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A Survey of Traveling Wave Protection Schemes in Electric Power Systems

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ABSTRACT As a result of the increase in penetration of inverter-based generation such as wind and solar, the dynamics of the grid are being modified. These modifications may threaten the stability of the power system since the dynamics of these devices are completely different from those of rotating generators. Protection schemes need to evolve with the changes in the grid to successfully deliver their objectives of maintaining safe and reliable grid operations. This paper explores the theory of traveling waves and how they can be used to enable fast protection mechanisms. It surveys a list of signal processing methods to extract information on power system signals following a disturbance. The paper also presents a literature review of traveling wave-based protection methods at the transmission and distribution levels of the grid and for AC and DC configurations. The paper then discusses simulations tools to help design and implement protection schemes. A discussion of the anticipated evolution of protection mechanisms with the challenges facing the grid is also presented.

INDEX TERMS Electromagnetic transient simulation, fault location, feature extraction, power systems protection, signal processing, traveling wave.

I. INTRODUCTION

Power system protection is a vital operating component of power systems to detect and isolate faults. A protection system is expected to meet sensitivity and selectivity requirements. Sensitivity refers to the ability to detect and isolate faulted regions fast enough to avoid damaging the other equipment in the power system. Selectivity refers to the intelligent and optimized isolation of faults to minimize the number of customers experiencing power outage. Synchronous generators produce up to six times the rated current during fault conditions [1]. Inverters on the other hand typically do not supply currents above 1.2-1.5 times the rated value [2]. New protection systems are needed to maintain the safe and reliable operations of the grid in the face of the changes brought by the increase of inverter-based resources such as wind and solar. Electric grid reliability has also been complicated with the increasing amount of inverter-based generation on the grid that causes the total inertia of the system to decrease because rotating generation is substituted for power electronic based generation. In low inertia power systems, the speed of the protection system is critical to remove the fault quickly before the grid reaches instability and is not able to recover. The increasing penetration of renewables in the system means that the protection system must be able to operate much faster, but also be less sensitive to rapidly changing dynamics from intermittent generation. In order to improve system reliability and resilience, there has been a decreasing trend in the time it takes protection elements to disconnect and break the fault from the system. This has led

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to the development of new fast-tripping protection schemes (FTPS), such as traveling wave (TW) protection.

TW protection schemes are based on high-frequency measurements and determining the arrival time of the fault wave signature. The high frequency electromagnetic transient propagates through the system at roughly the speed of light, allowing the protection equipment to detect the wave in less than 1ms after the fault. For systems with important penetration of inverter-based resources, this has the advantage of removing the fault much faster to avoid instability with the reduction in system inertia. In addition to improving system stability, a traveling wave is not dependent on the magnitude of the fault current injection, so it has the ability to detect faults in systems with high penetrations of renewable inverter-based generation with low short-circuit current. Some of the other benefits include being able to detect arcing or temporary high impedance faults, not being sensitive to fault type or resistance, and the ability to work in system with line compensation. Finally, as discussed later in the paper, using the precise arrival times of the wave, TW protection schemes provide very fine accuracy for determining the location of the fault on the line, which improves repair times by accurately dispatching crews. TW protection provides the benefits of accuracy and reliability for the grid of the future with renewable inverter-based generation.

FTPSs has gained a lot of attention in recent years. Given the large number of published work on FTPS, a thorough survey on existing approaches will be of particular importance. This paper attempts to bring together the existing FTPS for AC and DC power systems of different voltage levels. This paper will act as a comprehensive and thorough reference for the researchers and practicing engineers working in the area of power system protection. To this end, this paper reviews a wide range of FTPS in transmission and distribution AC systems as well as high voltage and medium voltage DC grids. Moreover, the existing software packages for simulation and analysis of high frequency fault components are surveyed.

The rest of this paper is organized as follows. Section II introduces the theory of TWs in power systems. Section III provides details on different TW detection and extraction methods discussed in literature. Section IV gives a detailed literature review of different applications of TW for fast-tripping protection schemes. Section V reviews patented and manufactured protection schemes based on TWs. Section VI reviews the different tools used in industry and research to develop protection schemes. Section VIII discuss the limitations of TW-based protection techniques. Section VII gives a summary of the state of the art. Section IX discusses the future trends for protection. Finally, Section X outlines the conclusions of this work.

II. THEORY AND APPLICATION OF TW IN POWER SYSTEMS

A. PRELIMINARIES

TWs are electromagnetic waves which are propagated along the power system equipment (e.g., lines, cables, etc.) as a result of a disturbance occurring in the power system. The disturbances can be defined as any fault, lightning, switching, etc. When these high frequency electromagnetic transients reach a power grid junction or terminal at which the circuit parameters are changed, the incident TW is divided into two TWs. A portion of the incident TW is reflected back while the other portion is refracted to the neighboring equipment at that specific terminal. Depending on the circuit parameters at both sides of the terminal, the amplitude of reflected and refracted TWs change accordingly. The reflection rate is defined as the ratio of the amplitudes between reflected and incident TWs. The refraction rate is defined as the ratio of refracted TW amplitude over incident TW amplitude. On each equipment, TWs keep hitting the terminals and are reflected back; their amplitudes are gradually attenuated after the incident [3], [4]. The so-called Bewley's lattice diagram [5] is an illustrative approach for describing this process. A sample lattice diagram is shown in Fig. 1.

