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Fault Diagnosis for Electrical Systems and Power Networks: A Review

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***Abstract*—In this paper, we review the state of the art in the detection, location, and diagnosis of faults in electrical wiring interconnection systems (EWIS) including in the electric power grid and vehicles and machines. Most electrical test methods rely on measurements of either currents and voltages or on high frequency reflections from impedance discontinuities. Of these high frequency test methods, we review phasor, travelling wave and reflectometry methods. The reflectometry methods summarized include time domain reflectometry (TDR), sequence time domain reflectometry (STDR), spread spectrum time domain reflectometry (SSTDR), orthogonal multi-tone reflectometry (OMTDR), noise domain reflectometry (NDR), chaos time domain reflectometry (CTDR), binary time domain reflectometry (BTDR), frequency domain reflectometry (FDR), multicarrier reflectometry (MCR), and time-frequency domain reflectometry (TFDR). All of these reflectometry methods result in complex data sets (reflectometry signatures) that are the result of reflections in the time/frequency/spatial domains. Automated analysis techniques are needed to detect, locate, and diagnose the fault including genetic algorithm (GA), neural networks (NN), particle swarm optimization, teaching–learning-based optimization, backtracking search optimization, inverse scattering, and iterative approaches. We summarize several of these methods including electromagnetic time-reversal (TR) and the matched-pulse (MP) approach. We also discuss the issue of soft faults (small impedance changes) and methods to augment their signatures, and the challenges of branched networks. We also suggest directions for future research and development.**

***Index Terms*—fault detection, fault, diagnosis, fault location, fault tolerance, frequency domain analysis, inverse problems, power networks, reflectometry, time domain analysis, transmission lines, wiring**

I. Introduction

ELECTRICAL wiring interconnection systems (EWIS) are ubiquitous everywhere the transfer of power and information is needed. Electrical machines and instruments are more complex than ever before, often with miles of wiring carrying data, power and control signals. Yet faults and failures in these systems are inevitable and can lead to catastrophic safety and economic problems. Fault detection, diagnosis and location are essential for ensuring safety, security, integrity and optimal performance in wiring systems in buildings, communication networks, power generation and distribution systems, vehicles (aircraft, trains, cars, etc.) and other types of moving machines. Electrical fault diagnosis could also be used for structural health monitoring of concrete anchors in dams, bridges, and other structures and long metallic structures such as oil and gas pipelines.

Sensors for non-destructive detection, diagnosis, and location of faults in electrical systems include circuit breakers (including ground and arc fault interrupters), voltage, current, and power sensors, and several types of reflectometry. Although many of these sensors are used for diagnosis after a fault has occurred and the system is down for maintenance, there is more and more demand for prognostic methods that can predict and locate faults in advance while the system is fully operational. Intelligent sensors combine and analyze the data, often from multiple sensors, to create a picture of the system's condition and detect, locate, and diagnose faults. Analysis tools are essential, and there is an ever-increasing demand for real-time analysis algorithms. This Special Issue of the IEEE Sensors Journal highlights advances in technologies for continuous health monitoring of electrical systems, which is one of the emerging advances and opportunities in sensors today.

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II. Emerging Health Monitoring Applications

Conditional health monitoring is emerging in many different applications where electrical health is essential for safe and effective operation such as the electric power grid and vehicles and machines, for which we give an overview in this section.

A. Electrical Machines

Failure modes in electrical machines include insulation failure in the stator or rotor windings, brush gear failure, slip ring failure, and mechanical modes such as bearing failure or stator/rotor mechanical integrity failure [1], [2], [3]. Condition monitoring based on visual inspection, current signal measurement, vibration monitoring, wear debris monitoring, acoustic measurements, and thermal monitoring that can minimize the downtime and increase the efficiency of the system has been extensively studied since the 1920's [4], [5]. For example, practical sensors to detect rotor failure [6] without having rotor-based sensors include analysis of the stator current (e.g., [7], [8]) with signal processing methods (e.g., [9], [10]) or artificial intelligence techniques (e.g., [11], [12]). Electrical faults in stator windings can be detected by measuring axial leakage flux and stray flux [13] or extracting features from the stator current signals to detect faults (e.g., [14], [15]).

B. Electric Power Grid

Transmission and distribution lines are the backbones of power systems in both remote and urban areas. These lines are prone to short-circuit faults due to faulty equipment, human error, vehicle accidents, falling trees, wind, and storms. In transmission networks, these faults can cause problems with damage to equipment, stability of the network, and severe cascading consequences. For power distribution lines the two largest issues are bushfires ignited by power line faults and power outages. Bushfires are a continual threat in many places (e.g. California, Australia, and Spain), and particularly in extended hot and dry weather conditions. Faults in electrical distribution networks have been one of the primary sources of major bushfires. Power line related faults cause 2-4% of all rural fires in Australia [16]. However, when weather conditions elevate fire risk, up to 50% of major fires are ignited by faults in distribution networks [16]. Rapid fault current limiters (REFCL) deployed in the distribution network limit the energy of the fault and reduce its ability to start a fire. However, since REFCLs greatly limit the fault current, this makes it more difficult to locate the fault. Fault location is even more challenging in distribution grids than in the transmission grid due to the presence of distributed energy resources (DERs) that inhibit existing fault location procedures, dissymmetry and unbalanced load conditions between phases of power lines, and superposition of the load and fault currents that change during the fault, and more.

Fault location problems in power lines have been investigated since the 1950s [17], and numerous fault location methods have been proposed. These can be classified into two main categories [18], [19]: phasor-based (frequency domain) methods, and travelling wave-based (time-domain) methods.

1) *Phasor-based fault location methods*

A straightforward approach to locate a fault in a network is to calculate the impedance (measured using the ratio of the measured voltage to current on the line) and use this to determine the fault location. Depending on the availability of measurement access points, phasor-based methods can be further classified into the following sub-categories: (i) single-end (one-terminal) measurement methods (e.g., [20], [21], [22], [23]), (ii) double-end (two-terminal) measurement methods (e.g., [24], [25], [26], [27]), and (iii) multi-end methods (e.g., [28], [29], [30], [31], [32]) that employ measurements from multiple ends of multi-terminal transmission lines. Double-end and multi-end measurement-based fault location methods can be based on either unsynchronized (e.g., [33], [34], [35], [36]), synchronized (e.g., [37], [38], [39]) or a hybrid of synchronized/unsynchronized (e.g., [32]) voltage/current measurements. The accuracy of the phasor-based fault location methods can be affected by the fault resistance and pre-fault conditions such as system load flow, and the presence of DERs [19]. Multi-end measurement-based methods can eliminate the effect of the fault resistance and other parameters that affect the measurements, and therefore minimize the fault location estimation error. However, these methods require efficient communication links which add non-negligible complexity to the system.

2) *Travelling wave-based methods*

Travelling wave (TW) based methods consider the voltage (and/or current) waves, which are travelling at the line propagation speed from the fault location towards the line terminals. Compared to phasor-based fault location methods, travelling wave-based methods are considered to be more precise and offer some advantages (e.g., [40], [41], [42], [43]) and are considered to be the best way to locate faults in DC transmission systems (e.g., [44]). These methods rely on the analysis of high-frequency components of the transient signals caused by the fault, which are relatively independent of the fault impedance [45]. Single or multiple measurement points may be used. Analyzing travelling wave data generally requires complex signal processing techniques (e.g. [18], [45], [46]).

The methods based on time of arrival identify the fault location by assessing the arrival time of the travelling waves at one (single-end) or different terminals of the line (multi-end) [47]. In single-end methods, the fault location is identified by assessing the time delay between successive reflections of the measured travelling wave signals at one terminal (e.g., [47], [48]). Single-end methods are simpler and less expensive than multi-end measurements, which require synchronization and communication links. However, the multiple measurements of multi-end systems generally make them more accurate, and the need for accurate line parameters can be eliminated (e.g. [49]).

TW-based fault location methods are generally more accurate than phasor based methods. However, their accuracy can be influenced by factors such as the uncertainties of the time synchronization between multiple observation points, reliability of the communication channels, and the sampling rate of the data acquisition system. Several time-reversal methods can be used to analyze TW measurements:

a) Electromagnetic Time-Reversal (EMTR) method

The electromagnetic time-reversal (EMTR) method [50] relies on the time-reversal (TR) invariance of the travelling wave equations in transmission lines and the closed reflective characteristic of the propagation medium in power networks. The EMTR technique requires only one measurement point for complex inhomogeneous networks and does not need time-synchronized measurements. Its performance is also robust against errors in measurement, fault impedance, and the topology of the network [51], [52], [53], [54]. The method comprises three steps:

Step 1: Fault-originated transient signals are measured at a single measurement point.
Step 2: For each candidate fault location (CFL), a computational model is created with a fault at that location, and the *time-reversed* measured signal is injected to the network model from the measurement point.
Step 3: For each CFL, the Fault Current Signal Energy (FCSE), (the energy of the current flowing through the fault at the CFL) is calculated. By TR theory, the back-propagated signals will focus at the source point, producing an energy peak there. The accuracy of the EMTR method has been validated through experimental setup [50], a full-scale experiment in un-energized overhead distribution lines [55], and on an energized medium voltage feeder [51].

