in much of North America, earth faults frequently produce currents with magnitudes lower than inrush transients from single-phase connected loads, making detection even more challenging. Even on three wire systems, however, detecting and clearing earth faults rapidly and cost-effectively remains a major challenge.**

In recent decades, the term "high-impedance fault" gained widespread usage. Despite being commonly used, the term is often used imprecisely and frequently creates confusion (often unknowingly!) in discussions among practitioners. When used colloquially, protection engineers usually appear to mean something like an energized downed conductor or possibly a tree contacting a line. More generally, the term appears to mean something like, "faults that are hard to detect" – a vibes-based definition not out of line with a 1996 report produced by the IEEE Power System Relaying Committee which defined the term as faults which, "do not produce enough fault current to be detectable by conventional overcurrent relays or fuses." Compounding this challenge is that so-called "high impedance faults" are not a homogeneous class of events, but rather a diverse set of conditions which share some characteristics in common but diverge drastically in others. While researchers and practitioners would generally agree with the previous statement, it does not stop them from casually lumping all such events together.

This paper begins by tracing the historical development of so-called "high-impedance faults" as both a term and concept, at least in North America. It then draws on over forty years of research experience on operational distribution circuits, conducted by the Power System Automation Laboratory at Texas A&M University, with actual examples of events which might reasonably be called "high-impedance faults," to argue that more precise language around the types of events protection engineers are interested in detecting and clearing – rather than resorting to a catch-all, poorly defined category – is an important step toward effective solutions.

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

I. Introduction and History

IN 1958, the United States Department of Agriculture's Rural Electrification Administration (REA) published REA Bulletin 61-2, titled, "Guide for making a sectionalizing study on rural electric systems." [1] Though today the REA often feels like a forgotten historical artifact, it is difficult to overstate its importance on the development of the electric system in the United States. The REA provided both financial and technical assistance for utilities across the country, and many REA-era practices are still highly influential. REA Bulletin 61-2 is one such document.

The development of hydraulic reclosers in the late 1930's allowed distribution utilities to improve reliability and operate their circuits more effectively by implementing automatic circuit reclosing – previously available only at substations – at multiple downstream points along radial circuits. [2, 3] Particularly for rural utilities which operated extremely long circuits in sometimes difficult to access geographical terrain, hydraulic reclosers offered a substantial improvement over previous practice. Utilities began widely deploying reclosing on distribution circuits in the 1940's, and by the end of the decade multiple papers began to explore the results of reclosing on reliability. [4-6] In 1949, "Overcurrent Investigation on a Rural Distribution System," included a non-descript figure showing measured fault currents for multiple events, along with curves for zero, twenty, thirty, and forty-ohm fault impedances. [7] Around the same time other groups were exploring the characteristics of faults, including fault resistance. [8-10]

In many ways, elements of these two projects converged in REA Bulletin 61-2. This REA guide provided concrete guidance to utility engineers as they performed coordination studies for their systems. One of the guide's practical recommendations that is still common across much of the rural utility industry is its recommendation of "2A, 2B" reclosing – which is to say, two fast trips, followed by two slow trips, followed by lockout. Another important artifact of REA 61-2, however, comes from its instructions on calculating minimum fault currents. In this section, the guide states:

> "The value of fault resistance is subject to judgment. The objective of selecting this resistance for calculation purposes is to make the probability of occurrence of faults with currents below this level as small as possible, while recognizing that with simple overcurrent devices, such as fuses and single-phase reclosers, it is not possible to detect faults whose magnitudes are smaller than load currents. Yet, faults can occur which produce a value of current below peak load current. A value of 30 to 40 ohms is a reasonable resistance to select in minimum fault current calculations. Forty ohms is more conservative and is recommended for

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[25kV circuits and 12kV circuits of a certain load rating]. Regardless of the assumed value of fault resistance, it is desirable to choose reclosers which will detect 200 ampere (or lower) phase-to-ground faults." [1]