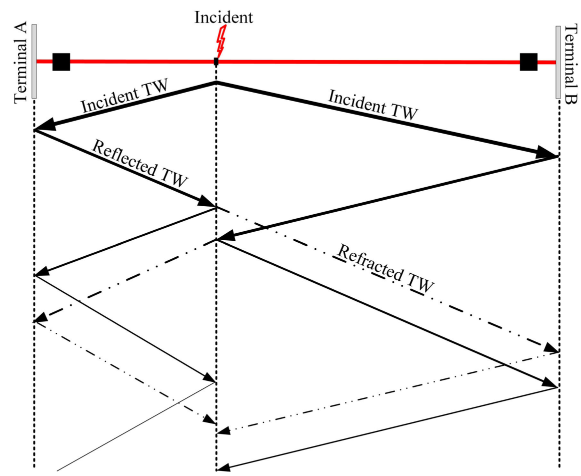

FIGURE 1. Sample lattice diagram.

TWs along transmission lines are governed by the *telegrapher's equations* which are coupled differential equations that determine the voltage ($v(x, t)$) and current ($i(x, t)$) at any point in time and space. In phasor domain the general solutions to these equations are

$$\tilde{I}(x, t) = I_0^+ e^{-\gamma x} + I_0^- e^{+\gamma x} \tag{1}$$

$$\tilde{V}(x, t) = V_0^+ e^{-\gamma x} + V_0^- e^{+\gamma x} \tag{2}$$

where I_0^+, V_0^+, I_0^-, V_0^- are Laplace transforms of the time functions representing the so-called traveling waves. x denotes the distance measured from the incident point, and γ denotes the propagation constant. In the case where I_0^+, V_0^+, I_0^-, V_0^- represent single frequency sinusoids, transformed back to time domain the expressions in (1) and (2) represent sinusoidal waves propagating along the transmission line in the $+x$ and $-x$ directions. In time domain

$$v^+(x, t) = Re\left\{V_0^+ e^{-\gamma x} e^{j\omega t}\right\} \tag{3}$$

$$= \left|V_0^+\right| e^{-\alpha x} \cos(\omega t - \beta x + \psi) \tag{4}$$

where ψ is the phase of V_0^+. The propagation constant is made of real and imaginary parts as

$$\gamma = \alpha + j\beta \tag{5}$$

α and β describe the attenuation constant and phase constant for each frequency component of the TWs [6]. A similar procedure to the one detailed in (3) and (4) for V_0^+ can be done for all the components of (1) and (2) to obtain their time domain representation. It is important to note that the frequency-dependent propagation constant is also described by

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}, \tag{6}$$

where R, L, G, and C are the per unit length of cable resistance, inductance, conductance, and capacitance. ω is the angular frequency corresponding to a specific frequency component of TW. The propagation velocity of the TW can be defined as $v = {}^{\omega}/_{\beta}$ [7], which shows that the higher frequency components of a TW travel faster than lower frequency components, asymptotically approaching the speed of light c. Moreover, higher frequency components are associated with a larger α and are more attenuated than lower frequency components. The reason is that α is directly proportional to R which adopts a higher value for higher frequency components due to the so-called skin effect leading to [8].

B. TW FOR FAULT LOCATION

Fast acting protection schemes play an important role for enhancing the resilience and stability of modern power grids. These schemes can be highly effective in some critical incidents which can have detrimental impacts on society, e.g., wildfires caused by the broken power lines. To this end, TW-based FTPS have gained much attention. These schemes mostly rely on the identification of high frequency components of TWs under a fault condition. They utilize the detected TWs for classifying and locating faults on transmission and distribution lines. The TW-based protection schemes can be categorized based on different factors in terms of the techniques and infrastructure required to implement them.

From the communication infrastructure requirement point of view, TW-based protection schemes are divided into single-ended and double-ended schemes. The single-ended versus double-ended TW-based protection schemes are reviewed in [9]. Double-ended schemes rely on a communication link from the remote terminal of the line to transmit the arrival time of incident TW at the remote terminal. The arrival time of incident TWs at local and remote terminals is used to identify the fault location. The requirement for a communication link in these schemes is a reliability bottleneck because when the communication link is compromised, the TW-based protection scheme fails to properly locate the faults. On the other hand, single-ended schemes obviate the requirement for a communication infrastructure. They usually rely on the arrival time of incident TW and first reflected TW from the fault location. The idea of using communications for TW-analysis has been extended beyond double-ended schemes and there exist some research showing that having information of multiple sensors in the network is helpful for TW-based fault location [10]. From another point of view, TW-based protection schemes can be divided into passive and active schemes. Passive schemes only use the TWs created by the faults at either terminals of the line to detect and locate the fault. On the other hand, active schemes inject a high frequency signal into the faulted transmission line and calculate the time difference between the injected signal and its reflection to find the fault location [4], [11].

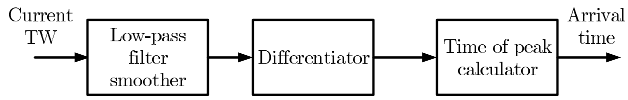

FIGURE 2. Smoother-differentiator technique [12].