Different studies have investigated various techniques to differentiate the true fault location in the EMTR process. In [56], it was shown that the ∞-norm can provide better accuracy than the FCSE metric in noisy environments. Potential ambiguities introduced by the FCSE metric can potentially be overcome by local normalization methods [57]. Another alternative is the Maximum Cross-Correlation Sequence metric [58]. Further research is needed to explore improved metrics to locate very high impedance faults in power networks as well as the possibility of locating partial discharges due to transmission line faults or contaminated power line insulators.

b) Fast Time-Reversal (FasTR) method

The EMTR approach has shown good results in giving a precise location of elusive faults in medium voltage (MV) networks. However, when dealing with larger networks, particularly those with very long cables, small reflections from the extremities of the network may be missed. Loads added to the extremities can ensure the occurrence of multiple reflections from these points and thus enable better network coverage of the EMTR method. The fast time-reversal (FasTR) method [59] was proposed to extend the scale EMTR by placing sensors for continuous monitoring on well-chosen nodes of the network. By using an accurate shared time synchronization system between sensors, transient signals can be recorded with precision and then processed on-the-fly with the FasTR algorithm.

The FasTR method is a variation of classical TR which enables faster fault localization with limited computing resources and minimal required knowledge of the network. It uses recorded signals from sensors placed at several strategic points in the network, calculates their time-reversed version and estimates a function representative of the energy propagated in the network. But rather than calculating this for a highly refined mesh (in time and distance) the signal is calculated for only one point in the network. Thanks to optimization-based algorithms, the FasTR method finds the position of maximum energy (the position of the fault) in a few steps [59]. This method was demonstrated on a 2.5 km MV network [59], demonstrating the capacity of FasTR as a portable system to detect transient faults in complex energized networks.

C. Vehicles and Machines

All wiring systems degrade over their lifespan due to chemical, thermal and mechanical stresses and additional damage due to use and maintenance [60], [61]. Wiring in aircraft and other vibrating machinery used in highly corrosive environments ages even more quickly [62]. Aging aircraft gained the public eye with the crashes of TWA 800 (1996) and SwissAir 111 (1998), both attributed to faults in the wiring [63], and numerous other events have been reported [64]. The U.S. Navy reported 1,101 mission aborts / year (401 in-flight aborts), an average of two in-flight fires/month, and during a 10 year period, six aircraft were lost due to electrical failure [65]. In addition to the safety problem, aircraft wiring systems are a maintenance burden. In the U.S. Navy, 7.3 maintenance hour/flight hour were expended due to wiring systems, with the information known to be underreported [65]. Replacement of a complete wiring system is estimated to cost $1-7 million (2003 USD), depending on the aircraft [66]. Even nearly new aircraft have wiring problems. In [67], it was reported that over 90% of U.S. Navy P-3 aircraft had experienced wiring problems in their first 5 years. Faults in aircraft include a wide variety of open and short circuits, solid and intermittent faults, arcs and chafing, as shown in Table I [68]. In addition to aging and natural degradation (which would be relatively predictable, if you knew the environmental history of the wire [67]), they can be caused by far less predictable human error such as out of specification installation and damage during maintenance. Thus, a combination of methods that include lifespan review and regular inspection should be coupled with sensors that detect and locate faults.

TABLE I
PREVALENCE OF DIFFERENT TYPES OF FAULTS ON U.S. NAVY AIRCRAFT. FROM [68].

Fault	
Chafed wire insulation leading to short circuit and/or arcing	31%
Broken wire	11%
Connector failure	9%
Miswire	8%
Failure due to corrosion	7%
Short circuit unspecified cause (includes arcing incidents)	3%
Insulation failure	3%
Loose connection	2%
Short due to corrosion	1%
Other	19%

Not surprisingly, after the TWA800 and Swissair 111 disasters, numerous programs were devoted to developing methods for locating aircraft wiring faults [69]. Visual inspection, the most common traditional method, was determined to be insufficient (most wiring faults are hidden from view), though it remains heavily used.

D. Structural health monitoring

Structural health monitoring (SHM) is a rapidly growing area for sensor development [70], [71], with demand particularly high for wireless sensors that can be deployed on existing aging structures [72]. SHM is applied to all types of civil structures (buildings, bridges, tunnels, pipelines, roadways and railways, etc.) as well as the structural components of vehicles (aircraft, trains [73], ships, etc.). and machinery (wind turbines [74], rotors, motors, cranes, etc.). Evaluation of composite materials (both at inception and as they age) is of particular interest in many applications [75]. Use of optical fiber sensors and mechanical sensors (e.g. vibration [75], [76] and strain sensors) are prevalent [77], [78]. Guided waves have been used as well [79]. Electrical sensors (e.g. reflectometry) are limited by the extensive interconnection of metallic components found in most structures [80]. These structural interconnections create electrical networks (with numerous electrical junctions) that are difficult to evaluate electrically, as described in Section IV.C.

SHM sensors that can be added to the structure but remain independent of it are easier to implement than sensors that must be built into a new structure. Optical sensors have gained particular popularity because of their durability, low cost, and flexibility. Optical time domain reflectometry (OTDR) is typically used to query these sensors, which can evaluate where the fiber is broken (potentially caused by a crack in the structure), where the strain or heat is too high, etc. [77], [78].

Low cost systems that can dependably find localized faults before they cause catastrophic failure are still the topic of extensive research and development today. Wireless sensors are of particular interest [72]. Structural sensors often produce very large scale datasets from multiple points on a structure, taken longitudinally over time. The failure characteristics may be non-linear [81]. Evaluation and interpretation of SHM data provides many rich and challenging research questions.

III. Sensors for Electrical Fault Detection, Location, and Diagnosis

Sensors for electrical health monitoring perform three major functions. Detection determines that a fault exists or is developing and is often used to shut down an electrical system to prevent hazard or damage and trigger a maintenance call. Maintainers need to locate the fault in order to repair it. Diagnosis is one step beyond detection. Diagnosis and location together are essential for prognostic application of sensor technologies. Diagnosing the extent of the fault can help determine that a fault is developing but is not yet serious enough to compromise the system, or it may tell what kind of fault is present, and even perhaps what caused it. In this section, we describe the many different types of sensors used for detecting, locating, and diagnosing electrical faults, their relative strengths and weaknesses and opportunities for further development.

A. Voltage, Current, and Power Sensing

Voltage, current, and/or power sensing are often used to detect that a fault exists and to trip (open up) to protect the circuit and equipment it is attached to. Circuit breakers and other circuit protection devices rely on a combination of these modalities. Many types of breakers now exist including those specifically designed to identify arc and ground faults.

Arc fault circuit breakers (AFCB) or interrupters (AFCI) detect intermittent electrical short circuits (arcs) that create a short duration, noise-like current surge. Arc faults have been implicated in house fires and aircraft crashes [69]. Parallel dry arcs are caused by wires vibrating together or against a metallic object. Series dry arcs can be caused by connectors or other interconnection components pulling apart. Wet arcs (series or parallel) are caused by water bridging electrical components, causing an unintended current path. All of these types of arcs cause surges of current [82]. Traditional circuit breakers often do not trip on arc faults, because although their current may be large, it is short in duration, and therefore the total energy experienced by the breaker may be too small to trip a heat-sensitive element or maximum current detector [83]. Sophisticated algorithms in AFCB/I are used to determine when the current is caused by an arc fault without tripping on normal noise in the system (e.g. switching noise) [84].

B. Electrical Reflectometry

Reflectometry methods are often used for finding faults in electrical systems [85]. A high frequency electrical signal ($V_{incident}$) is sent down the wire, where it reflects ($V_{reflected}$) from impedance discontinuities and returns to the tester. The voltage reflection coefficient gives a measure of this reflection:

$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_O}{Z_L + Z_O} \quad (1)$$

where *Zo* is the characteristic impedance of the transmission line, and Z_L is the impedance of the discontinuity (such as a fault). The reflection coefficient for an open circuit ($Z_L = \infty$) is 1 (all of the voltage is reflected in phase), and the reflection coefficient for a short circuit ($Z_L = 0$) is -1 (all of the voltage is reflected out of phase). The distance to the fault is found by multiplying the measured time delay between the incident and reflected signals by the velocity of propagation (*VOP* is typically about 2/3 the speed of light for most wire types). This means that both the *VOP* and *Zo* must be well-known in order to properly locate and diagnose the fault. These values depend on the transmission line, and if the line is not shielded, its nearby environment. The larger the reflection coefficient, the easier it is to pull the fault reflectometry signature out of the noise. Hard faults (open and short circuits that create large impedance changes on the wire) on low-loss systems are typically observable by reflectometry, but soft faults (damaged insulation, etc. that create only small impedance changes on the wire) are generally not [86]. This is particularly true when normal impedance variation in the system produces reflections that exceed those from the small faults. Smaller faults can be found on systems that are impedance controlled such as shielded coaxial cables [87] and structural dams [80], than on systems of uncontrolled impedance cables (such as unshielded cables, vibrating vehicles and machinery, etc.) [86].