While unintentional, this section had the effect of enshrining "40-ohms" as a cutoff value for so-called "high-impedance faults," at least on rural North American systems. While REA 61-2 does not use the term "high-impedance fault" specifically, it may in many respects be the origin, at least in the English-speaking tradition, for the concept of using a single, demarcated impedance value (resistance, in this case) to separate "high" and "low" impedance faults, in that 40-ohms was presented as an acceptable design target for recloser sensitivity. While REA 61-2 never explicitly states that 40-ohms is a *required* value, the suggestion that it was a *reasonable* value led to it becoming a de-facto standard in sectionalizing and coordination studies across much of the industry. [11] So much was this the case that the Rural Utilities Service (RUS) – the successor of the REA, states the following in the most recent sectionalizing guide:

"The question that has always been considered is 'What fault impedance should be used?' The previous version of this bulletin suggested 30 to 40 Ω for overhead lines and 10 to 20 Ω for underground lines. This led to some confusion and concern about the use of 40 Ω of ground fault resistance to calculate the minimum fault current available for overhead construction on distribution systems under the jurisdiction of the Rural Utilities Service. …

Studies have shown that the actual fault impedance when an energized conductor is in contact with the ground can vary from zero to infinity. Therefore it is impossible, using current technology, to select a minimum pickup value that will both detect energized conductors in contact with the ground and allow normal load currents to flow without interfering with normal system operation. The 40-ohm value described in RUS bulletins has always been a compromise, and was never intended to be an absolute value." [12]

In spite of this, in the United States, particularly on rural systems, the 40-ohm number still holds substantial sway, so much so that it is cited in the Cooper Power Systems distribution protection guide. [13] Rural protection engineers will frequently cite 40-ohms as the demarcation for a "high-impedance fault," even if they simultaneously recognize that it represents a sensitivity design target, not an absolute truth about faults. As we will see, however, even when we talk about "high-impedance faults," we are seldom talking about the fault's impedance.

II. Why Impedance?

Impedance calculations are common in transmission relays, particularly distance relays. [14] Because many protection engineering classes in universities focus on transmission systems, and because many of the most advanced protection schemes are deployed on transmission systems, it often surprises engineers unfamiliar with relaying on distribution circuits that impedance is traditionally not an operating quantity for medium voltage distribution, at least in North America.

The most common protection device on North American circuits is the fuse, which offers numerous benefits. Fuses are inexpensive, last for decades, operate reliably, generally require no maintenance, and are easily replaced. They require no power, no active communication, and no on-device settings. While the technology may be over 100 years old, fuses persist for good reasons. A typical North American distribution circuit might have as few as 2 or as many as 20 reclosers, but those same circuits would have hundreds if not thousands of fuses.

Because of the need to coordinate with fuses, most protection schemes on North American circuits rely on 50 or 51 elements (that is to say, definite or inverse time overcurrent). [15] Whether thermal, electromechanical, hydraulic, or microprocessor based, the key operating quantity for 50/51 protection is *current*, not *impedance.* [16] Many older relays, and even some modern protection devices (e.g., cutout-mounted reclosers) do not measure voltage, and as such do not calculate an impedance. Therefore, speaking about a fault's *impedance* rather than its *current magnitude* is already an abstraction away from what most devices on medium voltage systems use to sense and clear faults.

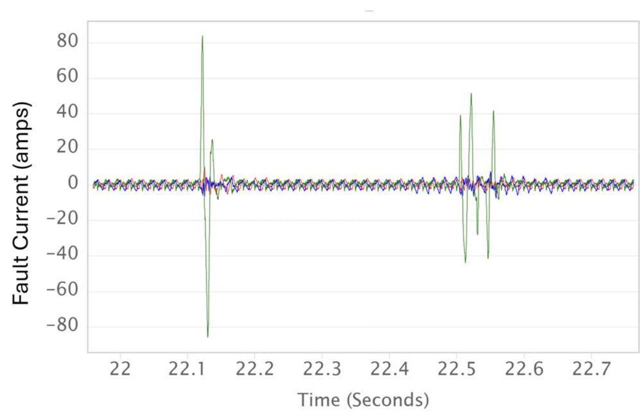

Fig. 1: Assuming a stable 25 kV voltage, what would the "impedance" of this fault be?