III. TW DETECTION AND EXTRACTION METHODS

This section presents an overview of the theory of different methods used to analyze power system waveforms with the objective of extracting information on TWs and more generally for fault detection. This section presents a list, by no means exhaustive, of nine methods for power system waveform analysis in Subsections III-A-III-J. The section ends with a discussion on the different presented methods in Subsection III-K.

A. TW ANALYSIS USING DIFFERENTIATOR-SMOOTHER FILTER

In order to identify the time of arrival (TOA) of TWs, in [12], a sequence of a smoother and a differentiator is utilized to determine when the peak of the current TWs occurs. In the proposed method, a high pass filter is first utilized to reject power frequencies (i.e., 60 Hz component and higher order harmonics). Then, a time stamping method is used to identify the peak of the TWs. In the time stamping method, a smoother is first employed to remove the distortions from the waveforms. The smoother is a low pass filter which makes the rising edge of the current TW less steep. Then, a differentiator is applied to the output of the smoother. The differentiated waveform has a peak value which corresponds to the instance that the smoothed TW signal has the steepest slope. The output of the differentiator looks like a parabola. Therefore, a parabola interpolation-based method can be used to identify the time of the occurrence of the peak, which is interpreted as the arrival time of the TW.

B. TW ANALYSIS USING WAVELET TRANSFORM

The wavelet transform (WT) is the result of works developed in different areas and in different points in time [13]. The first wavelet was proposed by Haar in 1909 [14] when the concept was not fully formalized. In the '80s and in the context of quantum physics, the continuous wavelet transform (CWT) was formalized [15]. The WT was partly developed as a tool to analyze time and frequency information simultaneously. That is, with the WT frequency contents can be localized in time (as opposed to the Fourier Transform where the frequency content is for the entire duration of the analyzed signal). Wavelet analysis requires a basis function called mother wavelet ($\psi(t)$) that needs to have a mean of zero and decay in time. The CWT of signal $x(t)$ is defined as

$$W_C(a, \tau) = \int_{-\infty}^{\infty} x(t)\psi_{a,\tau}^{*}\, dt = \langle x(t), \psi_{a,\tau}^{*} \rangle \tag{7}$$

where

$$\psi_{a,\tau} = \frac{1}{\sqrt{a}}\psi\left(\frac{t-\tau}{a}\right) \tag{8}$$

is a scaled and time-shifted version of the mother wavelet. The CWT $W(s, \tau)$ is a two-dimensional representation of the one-dimensional signal $x(t)$. The scale factor a is used to stretch or compress $\psi(t)$ to analyze the different frequency components of a signal. Small values of a will compress $\psi(t)$ to analyze the fast frequency components while large values of a stretch the mother wavelet to allow for analysis of the slower frequency components of $x(t)$.

The discrete wavelet transform (DWT) is defined as

$$W_D(m, k) = \frac{1}{\sqrt{a_0^m}} \sum_n x[n] g\left[\frac{k - nb_0 a_0^m}{a_0^m}\right] \tag{9}$$

where $g[n]$ is the mother wavelet. The convention used in (9) allows for the scaling and time-shift parameter to be a function of m ($a = a_0^m$ and $\tau = nb_0\, a_0^m$). Note that the CWT in (7) and the DWT in (9) yield two dimensional functions in time and scale, not frequency, however in most applications it is easy to find a relationship between scale and frequency. Note also that the WT is subject to the uncertainty principle of signal processing where both time and frequency cannot be located very precisely; the better the resolution in frequency, the worse it would be in time and vice versa.

Constructing wavelets is an important task of wavelet analysis. Multiresolution analysis (MRA), advanced by Mallat in the late '80s [16], is a practical approach for constructing wavelets and fully implementing the DWT. MRA details the procedure to obtain orthonormal wavelet basis with compact support. MRA can be implemented by a series of high-pass, low-pass filters and decimators as shown in Fig. 3. Respectively, approximation $a_i[n]$ and detail $d_i[n]$ signals are the outputs of the low and high-pass filters. It is important to note that in power systems applications, it is common to use the reconstructed coefficients of the WT [17].

The WT has been used in protection applications since the '90s [18]–[22]. The common feature of all these works is that they use the ability of WT to localize in time the occurrence of high frequencies, which indicate the presence of TWs. Different works localize high frequencies to estimate the TOA of TWs and others use the properties of the frequency to classify the faults. The performance of these methods is dependent on the mother wavelet and the Daubechies wavelets are the most commonly used in power system applications [10], [23]–[27]. The exact function, e.g. 'db4' or 'db15' is dependent on the application and other

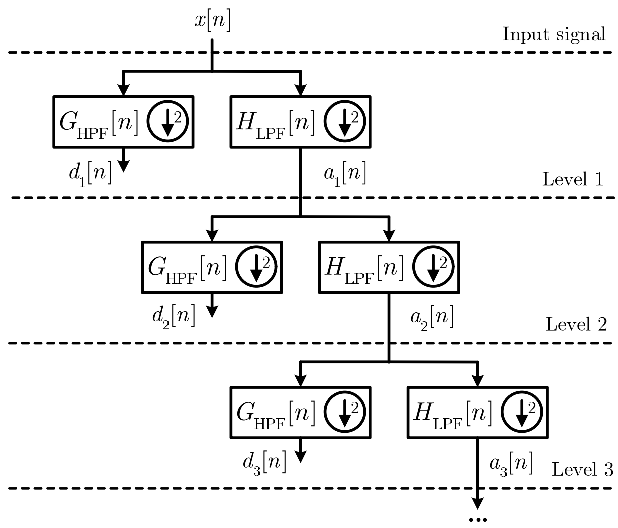

FIGURE 3. Schematic diagram of MRA.

parameters such as the sampling frequency of the data. The B-spline wavelet which is constructed using a spline function has also been used in the analysis of power system signals [28]–[30]. Some works have also studied the effect of the mother wavelet on their results [20], [31]–[33]. Another work [34] proposes its own custom wavelet constructed from recordings of disturbances in voltage signals.