There are numerous types of reflectometry, using various incident test signals and methods of evaluation. We will describe several of these methods in this section, followed by an assessment of the overall considerations for accuracy in sub-section 10).

1) *Time Domain Reflectometry (TDR)*

Time domain reflectometry (TDR) uses a short rise time voltage step or pulse as the incident signal. For loads that are not frequency dispersive such as open, short, and resistive loads, the reflected voltages are also step functions. The TDR response of a branched wire network is shown in Fig. 1, along with responses from other reflectometry methods. Steps in the response indicate reflections returned to the test point. The source of each reflection is marked on the figure. The TDR100 [88] used for the test shown in Fig. 1 generates a step function with a 14 µs rise time and samples the reflected wave at 12.2 ps intervals [88]. The expected accuracy is 0.24 cm, for a cable with VOP = 2/3 the speed of light. Similar results using a pulsed TDR are given in [89].

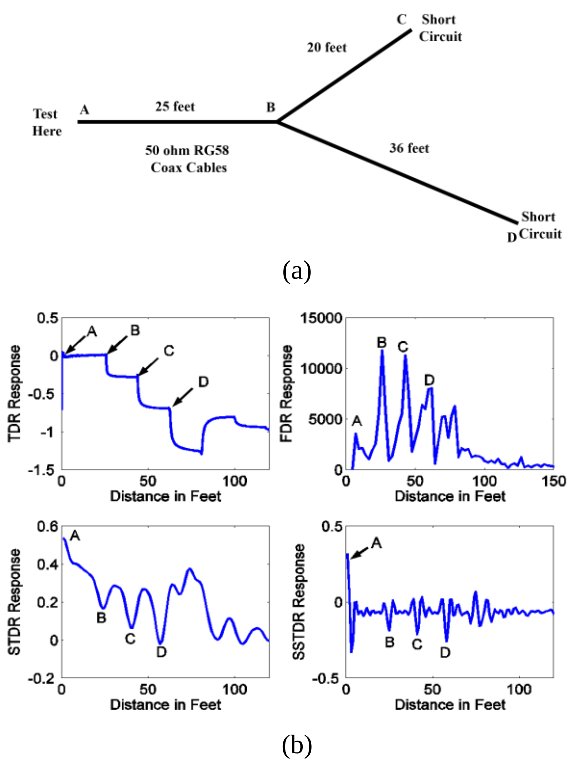

Fig. 1. (a) A network of RG-58 cables and (b) their measured responses using TDR, FDR, STDR, and SSTDR. From **[85].**

TDR is often used for electrical diagnosis, however, like all reflectometry methods, its practical use may be limited by the complexity of analyzing its reflections [69]. One challenge can be seen in Fig. 1, where the broad frequency voltage step experiences frequency dispersion (spreading out) as it goes down the cable. This makes it difficult to read the location of the reflections, and would limit the system's ability to read small reflections. This problem is seen in all other reflectometry methods, and underscores the need for smart, automated algorithms for system analysis, as described in Section IV.

2) *Sequence (STDR) and Spread Spectrum Time Domain Reflectometry (SSTDR)*

Sequence Time Domain Reflectometry (STDR) uses a pseudo noise (PN) code as the test signal, and Spread Spectrum Time Domain Reflectometry (SSTDR) uses a PN code modulated by a sine or square wave [90]. The reflected signal is correlated with the incident signal using either analog or digital hardware to produce the reflection response, such as the SSTDR response to a resistor at the end of a cable, shown in Fig. 2. The magnitude of the reflection response is proportional to the reflection coefficient in (1) for frequency-independent loads (open, short, resistor), and the delay is proportional to the distance to the fault. For frequency-dependent loads (e.g. capacitors, inductors), both the shape and magnitude of the signal change, as shown in Fig. 3. Specialized algorithms are needed to diagnose and locate changes involving frequency-dependent impedances [91]. For networks of cables or other systems with multiple reflections, the reflections can superimpose as shown in Fig. 1(b) for STDR and SSTDR.

STDR and SSTDR can be used on live (energized) electrical systems. The incident signal can be very small compared with existing signals on the wire and can be utilized well below the noise floor of the system, enabling detection and location of intermittent faults that occur while the system is operational [92]. The test system can be directly connected (embedded in the system itself) or coupled capacitively or inductively [93], [94]. SSTDR has been used for measurement of real and complex impedances [95], very small changes in impedance [80], and precise fault location [90], [96], even on intermittent (time-varying) arc faults [92], [97] and ground faults [98]. It has been used in a variety of applications including aircraft [90], [92], rail [99], structural health monitoring [80], electronics [100], [101] and photovoltaic (PV) arrays [102]. For PV systems, SSTDR has been evaluated to detect and in some cases locate ground faults [103], arc faults [104], disconnection faults [105], accelerated degradation [106], and broken panels [107]. The feasibility of using SSTDR to detect and locate faults for PV is summarized in Table II [102], [106].

SSTDR fault detection is independent of fault current levels [108], and it can be used on live, energized systems to detect and locate faults [109]. It generally will require a baseline from a known-good system for assessment [110], and it is more complex and less accurate on parallel branched circuits [111], which are common in PV systems. Adjusting the parameters can optimize bandwidth [96], signal to noise ratio [80], or measurement time [92]. It has been implemented as a chip [112], [113] and as a handheld or embedded instrumentation [114].

3) *Orthogonal Multi-Tone Time Domain Reflectometry (OMTDR)*

Orthogonal multi-tone time domain reflectometry (OMTDR) enables not only online diagnosis but also data communication

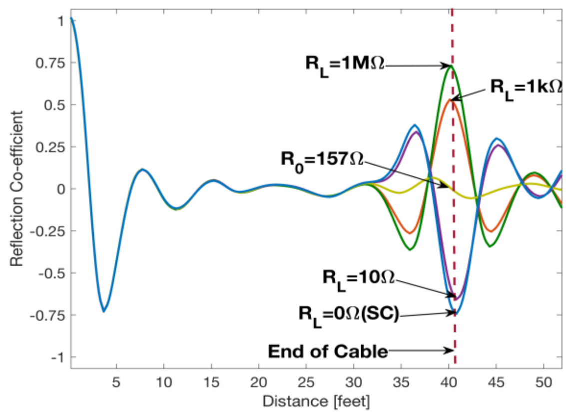

Fig. 2. SSTDR response of different resistors connected at the end of the 40-foot PV cable. The dashed red line in the figure denotes the end of the cable. From **[95]**.

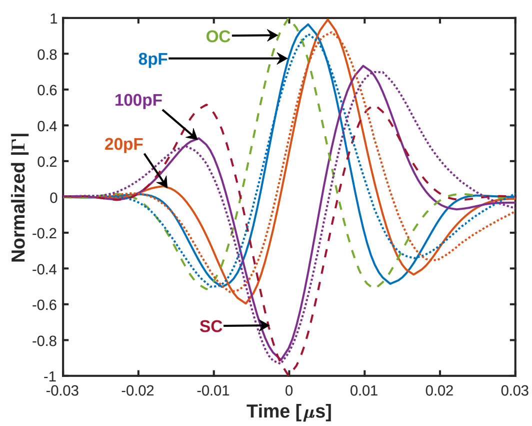

Fig. 3. SSTDR response of different capacitors connected at the end of a PV cable. From **[95]**.

TABLE II

OVERVIEW OF THE SSTDR TECHNIQUE FOR FAULT DETECTION AND LOCATION. A "D" OR "L" INDICATE THE METHOD HAS BEEN DEMONSTRATED FOR DETECTION OR LOCATION, RESPECTIVELY. A * MEANS IT IS FEASIBLE THAT THE METHOD COULD BE USED, BUT IT HAS NOT BEEN DEMONSTRATED. FROM [106].

Fault	Detection (D) Location (L) * = feasible	Ref.
Open/Short Circuit	D,L	[110]
Connection Fault	D,L	[110]
Ground Fault	D, L*	[115] [103]
Arc Fault	D,L*	[104]
Shading Fault	D,L*	[107]
Bypass Diode Fault	D*,L*	
Broken Panel	D*,L*	[107]
Accelerated Degradation	D,L*	[106]

in complex wiring networks [92], [93]. It has been demonstrated for detecting and locating hard faults (open and short circuits) [118], [119], soft faults (shielding damage) [120], and intermittent arcing [120] in a controlled laboratory setting.