When assessing real world faults, many classes of events which are commonly understood to be "high-impedance faults," do not have a single or even stable fault impedance. While the impedance of a conventional fault is frequently defined as the fundamental phasor of the voltage across the fault divided by the fundamental phasor of current flowing through it and is easy to calculate as a single complex number, 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 25 kV substation where the pre-fault load current (approximately 150 amperes in this event) has been estimated and removed, leaving only the fault current. Current bursts like this are common in many classes of so-called "high-impedance faults", and the magnitudes of such pulses may vary widely from one burst to the next, or they may not. In physical terms, this variability is a result of highly dynamic conditions specific to the interface between the energized apparatus (usually a conductor) and ground/earth 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.

Because many classes of "high-impedance faults" exhibit random behavior, along with significant harmonic contributions, phasor-based impedance calculations are arguably not applicable. As a result, it becomes difficult to know what is meant by "a 1,000 ohm fault" unless one specifies what method should be used to calculate an impedance from the measured quantities of current and voltage, over what interval, how to account for system load, etc.

III. Functional Definitions

A 1996 PSRC report on "high-impedance faults" defined them as faults which "do not produce enough fault current to be detectable by conventional overcurrent relays or fuses." [17]

Some observers, particularly international observers whose operational context includes non-effectively grounded systems where earth-faults behave differently, have noted that what is "conventional" varies from region to region. While it is certainly true that conventions vary, it does not therefore follow that they do not exist. Indeed, while the methods for detecting and mitigating earth faults differ substantially between four-wire multi-grounded systems common in much of North America and Petersen-coil systems common in many countries in Europe, and while one may set more aggressive targets with one grounding practice than another, it is important to note that in any prevailing set of conventions some faults will fail to clear. As one example, a medium voltage conductor that becomes detached from an insulator and rests on a wooden crossarm may slowly track current along the crossarm for an extended period until it sets the pole on fire. This initial leakage current is frequently believed to measure in the tens of milliamps and is undetectable by any current technology.

Perhaps a stronger criticism of the PSRC definition is that it makes the definition of a "high-impedance fault" dependent on system protection as much as the characteristics of the fault. As an example, consider a stable "20-ohm" fault on a 12.4 kV rural electric system. This hypothetical fault would draw 360 amperes. This fault would operate a standard 20T fuse – a reasonable value used near the end of many rural circuits – in between 11.5-15 cycles. If the same hypothetical fault occurred near the substation, however, it would likely fall below the ground pickup threshold for the substation circuit breaker and would fail to clear. In other words, two faults that are identical in terms of their electrical characteristics – and both of which fall well below the 40-ohm demarcation – would be classified differently according to the PSRC definition depending on where they occurred on the circuit.

Conversely, faults which have the same "macro" behavior may exhibit different "micro" electrical characteristics, depending on local variables. For example, for many years the authors operated a test facility where they conducted multiple staged experiments involving downed conductors. The most common protection arrangement at this facility during downed conductor tests was to use a standard 30K fuse. Researchers observed that for some types of tests (e.g., a 4/0 ACSR conductor laying in the grass) there would be one of three outcomes: 1) the fuse would operate immediately, 2) the fuse would operate after a few seconds, or 3) the fuse would fail to operate for an arbitrarily long time (i.e., tens of minutes). In this case, "the same fault" occurring in "the same place" on the same circuit produced multiple outcomes, sometimes clearing protection and sometimes failing to do so. One might argue that including some notion of "reliability" into the PSRC definition would fix this problem, but this merely shifts the discussion toward what level of "reliability" is acceptable.