C. TW ANALYSIS USING HIGH FREQUENCY SAMPLING AND TIME-FREQUENCY REPRESENTATION

Some of the surveyed techniques for identifying the TOA of TWs are usually implemented in a double-ended fashion and identify the fault location based on the arrival time of TWs at the terminals of the power line. On the other hand, time-frequency representations can be utilized to extract the high frequency components of TWs. Time-frequency representations are tools used to represent non stationary signals and analyze their time and frequency contents simultaneously. The Short Time Fourier Transform (STFT) is a linear version of these tools. The WT explained in Section III-B can also be interpreted as one of these tools when there is a clear relationship between scale and frequency. In addition to these linear methods, there exists a set of bilinear time-frequency representations. The most widely known of such representations is the Wigner-Ville Distribution (WVD) proposed by Wigner in the 1930's [35]. For a continuous time signal $x(t)$, the WVD is defined as

$$W_{WVD}(t, f) = \int_{-\infty}^{\infty} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) e^{-2\pi j f \tau} d\tau \tag{10}$$

where the WVD is the Fourier Transform of the central covariance. The WVD is part of larger class of time frequency distributions (TFDs) known as the Cohen class which are described by

$$p(t, f) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x\left(u + \frac{\tau}{2}\right) x^*\left(u - \frac{\tau}{2}\right) \phi(\tau, \nu) e^{-j(t\nu + \tau f - u\nu)} du\, d\nu\, d\tau \tag{11}$$

where the two dimensional function $\phi(\tau, \nu)$, is called the kernel. When the kernel takes the Gaussian form defined as

$$\phi(\tau, \nu) = e^{\frac{\nu^2\tau^2}{\sigma}} \tag{12}$$

the TFD obtained is known as the Choi-Williams distribution (CWD). Note than when the kernel takes a value of 1 the TFD obtained is the WVD.

TFDs have been used in protection applications in the same way as the WT: to help determine the high frequencies caused by TW in power system signals [36]–[38].

D. TW ANALYSIS USING MATHEMATICAL MORPHOLOGY

Mathematical morphology (MM) is a theory that provides tools for analyzing signals and images (two-dimensional signals). It was initially developed in the 1960's by Matheron and Serra for the analysis of binary images [39], [40]. MM is based on different branches of mathematics such as set and lattice theory and is used to analyze and modify the *shape* of the signal to analyze. The analysis of the signal requires another *signal* of predefined shape called the structuring element. MM is based on two elementary operations: dilation and erosion. For a one dimensional signal $x[n]$ and structuring element $s[n]$, dilation is defined as

$$y_d[n] = (x \oplus s)[n] = \max\{x[n-m] + s[m]\} \tag{13}$$

with $0 \le$ n-m $\le n$ and $m \ge 0$. For the same signal and structuring element, erosion is described by

$$y_e[n] = (x \ominus s)[n] = \min\{x[n+m] - s[m]\} \tag{14}$$

with $0 \le n+m \le n$ and $m \ge 0$. Dilation is the dual operation of erosion, however, they are not the inverse of each other. These operations are nonlinear. The next two main MM operations are *opening* and *closing* and they are based on the two elementary operations. *Opening* is simply an erosion followed by a dilation while *closing* is a dilation followed by an erosion. MM is very computationally efficient.

MM has been used as a tool to develop protection schemes [41]–[47], mainly to detect high frequency distortions of the raw or transformed power system signals. These distortions are the results of TWs. The performance of MM in these applications is mainly related to the structuring element and the type of MM operations used to analyze the signal. These final operations are a composition of the main operators, opening and closing as described above. The closing-opening-difference-operation (CODO) [44], [48], opening-closing maximal and close-opening minimal (OCCO) operation [49], and the close-opening open-closing morphological gradient (CO-OCG) transform [50] are some examples of these final operations. The work in [51] develops MM filters for polarity detection to propose a high speed protection scheme using traveling waves.