OMTDR is based on the principle of orthogonal frequency division multiplexing (OFDM), widely used in advanced wireless communication systems. The OMTDR divides the total bandwidth B into several sub-bands using orthogonal and then overlapped sub-carriers to increase the spectral efficiency and reduce interference. The sub-carriers are distributed with respect to Hermitian symmetry in order to generate the signal to be injected into the cable under test (CUT) [118]. Interference with sub-bands already in use by the system can be reduced by leaving them out of the OMTDR signal.

After binary data generation, M-phase shift keying (M-PSK) digital modulation is performed to set the phase of each sub-carrier where M is the PSK order (4 for Q-PSK, 8 for 8-PSK, etc.). Each sub-carrier S_k is defined as:

$$|S_k| = 1\ \forall f_n \text{ and } \phi(k) = \phi_n = i\frac{2\pi}{M},$$

where i is between 0 and $M-1$. An inverse fast-Fourier transform (IFFT) is employed to convert the modulated sub-carriers into the time domain, where the resulting signal is named s_n. Then, a digital-to-analog converter (DAC) is used to convert s_n into the signal $s(t)$ that will be injected into the CUT. When the reflected signal $r(t)$ returns to the test point, it is sampled by the analog-to-digital converter (ADC) to generate the reflected digital signal, r_n. A cross-correlation function is performed between the injected signal s_n and the reflection r_n to obtain the corresponding reflectogram. A simplified model of an OMTDR system for wire diagnosis is shown in Fig. 4.

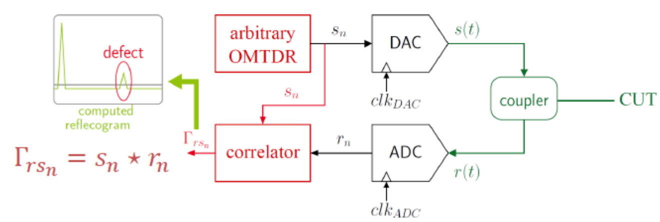

Fig. 4. Schematic diagram of wiring diagnosis based on OMTDR technology. From [111].

In complex wiring networks, conventional reflectometry techniques may suffer from ambiguity related to the fault position and signal attenuation [117] (see also Section IV.C). As a solution, distributed reflectometry has been proposed where multiple reflectometry-based sensors are implemented at various points of the target network. In this context, the OMTDR may serve as both the sensor as well as providing communication for data sharing between multiple sensors [116] using a sensor/slave communication protocol [119].

For communication, the whole reflectogram composed of N points must be decomposed on NQ bits, where Q is the quantification of each point of the reflectogram. These bits are grouped on M frames that are digitally treated by the transmitter shown in Fig. 5. They are sent one after the other to the binary block-chain. The first binary function is a cyclic redundancy check (CRC), which provides a verification utility for message integrity test. After that, the bits are scrambled in order to give a uniform power to the sent data. Hamming encoding is performed at the end of the chain. This is followed by the application of a bit interleaving procedure to increase the binary correction capacity. The remaining part of the transmitter is composed of the same OMTDR blocks, shown in Fig. 5, for performing reflectometry.

On the receiver side, each frame is transformed into the frequency domain by applying an FFT function. The frequency domain signal is equalized by compensating the phase-shift and the attenuation of each sub-carrier. The received bits are extracted from the set of sub-carriers by *M*-PSK de-mapping. After that, bit de-interleaving is applied, followed by a Hamming code error correction and a bit de-scrambling. Finally, a CRC block allows the receiver to determine if the data contains binary errors or not. The sensor fusion increases the diagnosis coverage, avoids the blind zone typically seen at the start of reflectometry data (see sub-section 10) and locates defects in complex wiring networks [110].

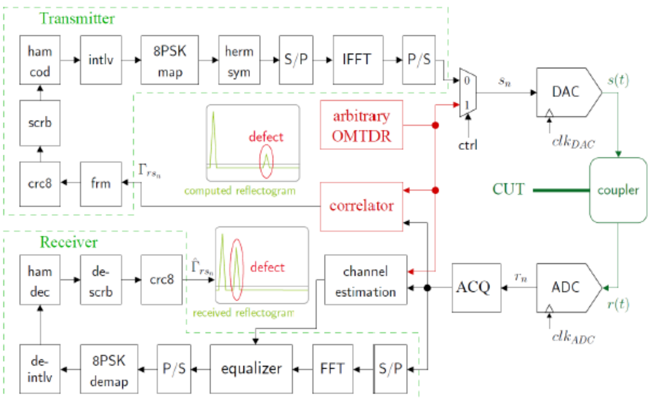

Fig. 5. A schematic diagram of sensor communication based on OMTDR technology. From [113].

4) *Noise Domain Reflectometry (NDR)*

Noise Domain Reflectometry (NDR) [121] uses existing data and/or noise signals already present in the system as the incident signals and does not need to inject any additional signals. This ability to detect faults non-intrusively makes NDR ideal for applications where data integrity is critical or where stealth is desired. Like other reflectometry approaches, the bandwidth of the noise either existing or injected in the system controls the accuracy of the results.

Analogous to STDR and SSTDR, NDR utilizes autocorrelation between the incident and reflected signals to produce a reflection signature for the system where peaks indicate the location of reflections. There are two types of NDR implementation, Type I (where incident and reflected signals are separated, as shown in Fig. 6) and Type II (where they are superimposed, as shown in Fig. 7). Because NDR Type II does not need the directional coupler to separate the signals, it is smaller and less expensive, and the bandwidth of operation is not limited by a directional coupler. Other types of correlators could be used, as well, including an implementation where the electrical signal is converted to an optical signal, and an optical correlator is used [122].

The peaks of the correlation functions indicate the location and nature of the impedance discontinuities, as shown in Fig. 8 for NDR Type II using a 50 MHz BPSK test signal sampled with a GHz oscilloscope and integrated over 131,000 points. The magnitude of the impedance discontinuity, which controls the reflection coefficient (1) also controls the magnitude of the correlation peaks. This is shown in Fig. 8 for short circuits, 20, 50, 100, 1000 Ω resistive loads and open circuits on RG58 (50 Ω) coaxial cable. Attenuation is also apparent. The location of the peaks indicates the distance to the fault, as shown in the inset of Fig. 8 for an open circuited (cut) wire (18 gauge paired wire -- Carol 02301.R5.02 18/2 spt 1).

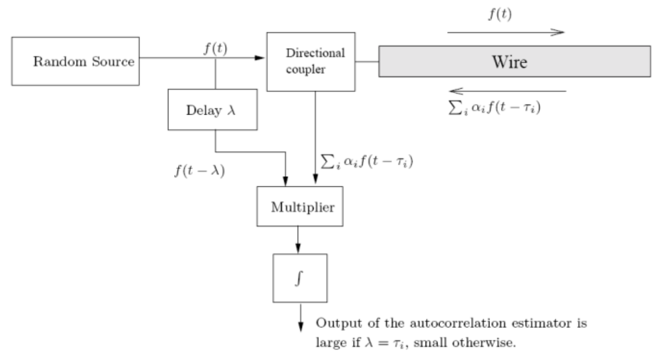

Fig. 6. NDR Type I Block Diagram. From **[121]**.

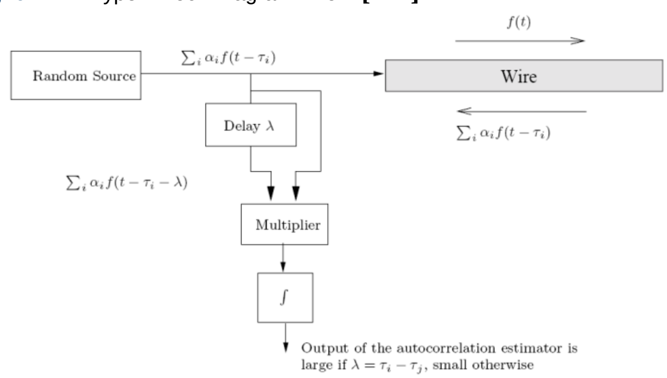

Fig. 7. NDR Type II Block Diagram. From **[121]**.

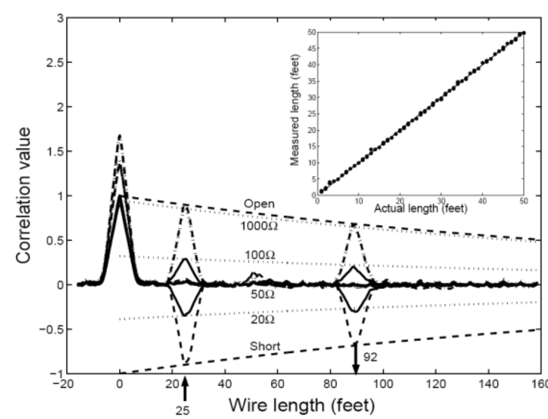

Fig. 8. Measured correlation of NDR Type II for 25 and 92 foot RG-58 (50 Ω) wires with resistive terminations. The inset shows the measured vs. actual length measured using an open circuited 18-gauge paired wire. This shows excellent linearity between the peak location and wire lengths. From [121].