Another problem with this definition is that 50/51 schemes commonly used in much of North America are inherently two-dimensional. In other words, a particular fault might fail to operate protection because its current magnitude was not high enough *or* might fail to operate protection because it does not persist long enough (i.e., it self clears before protection can operate).

Incipient cable fitting failures are a prime example of this and will be discussed more later in the paper. Incipient cable failures can produce sub cycle pulses over a period of months that go undetected by circuit owners because they do not persist for long enough to operate protection devices. In one documented example, researchers observed seventy-nine distinct current bursts produced by an incipient cable fitting failure across six months. Each of those cases self-cleared before upstream protection operated. The circuit operator in this event will occasionally enable extra sensitive protection settings with the goal of mitigating wildfire ignitions, effectively transitioning from inverse-time curves to an instantaneous curve. Three of the seventy-nine pulses occurred while this extra sensitive protection was enabled. In each of these three instances, the sub cycle fault current exceeded the pickup point for the upstream recloser, and because it was set to trip instantaneously the recloser initiated a trip sequence. By the time the recloser opened three cycles later, however, the fault was no longer present.

IV. Contemporary High-impedance Fault Research

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 specific methods these papers employ vary, their overall approach often shares certain common themes.

The most fundamental shortcoming in the majority of papers published in the last two decades has been an overreliance on simulated data. 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. Long-term data collection on operational circuits is difficult, expensive, and requires cooperation from circuit owners that is often impossible to attain. That said, models often do not and sometimes cannot adequately capture the nuanced behavior of many real-world events, even the ones they purport to simulate.

As machine learning based methods have become more common and popular, papers have increasingly followed a familiar trope: first, data are generated from decades-old arc models, almost all of which were designed with the assumption of effective grounding; next, an algorithm is designed or a model trained based on the features of the simulated data; finally, validation is performed, often on a modified IEEE 13 or 34 bus system with additional data derived from the same assumptions. It is perhaps not surprising that most of the methods developed from this protocol boast impressive results, far exceeding those claimed by existing commercial technology. Unfortunately, these results are all a kind of fiction, as the simulated data they produce generally fail to resemble signatures recorded on real circuits, both for supposed "high-impedance fault" signatures they detect, but also the "normal" signatures used to perform security analyses.

In the authors' opinion it is not possible to demonstrate that any "high-impedance fault detection" method is production-ready without meaningful testing on data derived from real circuits. One cannot demonstrate a method's sensitivity without testing it against large numbers (e.g., hundreds) of examples of real and varied fault data obtained from multiple operational circuits. Conversely, it is not possible to demonstrate the security of a proposed method without prolonged exposure to a significant amount of real, "normal" system activity (e.g., hundreds of circuit years) to ensure the method does not false trip at an unacceptable rate. We are aware of no methods published in any academic journal over the last 25 years that meet either of those criteria. The existence of dozens of varied methods in literature claiming extraordinary success rates (e.g., 90+% true detections with no or almost no false detections) suggest it is relatively easy to design "high-impedance fault detection" methods which work well in simulation. The fact that, to our knowledge, none of these methods have been successfully implemented in a commercial protection device or demonstrated on an operational circuit suggests there is a large gap between what works well in simulation, and what works well in the real world.

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 events, but also about the data collection process and methodology which produced this dataset. Key papers are provided in the references [18-24]. All figures in the paper were recorded at medium-voltage substations, and all currents and voltages specified in the text or plots are in primary values, unless otherwise noted.

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.