E. TW ANALYSIS USING KALMAN FILTER

Proposed in 1960 for linear systems [52], the Kalman Filter (KF) is a recursive estimation technique used in diverse applications such as tracking and data prediction. The classical KF formulation requires the model of the system in state space form and discretized in time domain

$$\mathbf{x}_{k+1} = \mathbf{F_k}\mathbf{x}_k + \mathbf{w}_k \tag{15}$$

where $\mathbf{x}_k$ are the states of the process or system at time k, $\mathbf{F_k}$ is the state transition matrix, and $\mathbf{w}_k$ is the noise of the system. In addition, a model of the observation or measurement of the process is assumed to be described by,

$$\mathbf{z}_k = \mathbf{H_k}\mathbf{x}_k + \nu_k \tag{16}$$

where $\mathbf{H_k}$ is the observation matrix, ν_k is the measurement noise, and $\mathbf{z}_k$ are the measurements to which the user have access. The KF is a mean squared error minimizer and requires knowledge of the statistics of the process and measurement noises. The KF works in two steps cyclically. These steps are: State prediction and measurement update. In the state prediction step the state at the current time step is ''predicted'' using the state estimate of the previous time step. In the measurement update step, the observation or measurement at the current time step is used to improve or ''update'' the estimate of the current time step. Extensions to this filter have been proposed for nonlinear systems; the most common of which are the Extended Kalman Filter (EKF) [53] and the Unscented Kalman Filter (UKF) [54]–[56]. For nonlinear systems the process and measurement equations in (15) and (16) take the forms of

$$\mathbf{x}_{k+1} = \mathbf{f}(\mathbf{x}_k) + \mathbf{w}_k \tag{17}$$

$$\mathbf{z}_k = \mathbf{h}(\mathbf{x}_k) + \nu_k \tag{18}$$

The EKF works by linearizing (17) and (18) using a Taylor approximation at each time step so they become of the form in (15) and (16). The UKF is based on the unscented transform that is used as a statistical linearization of the state and covariances of the filter. The performance of KF is related to how well the actual system resembles the model (represented by equations(15) and (16) in its linear form or (17) and (18)).

In the power system protection application that uses KF the model of the system (or a signal) is that of a simple sinusoidal. This model is often extended to include harmonics. This model in state space form is nonlinear and hence the EKF or UKF extensions are used. KF methods do not require a sample window of data to analyze; they produce a new estimate as soon as a new data sample is received.

Kalman Filters have been used since the '80s in protection applications. In the works in [57]–[59] the fault is detected by determining anomalies in the KF estimated power system signals (amplitudes of currents and/or voltages). Kalman filters have also been used recently in protection applications, [60]–[62], by the same set of authors, use an EKF approach to estimate the TOAs of TWs. These works propose double-ended methods for fault location based on the TOA of TWs. While in [60] the TOA are determined based on singularities of the estimated amplitudes of the power system signals, in [61] the TOA is determined by looking at the residual of the KF states. The work in [62] also uses the residual for determining TOAs but it is meant exclusively to detect lightning strikes, a feature that is reflected in the model used by the KF.

F. TW ANALYSIS USING TEAGER ENERGY OPERATOR

The Teager Energy Operator (TEO) was proposed by Teager in the '80s and early '90s to introduce nonlinearities to speech modeling [63]. Based on that work, Kaiser, in the early '90s proposed an algorithm to compute the energy of a signal and studied the properties of the operator [64], [65]. For this reason the TEO is sometimes referred to as the Teager–Kaiser Energy Operator (TKEO). In discrete time the TKEO is defined as

$$\Psi[x_k] = x_k^2 - x_{k+1}x_{k-1} \tag{19}$$

where x_k is the signal to analyze at time instant k. The TKEO can be interpreted as a nonlinear transform that can be used to estimate the instantaneous energy of a signal. Calculating the TKEO only requires three samples of a signal and is computationally very efficient.

Recently, the TKEO has been used to extract the TWs of power system signals. A series of works [66]–[68] by the same group of researchers have proposed fast protection schemes that use the TKEO to analyze the TW of the modal components of power system signals. Based on the information extracted with the TKEO the fault is classified and actions are taken accordingly.

G. TW ANALYSIS USING PRINCIPAL COMPONENT ANALYSIS

Principal component analysis (PCA) is a statistical technique used to reduce the dimensionality of data sets where the variables are potentially highly correlated. The origins of PCA are difficult to determine but the earliest description of the technique are attributed to Pearson and Hotelling [69], [70].

Typically, a dataset is pre-processed to have a zero mean and a unit variance before using PCA on it. For a dataset $\{x^{(i)} \mid i = 1, \ldots, m\}$ of m different variables and with $x^{(i)} \in \mathbb{R}^n$ that has been pre-processed as mentioned above, using PCA the data can be represented as

$$y^{(i)} = \begin{bmatrix} u_1^\top x^{(i)} \\ u_2^\top x^{(i)} \\ \vdots \\ u_k^\top x^{(i)} \end{bmatrix} \in \mathbb{R}^k \tag{20}$$

where the vectors $u_1, \ldots, u_k$ are called the first k principal components and correspond to the first k eigenvectors of the empirical covariance matrix Σ, defined as

$$\Sigma = \frac{1}{m} \sum_{i=1}^{m} x^{(i)} x^{(i)\top}. \tag{21}$$

Note that the new vector $y^{(i)}$ is of dimension k which is lower than the initial dimension n and that eigenvectors u_i form an orthogonal basis to represent the data. PCA is often used in datasets to reduce the redundancy and to make it easy to determine if patterns arise.

PCA has also been utilized to help develop better protection schemes [28], [71]–[74]. PCA is typically used to help classify faults and to reduce the time of operation the protection device needs to take action. These methods use a windowed version of the signals to analyze, and require a significant amount of data, normally in the form of simulations of multiple faults under different conditions.