5) *Chaos Time Domain Reflectometry (CTDR)*

Chaos Time Domain Reflectometry (CTDR) is a spread-spectrum reflectometry method using pseudo-random signals generated by a chaotic process [123], [124]. The signal generation procedure in [125] takes advantage of the combined use of a chaotic Bernoulli process and a logistic map [123] to increase the signal's robustness to sampling. This feature also increases the diversity of the signals that can be generated, enabling a virtually infinite number of uncorrelated signals to be used concurrently by several reflectometers on a single complex network without interference between them (such as for distributed diagnosis) or with the system being tested (provided the combined CTDR signals are kept below its noise margin) [126].

CTDR reduces the correlation side lobes, which is an advantage for the detection of soft defects. It was shown in [126] that the secondary lobes and maximum cross-correlation levels without noise are roughly equal to $L = -7\log10(N)$ where N is the number of samples in the signal. 20000 samples will show −30 dB maximum cross-correlation, thus enabling the detection of very low amplitude reflections. For higher secondary lobe rejection levels, it is possible to combine CTDR with circular signals [127], to reach more than 300 dB rejection.

CTDR provides a powerful tool for the detection and characterization of very short duration intermittent faults (IF) that can indicate degradation of a system and increase over time, leading to permanent faults [128]. CTDR enables the detection and location of IFs lasting a few microseconds and gives an estimate of their time of appearance and duration. This is done with the continuous CTDR method (CCTDR), which uses a moving window for the correlation computation, and the short-time normalized reflectogram to follow the evolution of the correlation in time.

6) *Binary Time Domain Reflectometry (BTDR)*

The CTDR can be implemented in a purely digital way called the binary TDR (BTDR) method, eliminating the need for DACs and ADCs and providing a simpler, lower cost test system that is not limited by the sampling rates of the ADC/DACs. BTDR can reach 1 GHz for modern FPGAs [129]. Using an accelerated digital correlation computation process which takes advantage of the CCTDR principle enables the design of a completely embedded real-time reflectometry system.

A recent development of BTDR [130] based on the addition of an equalizing device at the interface of the cable forces phase cancellation of the input and end peaks and thus amplifies small reflections that may enable the detection of small defects for predictive maintenance. The method uses phase opposition to cancel the reflections from the interface to the reflectometry and the load and saturates the amplitudes of the remaining peaks. A low complexity balancing device, made of two controllable digital potentiometers, is added at the cable's interface to meet this requirement. Simulations have shown the possibility of detecting a 2 cm defect with a 1 **Ω** impedance change on a 100 **Ω** cable (Fig. 9) with a 1 GHz sampling rate [129]**.**

7) *Frequency Domain Reflectometry (FDR)*

Frequency domain reflectometry (FDR) methods measure the frequency, magnitude, and phase of *sine* waves to find the distance to a fault. Frequency modulated continuous wave (FMCW) systems measures frequency shift [131], phase detection frequency domain reflectometry (PD-FDR) measures phase shift [132], [133], and standing wave reflectometry (SWR) systems measures amplitude or nulls of the standing wave. Vector network analyzers (VNAs) that measure the magnitude and phase of the reflected signal would also fall in the FDR category. FDR systems can be less expensive than TDR, as the electronics are simpler, and for simple loads (open or short circuits), automatic analysis is easier than TDR. FDR methods may be used on live wires, in cases where the test frequencies and existing signals/noise on the wire can be chosen so as not to interfere. When analyzing short distances, a blind spot similar to a TDR exists and must be handled specially [132], [133] (see also sub-section 10).

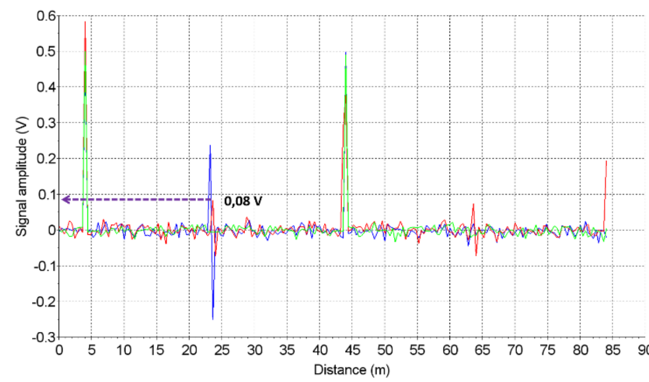

Fig. 9 Amplification of a soft defect's peak (1 Ω change of a 100 Ω line over 2 cm): Pspice model (red) and numerical model (blue) vs. standard CTDR (green). From **[130]**.

a) *Frequency Modulated Carrier Wave (FMCW)*

FMCW systems sweep the frequency of the *sine* wave over time, generally in a ramp function, and measure the frequency shift between incident and reflected signals, which can be converted to time delay knowing the speed of the frequency sweep [131]. We are not aware of this being implemented for wire testing, because of limitations on the speed at which the frequency can be swept and the accuracy to which the frequency shift (and, hence, distance) can be measured.

b) *Phase Detection Frequency Domain Reflectometry (PD-FDR)*

Phase Detection Frequency Domain reflectometry (PD-FDR), shown in Fig. 10, uses the phase shift between incident and reflected *sine* waves to determine the reflection delay and hence location of a fault [132], [133]. A voltage-controlled oscillator (VCO) steps through a band of frequencies, sending a small sample of the incident signal to the mixer, and the remainder down the cable. The reflection from the end of the cable is isolated from the incident wave by the second directional coupler and is also sent to the mixer. The mixer multiplies the two (same frequency) *sine* waves, giving a DC voltage that is a sinusoidal function of frequency. If the fault is an open or short circuit, the period of this function is proportional to the length of the wire or distance to fault.

c) *Standing Wave Ratio Reflectometry (SWR)*

Standing wave ratio (SWR) systems measure the magnitude of the standing wave created by the superposition of the incident and reflected sinusoidal signals on the wire. The standing wave has a series of peaks caused by constructive interference and nulls caused by destructive interference. Measuring either these peaks or nulls as a function of frequency can be used to determine the distance to an open or short circuit [134], [135]. For smaller faults, the standing wave ratio is reduced, and accuracy is compromised, effectively limiting the SWR to hard faults (open/near-open or short/near-short circuits) on unbranched networks.

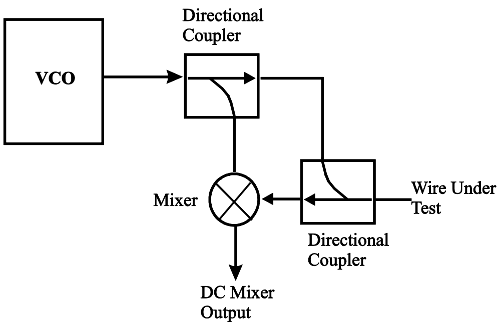

Fig. 10. PD-FDR Block Diagram. From **[132]**.

d) Mixed Signal Reflectometry (MSR)

A mixed signal reflectometer (MSR) [136], shown in Fig. 11, is like a PD-FDR without the directional couplers (thus reducing cost) or an SWR that measures the squared magnitude of the standing wave over all frequencies (thus improving accuracy, especially for smaller reflections). A sinusoidal incident signal is stepped over a band of frequencies, for each of which a standing wave is produced and fed into the mixer. This squares the standing wave signal, producing the first harmonic of the *sine* wave and a DC value, which is the same as for the PD-FDR. The MSR is more accurate than the SWR for small reflections and less expensive and smaller than PD-FDR.

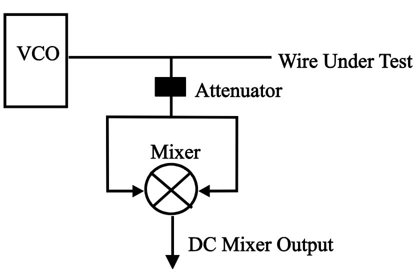

Fig. 11. MSR Circuit Diagram. From **[136]**.

8) *Multicarrier Reflectometry (MCR)*

Multiple carrier reflectometry (MCR) [137] is similar to PD-FDR and MSR, as it uses multiple sinusoidal incident signals. While PD-FDR and MSR use these frequencies sequentially, MCR superimposes the frequencies in one periodic test signal, effectively using all of the frequencies simultaneously. This is similar to TDR, where the incident step function can be thought of as an infinite sum of sine waves. This parallelization can make MCR testing faster than other FDR approaches.