V. Real-world "high-impedance faults"

A. System considerations

Before addressing specific classes of events, it is important to briefly discuss a topic which is often glossed or ignored in the discussion of high-impedance faults, namely earthing or grounding. It is unfortunate that this must be explicitly stated, but earth faults behave very differently depending on the grounding/earthing configuration of the circuit. In much of North America, the most common circuit configuration is a wye-connected, four-wire, multi-grounded neutral for medium voltage service. There are some older 4 kV delta configurations that remain in service, and many utilities in California operate 15 kV class 3-wire uni-grounded distribution systems (that is to say, three phase conductors originating at the substation from a wye-connected transformer, with the neutral point firmly earthed to ground, but no neutral conductor run along the length of the circuit). But in general, almost all medium voltage circuits in North America are solidly (effectively) grounded.

This is not the case in much of the rest of the world. While many UK and former Commonwealth countries do employ large numbers of effectively grounded 3-wire systems, many other countries run circuits that are 3-wire and wye-connected, but where the transformer neutral is either isolated (not connected at all), earthed through a resistor (either high or low-impedance earthing, sometimes called a neutral earthing resistor or NER), or earthed through a tuned inductor (a compensated neutral, often called an arc suppression coil or Petersen coil, after its inventor). In each of these arrangements, a single earth fault does not automatically render the circuit inoperable. In the case of an isolated neutral, as an example, the first connection between an energized conductor and earth grounds that leg of the wye, and the other two phases experience line-to-line voltage with respect to earth.

A full overview of these practices is outside the scope of this paper, but interested readers should consult [25, 26]. The key point to note is that so-called "high-impedance faults" behave quite differently depending on the grounding configuration, and as the topic has gained popularity little attention has been given to which models and methods were developed with which assumptions, and whether those assumptions are valid in other contexts.

For example, the 1996 PSRC report lists varying current magnitude levels observed from downed conductors on different surfaces, ranging from 0-75 amperes. What the report fails to explicitly state is that all these numbers were acquired on four-wire, multi-grounded distribution circuits, and none of them are broadly valid on non-effectively grounded systems. Despite this, many of these values are reproduced without consideration in recent papers developing methods for non-effectively grounded systems.

B. Categories of faults with low-magnitude currents

As observed from the medium voltage distribution system, there are multiple classes of fault events which result in low fault current magnitude. In some cases, the magnitude of the fault current is limited by the impedance of the fault itself – for example, energized downed conductors. In other cases, for example a fire in a customer's secondary service, the impedance may also be limited by a service transformer between the medium-voltage measurement point and the fault on the secondary side of the transformer.

This distinction is important, because arcing faults and arc-like loads on the low-voltage side of transformers can and do produce signatures which in many respects look similar to and have similar magnitudes as impedance-limited primary-side faults. Algorithm designers should be aware that such cases exist and can result in protection mis-operations.

The following list of cases is not intended to be exhaustive, nor are we able, given space constraints, to provide multiple signatures for each category. The list is intended, rather, to give a flavor of multiple types of events which are often not considered when engineers use the term "high-impedance fault," but which can produce substantially similar characteristics.

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 [27-30].

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.

2) Vegetation contact

The authors of this paper have conducted multiple staged experiments on operational circuits to explore the progression of vegetation related faults [31, 32]. Figure 2 shows one such test. 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 [33-35].

Fig. 2: Flashover produced by vegetation contact.

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, the term "vegetation fault" is frequently used ambiguously, particularly in utility outage records but also in papers, 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 [36]. Series arcing, on the other hand, is an unintended interruption of an intended current flow.

Series arcing develops as a hot spot or imperfection in a load carrying path. It is most commonly associated with switches and clamps, like the damaged clamp shown in Figure 3, 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.

Fig. 3: Arcing clamp detected and repaired before 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.