H. TW ANALYSIS USING EMPIRICAL MODE DECOMPOSITION (EMD) AND HILBERT HUANG TRANSFORM (HHT)

The Empirical Mode Decomposition (EMD) is a tool for analyzing non-stationary signals that often represent nonlinear dynamics. It works by decomposing the signal into various components called intrinsic mode functions (IMFs) which are always in the time domain (as opposed to other methods like the Fourier transform or the WT which make use of the frequency domain). The EMD is a crucial step of the Hilbert-Huang Transform (HHT) which was proposed by Huang in in 1996 [75]. For a signal or time series $x(t)$ the EMD is defined as

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \tag{22}$$

where $c_i(t)$ is the i^{th} IMF and $r_n(t)$ is the residue from which no IMF can be extracted. The process of extracting the IMFs, called the sifting process, is beyond the scope of this work and can be found in [75]. An IMF is a function that: (i) the difference number of maxima and minima is at most 1 (meaning it only has one extreme between zero crossings), and (ii) has a mean of zero. IMFs are notorious because they admit well-behaved Hilbert transforms (HT) and they are orthogonal in practice (though not guaranteed in theory).

The Hilbert-Huang Transform (HHT) consist of decomposing the analyzed signal ($x(t)$) in IMFs via the EMD, and applying the HT to them to obtain the instantaneous frequency. The signal $x(t)$ can be expressed as

$$x(t) = \sum_{i=1}^{n} a_i(t) e^{j \int \omega_i(t)\, dt} \tag{23}$$

where the residue is disregarded on purpose. The form of (23) is similar to the Fourier transform and hence it can be seen as a generalized Fourier expansion where the coefficients and frequencies are time-varying.

When a power system fault occurs, due to TWs, the subsequent signals (voltages and currents) are non-stationary. EMD and HHT have been used to analyze these non-stationary signals to detect and extract TWs and enhance the operation of protection systems [76]–[80].

Extensions to EMD such as the variational mode decomposition (VMD), which is more robust for sampling and noise, have been proposed [81]. This technique has also been applied in protection applications [82].

I. TW ANALYSIS USING PARK's TRANSFORMATION

The Park transformation is a tensor to convert vector spaces. It transforms signals of a three-phase stationary reference frame to a rotating reference frame. This means that balanced sinusoidal (AC) signals become DC signals under the Park transformation. The DC signals are then usually easy to manipulate and analyze. The Park transformation was introduced in the late 1920s by R.H. Park in a paper on how to model synchronous machines [83]. It was very important because it has the property of time-varying impedances from the analysis of synchronous machines. For a three phase signal $u_{abc} = [u_a \; u_b \; u_c]^\top$ the Park transformation is defined as

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{24}$$

where $u_{dq0} = [u_d \; u_q \; u_0]^\top$ are DC quantities known as the direct (d), quadrature (q), and zero (0) components.

The Park transformation has been used in protection application primarily because the 'd', 'q' and '0' are affected following a fault in the system. Analyzing some or all of this components has been as a means to detect faults [84]–[86].

J. TW ANALYSIS USING MACHINE LEARNING ALGORITHMS

Machine learning (ML) is the study of learning algorithms that improve their performance in a defined task based on some given experience. The term *machine learning* was first used in the late '50s by Samuel [87]. The fundamental component of ML is a set of data that is obtained by the *experience* and its main focus is on how a process/algorithm can program itself (adapt) using this experience and an initial structure. ML is related to other fields such as computer science, statistics, and adaptive control theory, among others. Fig. 4 shows a general ML system. This figure shows two sets that can be respectively associated with data set inputs and outputs $\mathcal{X}$ and $\mathcal{Y}$, and a function (pattern) that relates them. Fig. 4 also shows the data set of inputs and outputs $(\mathbf{x}_1, \mathbf{y}_1)\ldots(\mathbf{x}_N, \mathbf{y}_N)$ and the set of learning algorithms $\mathcal{A}$ and hypothesis (or structures or models) $\mathcal{H}$.

The main learning algorithm paradigms are:

- Supervised learning – these type of algorithms have inputs $\mathbf{x}_i$ and outputs $\mathbf{y}_i$ clearly defined. These algorithms then use the information of the data set (also called training data) to build or improve the structure from $\mathcal{H}$ (this structure is a mathematical model).
- Unsupervised learning – these type of algorithms have only input data $\mathbf{x}_i$ without clear information about the output. Given this lack of feedback these algorithms mainly work by finding commonalities in the data to cluster them.
- Reinforcement learning – these type of algorithms have input data $\mathbf{x}_i$ some output data that is graded. These algorithms try to determine what are the best actions to take to maximize a reward (stemming from the grades of the outputs).

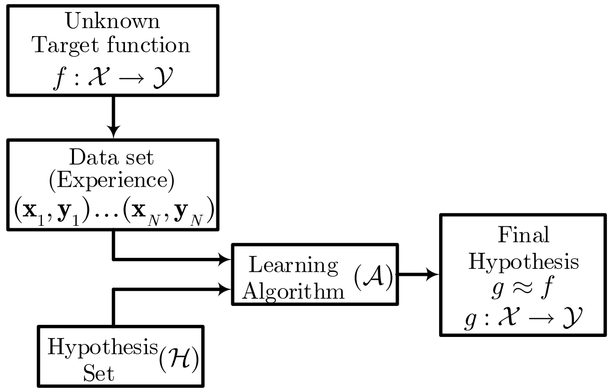

FIGURE 4. Schematic of the components of machine learning. Adapted from [88].