9) *Time-Frequency Domain Reflectometry (TFDR)*

Time-frequency domain reflectometry (TFDR) uses a Gaussian enveloped chirp signal as the incident signal. The Gaussian envelope localizes the incident signal in both time domain and frequency domains, while the instantaneous frequency of the incident signal is linearly modulated with time [138]–[141]. For detection, localization, and monitoring of impedance discontinuities, TFDR uses three different types of time-frequency analysis: time-frequency cross-correlation [138], tangent distance pattern recognition [142] and time-frequency phase difference spectrum [100].

TFDR can be applied for energized electrical systems. Since TFDR calculates the similarities between the incident signal and reflected signals which have both time and frequency domain localization, inductive couplers that pass a specific band of the incident signal can be used, thus also improving the signal to noise ratio for detection [144]. TFDR has been used in a variety of applications including communication cables [138]–[140], nuclear power plant cables [145]–[147], high voltage DC (HVDC) submarine power cables [142], high temperature superconducting (HTS) power cables [143], [148]–[150], and stranded pre-stressed concrete anchors [151]. It has also been used to classify the defective cores of multi-core cables via a convolutional neural network [146], [152] and to estimate both fault location and reflection coefficient via a general regression neural network [146], [147], [153]. Three types of analysis methods are commonly used: time-frequency cross correlation (TFCC), tangent distance pattern recognition, and time-frequency phase distance spectrum, which are described below.

a) Time-Frequency Cross-Correlation (TFCC)

TFDR uses the Wigner-Ville distribution (WVD), which improves the resolution in the time-frequency distribution. Then the time-frequency cross-correlation (TFCC) function compares the similarities of time-frequency information between the incident and reflected signals. The local peak time of the TFCC function is utilized to measure the propagation delay of the reflected signal, which is multiplied by the *VOP* to give the distance to the fault [138]–[141].

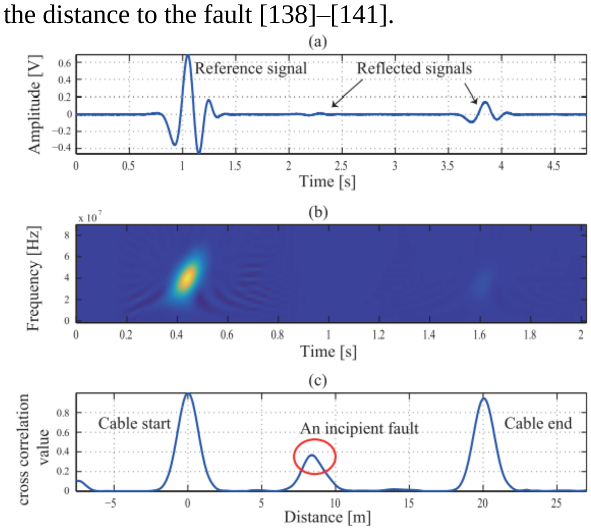

Fig. 12. Experimental results of TFDR. (a) TFDR measured signal. (b) Time–frequency distribution of the measured signal. (c) Time-frequency cross-correlation value. From **[145]**.

Fig. 12 presents TFDR measurement signals on a cable insulated with ethylene propylene rubber (EPR) with a soft shunt fault at 8.5 m on a 20 m long cable [145]. Fig. 12(b) shows the time-frequency distribution, and Fig. 12(c) shows the normalized TFCC value between the incident signal and the reflected signals. The terminals of the cable can be easily detected, however the incipient fault at 8.5 m cannot be distinguished from noise in the time domain. On the other hand, the incipient fault can be determined by calculating the TFCC.

b) Tangent Distance Pattern Recognition

As a signal propagates along a lossy transmission line, it attenuates and disperses, changing both its magnitude and shape. In tangent distance pattern recognition [142], the attenuation and dispersion of the reference signal are emulated by y-axis translation and rotation of the time-frequency distribution, respectively [154]. Then tangent vectors of y-axis translation and rotation construct the tangent plane. As shown in Fig. 13, the tangent distance can be calculated by the distance between the reflected time-frequency distribution and its projection to the tangent plane. The tangent distance can be converted to a fault location by using the *VOP* and Euclidean distance. The tangent distance cannot be longer than Euclidean distance and allows more precise arrival time calculations.

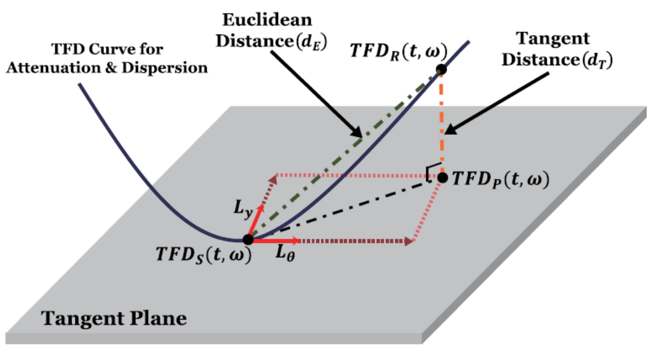

Fig. 13. Illustration of Euclidean distance and tangent distance for time-frequency distributions. From **[142]**.

c) Time-Frequency Phase Difference Spectrum

Time-frequency phase difference spectrum can be extracted from the cross term of the WVD between two different propagated signals [100]. The time-frequency phase difference spectrum is a function of the wave number, which depends on the permittivity of the cable, allowing analysis of the non-stationary characteristics of the cable.

Time-frequency phase difference spectrum was used to detect abnormalities in a 22.9 kV High Temperature Superconducting (HTS) cable, as shown in Fig. 14. The AC 22.9 kV HTS cable system consists of two cables of different lengths (270 m and 150 m), a junction to connect them, and two terminations at the ends. The source termination is connected to the current source which applies the three-phase current, and the load is terminated with a three-phase delta-connection. The current imbalance of three phases occurs at 45 min. Fig. 14(b) shows a temperature profile at the source and load and junction box input and output. The time-frequency phase difference spectrum of the A-phase junction box (Fig. 14(c)) responds to the current imbalance 1-3 min faster than temperature sensors.

10) *Reflectometry Accuracy*

In this section, we will describe the important considerations of applying reflectometry in practical applications including its accuracy, signal to noise ratio, blind spots, etc.

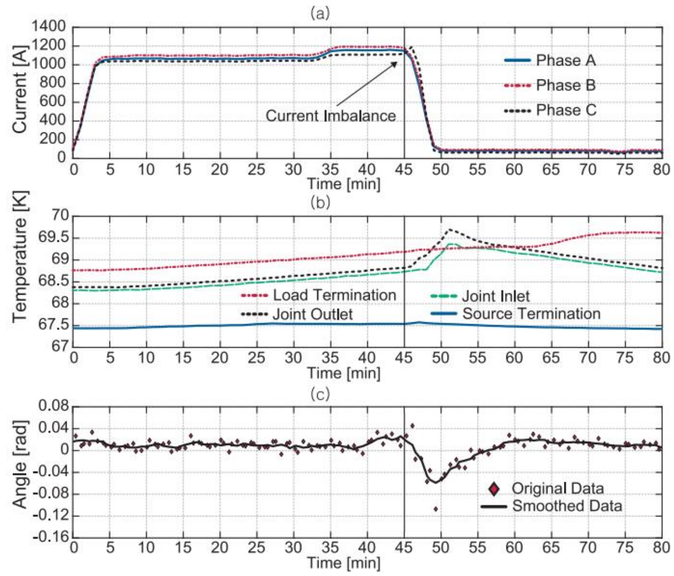

Fig. 14. Results of the current imbalance induction test. (a) Current profile. (b) Temperature profile. (c) Time-frequency phase spectrum at the joint box. From [100].

For reflectometry accuracy (how precisely a fault could be located) the larger the bandwidth, the higher the accuracy [85]. The frequency band is controlled by the bandwidth of the input signal and its receiver modality (analog or digital correlator, sampler, or etc.). It is also limited by the bandwidth of the system under test. Higher frequencies attenuate faster than low frequencies, and longer cables have more attenuation than short ones. Thus, longer transmission lines with faults further away may be limited to lower bandwidths.

Noise in the system also limits the signal to noise ratio (SNR) and hence the dynamic range (ability to identify small faults). Different reflectometry methods have different tolerances to electrical noise. Correlation-based methods such as STDR, SSTDR, CTDR, BTDR, and TFDR can be designed to work on energized electrical systems. NDR actually uses the existing energized signal as the test signal. TDR is not generally used on live systems. Sinusoidal methods could be tuned out of energized bands, enabling use on some energized systems.