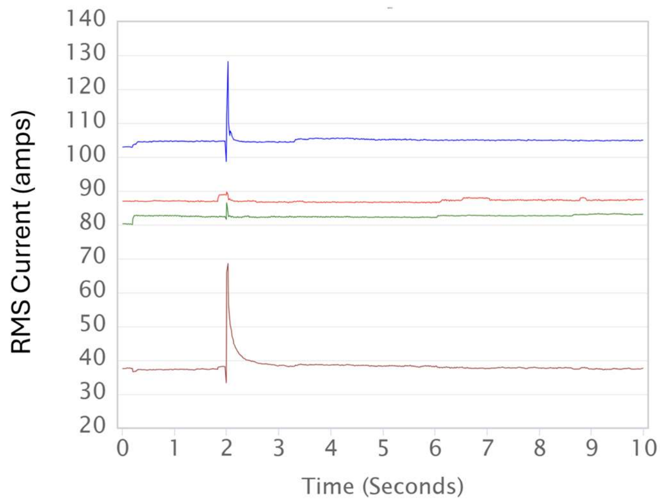

Fig. 4: RMS signals from incipient failure of voltage regulator contacts.

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. While the actual fault itself may have low or near-zero impedance on the low voltage side, particularly for faults occurring on 240V split-phase service in North American systems, the fault as observed from the primary substation is impedance limited by the transformer and secondary cabling. 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, depending on the ratio of the service transformer. Secondary faults at larger facilities (e.g., industrial facilities served by a 1,000 or 2,000 kVA transformer) have been documented to produce hundreds of amperes of primary fault current, sometimes with significant arc-like behavior. In cases where a large customer is connected to the medium voltage circuit through a transformer with a grounded-wye primary connection, major arc flash events on the low-voltage secondary bus can produce substantial $3I_0$ levels on the primary feeder which, depending on the arc impedance characteristics could reasonably resemble zero-sequence currents produced during a primary "high-impedance" fault. For larger facilities, if secondary protection (i.e., at the customer's service entrance) fails and the low-voltage fault persists long enough, primary protection at the transformer, generally fuses in a North American context, can operate. In many cases, however, these faults will clear without the operation of medium-voltage protection, either because low-voltage protection operated, or because enough physical damage occurred to destroy apparatus and deenergize the fault.

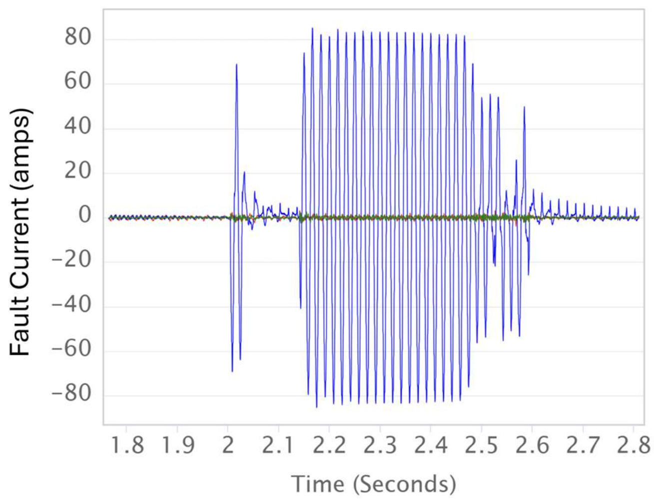

Fig. 5: A "high-impedance" fault believed to be a low-impedance fault on the secondary side of a customer transformer.

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). These "shunt arcing" events are frequently observed, in some cases many times a week on a substantial percentage North American distribution circuits but seldom appear to increase in severity or result in any identifiable outage or damage from the utility company's perspective.