In addition to electrical noise in the system, there are other sources of measurement noise that can limit practical reflectometry applications. Reflections are caused by normal impedance variation in the system such as mechanical vibration, temperature, moisture (e.g. being partially immersed in water), connecting and reconnecting wires, moving them around, etc. can change the local impedance of cables, particularly on unshielded, uncontrolled impedance cables [86]. Irradiance, temperature, humidity, shading, etc. can change the impedance of photovoltaic systems. Switching systems and all other normal operational changes create impedance changes throughout the system, that must be considered. These normal changes to impedance within the system will cause additional, often time-varying reflections that add measurement noise in reflectometry tests. They effectively limit the SNR, and therefore the dynamic range of the test system. Methods to time-gate, average out, or otherwise manage these types of noise errors can help improve the signal-to-noise ratio. Others cannot and form a fundamental system-dependent noise floor that limits detection of smaller impedance faults. New algorithms for detection and location of small faults is of significant interest. These should be coupled with analysis of the specific type of system under test and prospective methods for managing its normal impedance variations. Further discussion of this challenge is found in Section IV.B.

Another well-known challenge for reflectometry systems is referred to as a “blind spot” at the start of the cable [132], [133]. This is caused by the (large) reflection between the reflectometer and the cable under test. If a fault occurs very near the start of the cable, its reflection will overlap on this large initial reflection, thus “blinding” the system to faults in this region. A baseline approach [155] subtracts the responses of a good system from a faulted system, eliminating this initial reflection and reflections from connectors, etc., limited only by the replicability of each test. Alternatively, using a long leader cable from the reflectometer will move the reflections from the system out of the range of the blind spot of the reflectometer.

C. Other Methods

A few other electrical fault detection, location, and diagnostic methods are important to mention here. Acoustic-based methods have been proposed for the detection of arc faults [156]. For open and short circuits on a single wire, very simple capacitance and inductance sensors can be used [157].

IV. Analysis Methods for Fault Detection, Location, and Diagnosis

All of the sensing methods mentioned above produce various signatures that are functions of the location, type, and magnitude of impedance discontinuities throughout the system. Automated analysis algorithms are described in this section. Much opportunity remains in developing methods that are tailored to specific applications and implementations

.

A. Electromagnetic Time-Reversal (EMTR)

Time-reversal (TR) (Section II.B.2) is an adaptive focusing technique to focus waves in space and time. It exploits the invariance of the wave equation (in lossless and stationary media) to provide focusing on a scattering object or radiating source. This is achieved by physically or synthetically re-transmitting a time-reversed version of the scattered/radiated field collected over an array of sensors. Basic TR is applied as a matched-filter signal processing tool to maximize the reflection (echo) from the fault for a given injected energy. Two other TR variants, decomposition of the time reversal operator (DORT) and TR multiple signal classification (TR-MUSIC), have been also introduced [158], [159]. These approaches are described in more detail below.

1) *Matched Pulse (MP) Time Reversal*

The matched pulse (MP) time-reversal method seeks to optimize the reflected signal for given input energy [160] and can be applied to any reflectometry method. It is particularly good for fault location on branched networks (with multiple reflections) in the presence of noise [158], [161] and has been applied to detection of cable aging [162],[163]. Standard reflectometry is based on inputting a signal, $i_{ST}(t)$, which produces a reflected echo response, $e_{ST}(t)$. On the other hand, MP defines an ad hoc test signal, $i_{MP}(t) = e_{ST}(T - t)$, where T is the duration of $e_{ST}(t)$. By using the properties of TR signal processing, the reflection $e_{ST}(t)$ from the fault is maximized. In practice, $i_{MP}(t)$ maximizes the instantaneous power impinging over the fault, thus producing the strongest echo. Also less energy interacts with other discontinuities, reducing their respective echoes and helping the fault echo stand out. This property, directly inherited from matched-filter theory, is the main reason for the effectiveness of MP testing, which is by definition self-adaptive and optimal. The MP approach was integrated with OMTDR [164] to take advantage of OMTDR’s online network diagnosis and sensor communication for locating soft faults in energized complex networks.

Another application of an MP approach uses the shape of the signal, rather than location, for analysis of cable aging [163]. As cables age, their dielectric properties change. This creates a frequency-dependent change in the *VOP*, and hence skews the reflected signal. A symmetrical signal is injected into a good (unaged) cable and the reflected signal is collected, which is then time-reversed and stored for future testing. When the TR signal is injected, a symmetric signal is returned if the system is unchanged, and an asymmetric signal if there has been a change (such as aging). This asymmetry (skewness) is measured to estimate the aging of the cable.

2) *Time-Reversal (TR) Imaging Methods*

Identifying a fault in a wire network is fundamentally the same problem as imaging a scatterer in a generic medium, where methods can be adapted to analyzing guided-wave propagation in wire networks. Multiple testing ports are used thus allowing the simultaneous analysis of multi-port data, and a more general characterization of system is produced (with the fault eventually inferred from the overall scattering matrix).

TR imaging for wire networks is done as follows:

a. Define N test ports on the network.
b. Find the scattering matrix $\boldsymbol{S}_h(\omega)$ (reflections and transmissions) between the test ports of the healthy system. This can be done with either simulation or measurement (such as using a vector network analyzer (VNA) or other reflectometry system).
c. Measuring the scattering matrix $\boldsymbol{S}_f(\omega)$ from the same test ports when the system is faulty.
d. Compute the differential scattering matrix $\boldsymbol{S}(\omega) = \boldsymbol{S}_f(\omega) - \boldsymbol{S}_h(\omega)$ and the TR operator (TRO) $\boldsymbol{K}(\omega) = \boldsymbol{S}(\omega)\boldsymbol{S}^{\dagger}(\omega)$, where † stands for the Hermitian transpose.

$\boldsymbol{S}(\omega)$ is also known as the baselined scattering matrix, which is often found when dealing with soft faults. Baselining removes the echoes from permanent impedance discontinuities in the system such as junctions and connectors, leaving only those echoes caused by changes in the system (faults) [155]. On the other hand, $\boldsymbol{K}(\omega)$ is shown to result in an equivalent description of a fault acting as a secondary source, an important feature for the proper application of TR.

e. Solve $\boldsymbol{K}(\omega)v_k(\omega) = \lambda_k(\omega)v_k(\omega), \forall\, k \in [1, N]$ to find the eigenvalues and eigenvectors of $\boldsymbol{K}(\omega)$.

The number $M < N$ of the non-negligible eigenvalues hints at the number of potential faults in the system. The eigenvalue decomposition of the TRO is the basis of TR imaging methods.

a) Decomposition of the Time Reversal Operator (DORT) method

The decomposition of the time reversal operator (DORT) employs the signal subspace $\mathcal{S}$ of $\boldsymbol{K}$, where $\mathcal{S} = \text{span}\{\boldsymbol{v}_k: \lambda_k > \lambda_{th}\}$ with λ_k and $\boldsymbol{v}_k$ being the eigenvalues and their corresponding eigenvectors, respectively; λ_{th} is usually set after analyzing the scree plot of the eigenvalues of $\boldsymbol{K}$ [165].

The first transposition of DORT to transmission lines was introduced in [166] and has shown an ability of emphasizing the most compelling (severest) fault in the system. It does so by monitoring the propagation of input signals whose Fourier spectra would be defined by the scalar components of $\boldsymbol{v}_k$ corresponding to the largest λ_k. This operation can be carried out by means of a numerical simulator for transmission lines, modeling the layout of the healthy system; the fault's position would be found by looking for maximal energy focusing in the so-called space-time (ZT) diagram [166] as shown in Fig. 15.

Nevertheless, multiple faults cannot be resolved separately due to their strong coupling via guided propagation. Instead, an alternative formulation of the DORT (EDORT) based on an updating scheme can be used for selective focusing on multiple soft faults in complex branched networks [167], [168].

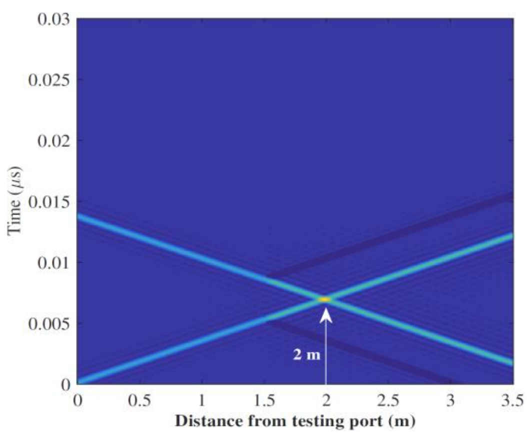

Fig. 15. A space-time ZT diagram of a single Y-junction network showing the voltage propagation after applying DORT method where a focal spot can be on the position of the soft fault. From **[159]**.

b) TR multiple signal classification (TR-MUSIC) method

Although most fault diagnosis techniques rely on the use of wideband excitation signals, it has recently been demonstrated that soft faults may be located with sub-millimeter precision by using single-frequency continuous-wave tests, thanks to the super-resolution properties of time-reversal-based multiple signal classification (TR-MUSIC) [169]. In particular, test signals below 10 MHz were shown in [170] to result in estimates of fault locations within a few millimeters (about 1/20000 of wavelength of the test signal) in communication networks. Similar spatial resolutions would require test signals covering bandwidths spanning several GHz when using reflectometry techniques.

TR-MUSIC shares the same foundations as DORT but follows a different way to translate multi-static data into a fault position by spanning the noise space $\mathcal{N} = \text{span}\{\boldsymbol{v}_k: \lambda_k < \lambda_{th}\}$ of $\boldsymbol{K}$ [171]. Under the condition of $M < N$, the locations of soft faults are inferred from local maxima in the pseudo-spectrum $\Phi(x, \omega)$ shown in Fig. 16, which is defined as

$$\Phi(x,\omega) = \left(\sum_{v_k \in \mathcal{N}} \left|\boldsymbol{v}_k^{\dagger}\boldsymbol{g}(x,\omega)\right|^2\right)^{-1}$$

where $\boldsymbol{g}(x, \omega)$ is a vector consisting of the N Green's functions of the healthy system. These are defined as the N spatial distributions, in the coordinate x, of voltages observed along the network, when separately excited from each testing port. These distributions can be estimated from a numerical model of the system, e.g., based on transmission-line theory.

Experiments have shown TR-MUSIC to be an efficient single-frequency fault-detection technique capable of locating single as well as multiple soft faults in complex branched networks, with the key ability to give a submillimeter resolution while using relatively low test frequencies. Of practical importance is its capacity to retrieve a fault's reflection coefficient even though a reflectogram is not defined [169].

Theory indicates that MUSIC-based processing can potentially achieve unlimited resolution with noiseless data [172], [173]. However, real-life systems and the associated testing equipment are affected by background and natural noise or signals, which might be sufficiently high to degrade the quality of MUSIC processing [174]. An alternative multi-frequency estimator was proposed in [175] that showed a feasibility of preserving a super-resolved location of soft faults even with SNR levels as low as 5 dBs.

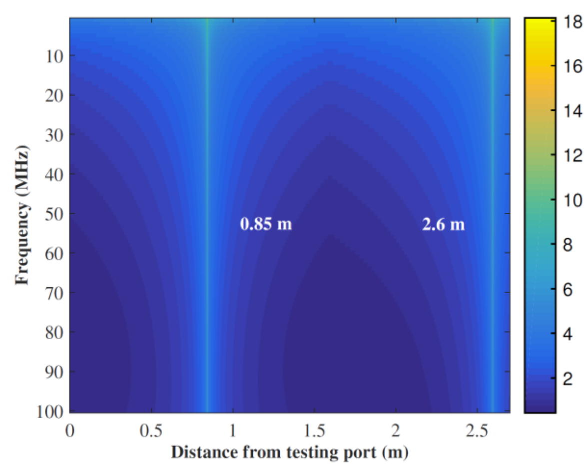

Fig. 16. Pseudo-spectrum of a single Y-junction NUT containing two soft faults, after applying the TR-MUSIC method on a frequency range from 1 to 100 MHz. From **[170]**.

B. Analysis of Soft Faults

A "soft fault", mentioned in the context of several methods above, is a fault where the impedance mismatch between the fault and wire is very small, such as a chafe or fray. A "hard fault", by contrast, has a significant impedance change, such as an open or short circuit. Hard faults create large reflections, and soft faults create only small reflections. Two types of challenges occur when trying to analyze soft faults.

The first challenge is to create a sensor system where the signal associated with the soft fault is larger than noise or variation in the measurements system. This is something over which the sensor designer has substantial control. The second challenge is to be sure the impedance change from the soft fault is larger than natural impedance variations in the system under test. Examples of natural impedance variation include vibration, thermal changes, switching systems, etc. These system effects are usually not under the control of the sensor designer. We will describe each of these challenges in the following.

The first challenge, creating a sensor system with enough measurement signal to noise ratio is akin to creating a sensor system with a large enough dynamic range to measure both the largest and smallest impedance changes expected. Reflectometry systems can be made to be very sensitive, particularly if the signatures are averaged over a significant period of time [80], baselining (subtracting off the response from a known-good system) is used to remove the known reflection signature for a given system [86], [155], and/or analysis algorithms are used to improve the results. For very well-controlled environments such as structural health monitoring for pre-stressed concrete anchors where the structure does not move [80][151], or in a well-controlled laboratory settings [176], or for shielded cables [87], [161], reflectometry systems can be made very sensitive indeed.

Several signal processing methods have been proposed for improving the detection and location of soft faults. These are typically more distinguishable at high frequencies than low frequencies [177], [178]. Methods proposed for detecting, and in some cases locating, soft faults include a matched-pulse approach in [161], matched filter [179], sliding correlators [177], [180], inverse scattering [181], using a combination (cluster) of reflectometry measurements plus crosstalk between multiple wires in a bundle [182], an iterative deconvolution [183], and BTDR algorithms to remove large reflections and emphasize small reflections [130]. These design and algorithm choices that can improve the dynamic range of the system are generally under the control of the system designer.

By contrast, the limiting factor for detecting soft faults is more often naturally occurring impedance variation within the system (such as from vibration, moisture on the wire, thermal changes, etc.). If these impedance variations are as large or larger than those from the faults, the faults cannot be distinguished from this natural variation [86], [184]. These naturally occurring impedance variations are generally not under the control of the system designer, and will often be the limiting factors in the ability to detect small impedance changes in a given system.

C. Analysis of Networks and Multiple Reflections

A network of cables, with multiple branches for signal propagation, such as the one shown in Fig. 1 creates a particular testing challenge. Multiple reflections occur at each junction and the end of each branch, creating the very complex and sometimes overlapping reflection signatures seen in Fig. 1(b). Each additional reflection reduces the amplitudes of the next reflection. Regardless of the analysis method used, it can be difficult or impossible to see beyond more than 2-3 junctions in a branched network [185]. Like soft faults, the natural impedance variation in the system can reduce the useable dynamic range of the test system. In addition, if both arms in a branched network are of the same length, this creates an ambiguity of which arm contains the fault. This can be resolved by using multiple sensors distributed throughout the network (such as described for OMTDR in Section II.B.3).

Many methods have been developed [186], [187], [188] to analyze the complex signatures produced by faults in a branched network including time reversal (described in Sections II.B.2) and IV.A.2) the genetic algorithm (GA) [89], [189], [190], neural networks (NN) [189], particle swarm optimization [191], teaching–learning-based optimization [192], backtracking search optimization [193], inverse scattering [181], a matched-pulse approach in [161], iterative evaluation of the network [89],[185], and more. Baselining (subtracting the reflectometry signatures from the network is its un-faulted state) can be used to remove the reflections from normal impedance discontinuities within the system (connectors, junctions, etc.) [86], [155]. This enhances the responses from faults.

Much work related to network reconstruction relies on prior knowledge of the network's topology to estimate the branch lengths [94], [181], [182], [183], [184], [185]. Many of these methods rely on adding predefined loads (open or short circuits) on the ends of the network to provide significant known reflections. However, in practice, disconnecting the network and connecting in these loads is not always possible (nuclear power plants, underground cables, aeronautics, etc.).

Other methods such as [185], which iteratively maps out reflectometry responses from branches and loads from early to late time, do not require prior knowledge of the network configuration. Recent work has applied graph theory with optimization based algorithms to solve the inverse problem of measured TDR responses from a single point for totally unknown networks [195]–[198]. These joint graph optimization-reflectometry (GOR) techniques deal with the network as a black-box and successfully enable a blind reconstruction of the network to estimate its branch lengths and load impedances [199].

D. Defect Correction in Transmission Lines (TL)

Researchers and engineers have invested much effort to detect and locate faults in order to repair them, but sometimes faults may be located in hard-to-access areas (radioactive zones in nuclear plants, satellites in the outer space, etc.) and thus inaccessible to maintenance processes. In such cases, alternative approaches are needed to correct the effects of faulty systems without accessing the detected faults. Adding new input signals (either physically in the system [174] or in software during post-processing [200]) to compensate for the effects of the faults can recover healthy system outputs. The linear combination of configuration field (LCCF) method [200] identifies sources in time domain using the linear impulse response of the TL network and then adds compensating inputs to impose the desired voltage [200], [201]. Another approach, commonly used in high-speed chips and circuits, is the decision feedback equalizer (DFE) [175] that uses the impulse response of the channel to set hardware taps to compensate for (equalize) the attenuation and reflections.

V. Conclusion

In this review, we have described sensors for fault detection, location, and diagnosis in electrical wiring and interconnection systems (EWIS) and in some types of structural health monitoring. Ongoing research is continually expanding sensors types and modalities as well as how these sensors are evaluated, as the other papers in this special issue will show.

Disclosure

Dr. Furse is a co-founder of LiveWire Innovation, Inc. which is commercializing SSTDR technology, and therefore has a financial conflict of interest with this company.

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