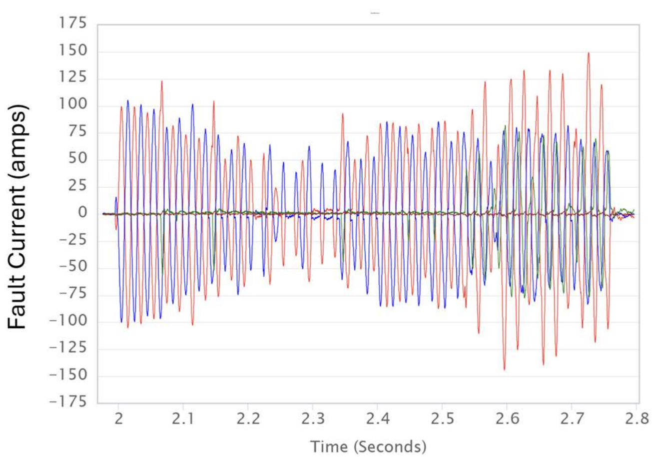

Fig. 6: Low-voltage (230/400Y) fault recorded from the medium voltage system

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 an 11 kV circuit serving a 230/400 V 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. Multiple cases have been documented where arcing faults on secondary networks caused recloser operations on 11 kV primary feeders serving the network.

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.

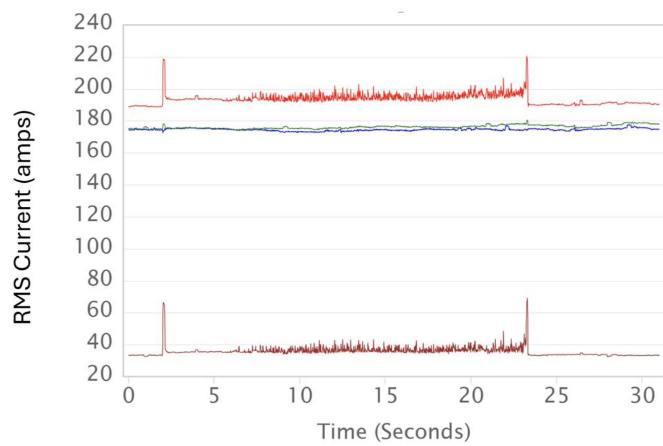

Fig. 7: Is this signature a downed conductor or an arc welder?

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. Absent testing, it cannot be definitively known whether any particular downed-conductor detection method operating on the medium-voltage system would falsely detect this signature as an energized downed conductor. But the large overlap between certain characteristics of this intentional, "normal" signature and field-recordings of energized downed conductors makes that a possibility any algorithm designer of methods applied to four-wire multi-grounded systems should consider.

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-six 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 (completely self-protected) transformer clearing the fault, but only after 30 minutes of intermittent fault behavior. As with the previous case, one cannot say with confidence how downed-conductor detection methods would perform on these types of events, but many of their electrical characteristics share important features.

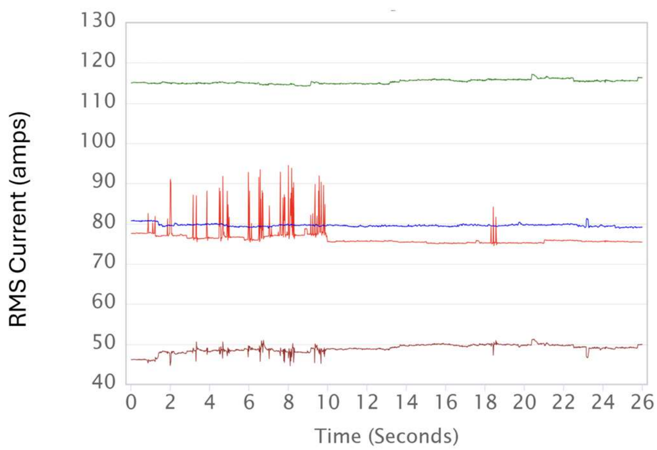

Fig. 8: Twenty-six seconds of RMS current resulting from a fire in customer's secondary service.

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

1) Cable termination and splice failures

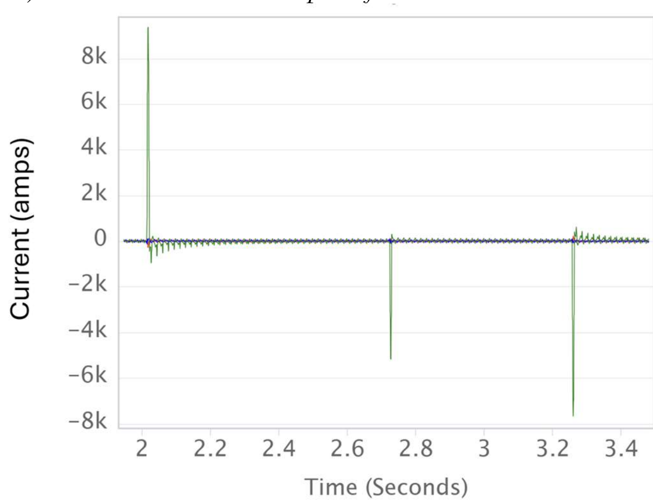

Figure 9: three pulses from an incipient cable fitting failure.

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 thousands of amperes.

Figure 9 shows a single instance of an incipient cable termination failure near a 12 kV distribution substation where three 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 6,500 amperes of bolted available line-to-ground fault current. A second important observation about these events is that they fail to operate system protection (in this case, the substation circuit breaker) 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 [24]. 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. Typical load on the circuit is approximately 50 amperes.

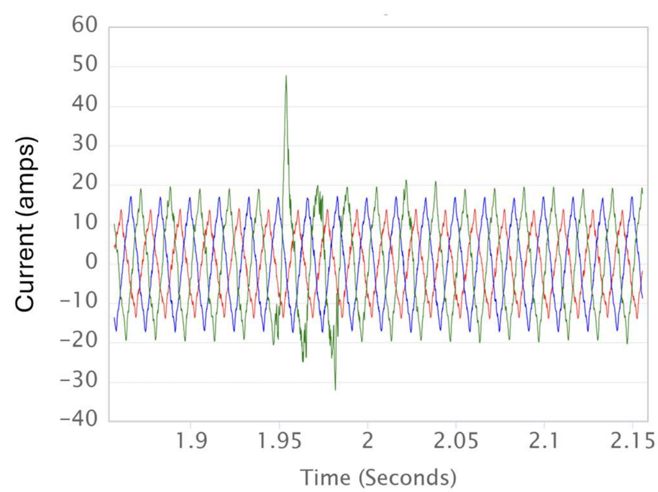

Fig. 10: Early-stage failure associated with lightning arrester

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.

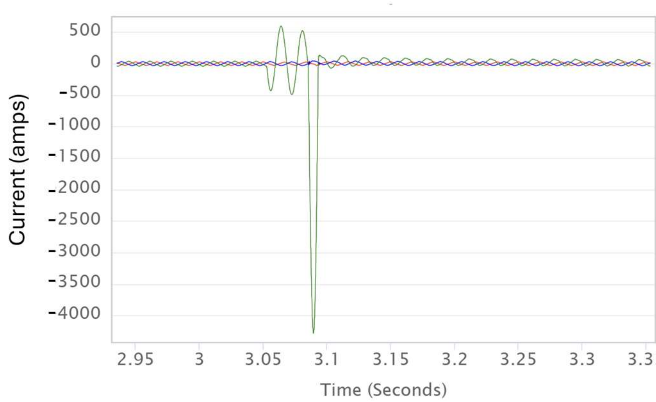

Fig. 11: Failure of the same lightning arrester (from Fig. 10) captured 9 hours later.

VI. 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 therefore often creates misunderstandings where two engineers believe they are talking about the same thing, but where each has distinct and different ideas in mind. 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. Algorithm designers should take care to understand the nuances of the variety of events which might produce signatures which could cause their designs to false trip. Approaches which group all such faults together without recognizing their distinctive character are doomed to failure.

Additionally, customers seeking "high-impedance fault detection" technology should ask vendors precisely what is meant by that term. If the vendor cannot answer, or does not understand the question, that might signal the need for additional follow-up questions regarding the effectiveness of the proposed technology.

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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VIII. Biographies

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