The main types of hypothesis sets or models are:

- Artificial Neural Networks (ANN) [89], [90],
- Decision Trees [91],
- Support Vector Machines (SVM) [92],
- Bayesian Networks [93].

In power systems protection applications ML models have been applied to better detect, determine, and classify faults. They are usually used in conjunction with other extraction methods presented in this section, such as mathematical morphology or wavelet transform. Typically, the other method is used to pre-process the data and obtain a reduced order representation of the power system signals. References [94]–[98] present works where SVM has been used in detection and classification of faults while the work in [99], [100] uses ANNs for the same purpose. The ML work in protection is done with supervised learning techniques for the most part because the data is usually classified. ML techniques are useful because they can perform in tasks for which they were not explicitly designed but they have the downside of needing a considerable amount of data to construct a *complete* data set that allows for robust model selection.

K. DISCUSSION AND COMPARISON OF TW ANALYSIS METHODS

This section has presented nine different methods for extracting TW information from power system signals (or some associated effects) with the objective of detecting, identifying and classifying faults in the system. The list of presented methods is by no means exhaustive but it does comprise of the most popular and effective methods for TW analysis found in the literature. Table 1 shows information and a comparison on the methods with respect to their computational complexity

TABLE 1. TW Detection and Extraction Methods.

Method	Model-based	Window-based	Single or three-phase	AC or DC	Transmission or distribution	Is prototype commercial-ized?
Smoother-Differentiator Technique	N	Y	Both	Both	Transmission	Y [101], [102]
Wavelet Transform	N	Y	Both	Both	Both	N
High Frequency Sampling and Time Frequency Representations	N	Y	Both	Both	Both	Y [103]
Kalman Filter	Y	N	Both	AC	Both	N
Teager Energy Operator	N	N	Both	AC	Transmission	N
Principal Component Analysis revN	Y	Y	Both	AC	Transmission	
Empirical Mode Decomposition revN	N	Y	Both	Both	Transmission	
Hilbert Huang Transform	N	Y	Both	AC	Transmission	N
Mathematical Morphology	N	Y	Both	Both	Both	N
Park's Transformation	N	N	Three-phase	AC	Both	N
Machine learning	Optional	Optional	Both	Both	Both	N

and on whether they can be used with single or three-phase data. Table 1 shows that ML approaches due to their variety can have low or high computational complexity. It is worth noting that some of these approaches can have low computational complexity in normal operations but a high computational complexity when training and obtaining the optimal model. The only method that requires three-phase information is the one that uses the Park Transformation. However, note that because sometimes it is *easier* to analyze the data coming out of the Park Transform (or other modal transform) with any of the other methods, this causes them to be only suitable for three-phase data. The third column in Table 1 refers to the ability of the presented methods to work in real-time. For real-time operations most methods require a window of data to operate. This window determines the amount of data available to perform the analysis. Methods that require a window of information are computationally more expensive and have a delay in their output, both of which are dependent on the length of the window. This becomes a crucial parameter in their performance. Kalman Filter based methods are recursive algorithms that produce an output estimate when a new data point arrive. Because they are recursive the new data point depends indirectly on all previous data points. The Park Transformation and the TKEO methods do not require a window either, and unlike the KF they are not recursive. Most methods discussed do not required a model of the signals or the system that generates them, they are rather *signal processing* techniques that take input data and analyze them with the appropriate tools and whose structure does not depend on these data. The KF and PCA methods do require a model and their performance is dependent on it. Most methods are dependent of particular parameters from the structuring element in MM-methods to the level of decomposition and mother wavelet in WT-based methods. In Table 1, we have also compared these techniques based on their specific application (i.e., AC versus DC or transmission versus distribution). Some of these techniques have only been used for fault location in AC systems, while the others have been utilized for both AC and DC systems. Moreover, it is specified whether these techniques have been used in a manufactured TW relay or not.

IV. APPLICATION-BASED CLASSIFICATION OF TW-BASE PROTECTION SCHEMES

A. AC POWER SYSTEMS

1) TRANSMISSION SYSTEMS

In the following, the TW methods for transmission system protection are divided into single-ended and double-ended categories:

Single-Ended Methods: In [104], a TW-based protection for transmission lines is proposed that uses both the time and frequency domain of the waveform. This is done to avoid any confusion with a reflected waveform that is present when the algorithm only uses the time domain of the TW. To this end, continuous wavelet transformation (CWT) is utilized. This method is single-ended and does not require any communication infrastructure. The proposed method is verified on a 500 kV transmission system in PSCAD/EMTDC. Reference [24] proposes a distance protection scheme based on DWT and Kalman filtering methods. The paper verifies the proposed method for solid ground faults, phase faults, high impedance and nonlinear ground faults, and line charging on a 500 kV transmission system using PSCAD/EMTDC. db1 and db4 are used as the mother wavelets. Reference [23] proposes using DWT to perform ultra-high speed relaying in UHV transmission systems. The series compensated transmission lines or MOV's have varying impedance which is addressed in this paper. The proposed method uses DWT with db3 as the mother wavelet. The proposed method is verified using EMTP/ATP on a 750 kV transmission system. In [105], a time-domain DWT-based method is proposed. This method does not need to calculate any phasors as opposed to more common phasor-domain methods. In the phasor-domain approach, DWT solutions have trouble filtering out some harmonics of the signals. Using the DWT in the time-domain space should allow a more robust protection scheme where harmonics are not an issue. db8 is used as the mother wavelet. The proposed method is verified on a 230 kV transmission system using Matlab. Reference [60] utilizes an adaptive Kalman filter for identification of TWs. The adaptive extended Kalman filter estimates the instantaneous amplitudes of the TWs. The method combines the estimated optimal state of the wave (without noise) and a noise additive component. It compares the received TW to its estimates of what the TW of a certain distance should look like to determine the location of the fault. ATP is used to verify the effectiveness of the proposed method on a 220 kV transmission system. In [106], single-ended TW-based protection of transmission systems is studied. This paper focuses on analyzing the boundary elements effect on high frequency current differences. These boundary effects are used to determine if the fault is internal or external. The paper focuses on the stabilization process during the fault period to determine the boundary element effect on the harmonics. The paper simulates the algorithm using PSCAD/EMTDC. Reference [107] uses DWT in time-domain on a hybrid system consisting of a three phase wind generator, three phase load in parallel with the generator, and a 120 kV transmission system. As they discovered in their findings, to get a proper accuracy in detecting the fault they needed to choose a proper mother wavelet and given certain faults on the transmission system the signal decomposition will vary. In [108], fault location in transmission lines is performed using extreme learning machine on TW frequencies. TW frequencies are detected from the transient frequency spectrum extracted using FFT. Extreme learning machine is used as a regression method for improving fault location capability. The proposed method is verified on a 380 kV overhead transmission system modelled in ATP/EMTP. In [95], SVM is applied to the DWT coefficients for fault location and classification. The proposed method is verified on 230 kV transmission system simulated in ATP. In [78]–[80], EMD is used to analyze the TW fault components. These techniques have been applied to high voltage transmission lines where the sampling frequency of EMD varies from 1 kHz to 1 MHz. Single-ended TW-based protection using PCA has been utilized in [71], [73]. These methods are verified on high voltage transmission systems.

Double-Ended Methods: In [109], a protection scheme using TWs for Ultra High Voltage (UHV) transmission lines is proposed. This paper specifically looks at the characteristics of coupling capacitor voltage transformers and current transformers and their influences on TWs. This paper also validates its prototype protection scheme on a 750 kV UHV transmission line. TWs are analyzed using DWT with derivative of the cubic B-spline function as mother wavelet. The proposed method is double-ended and requires communication from the remote terminal of line. This paper uses EMTP to verify the validity of the proposed method. In [67], a TW-based protection scheme for parallel transmission lines is proposed. This scheme notably uses the Teager Energy Operator (TEO) to analyze the TW. The TEO only needs three samples to perform its analysis so its resolution is extremely high. This speed allows the algorithm to separate successive TWs that enter the relay. This paper uses PSCAD/EMTDC to verify the proposed method on a 400 kV transmission system. Reference [110] proposes a protection scheme based on placing a relay on terminals of two parallel transmission lines. The scheme uses a wavelet transform to detect disturbances on the lines as well as estimating the corresponding phasors. Then, it compares the magnitudes of the currents and phasors between the two lines. However, backup protection is needed as this method cannot detect all types of faults. The proposed method requires communication from remote terminals. It uses DWT with db4 as the mother wavelet. The proposed method is verified using PSCAD/EMTDC on a 400 kV transmission system.

Reference [111] proposes a method for protecting UHV transmission lines using a differential TW approach. However, this method does rely on limited communication. The authors are trying to achieve both high sensitivity and high reliability. This paper proposes applying DWT to the TWs with the derivative of the cubic B-spline function as the mother wavelet. EMTP is used for verifying the proposed method on a 750 kV transmission system.

In [112], the double-ended fault location method is used for analyzing the TW dispersion effect on transmission lines. This method is verified on a 500 kV, 414 km transposed transmission line that is modeled in ATP/EMTP.

The geometry of the transmission line is introduced to a classical J. Marti model in which the frequencies of the line are analyzed. This reference simulates a single line to ground fault at the 100 km on the line. The simulation studies consider changing the transition resistance and fault inception angle. The simulation results show that the proposed method renders less error compared to the traditional methods. Double-ended TW-based protection using PCA has been utilized in [74]. This method is verified on a high voltage transmission system. In [77], HHT is used to implement a fast-tripping differential protection approach for shunt-compensated transmission lines. The proposed approach is verified on 230 kV transmission system simulated in PSCAD/EMTDC.

2) DISTRIBUTION SYSTEMS

In [34], voltage TWs are analyzed by CWT. An algorithm is also proposed to build the mother wavelet using the voltage transients generated from the original fault. This is then compared to the traditional Morlet mother wavelet. The proposed method is verified on IEEE 34 Bus system using EMTP-RV. This method is single-ended and does not require any communication infrastructure. In [113], [114], a TW-based protection system for medium voltage distribution systems with distributed generation is proposed. The proposed method only uses local high-frequency current measurements. This method does not require communication links. Also, a disturbance classification algorithm is derived to reduce the risk of any false tripping due to other incidents that may produce a TW. The proposed method is verified on IEEE 34 Bus system using EMTP-RV.

Reference [115] proposes a TW-based protection scheme that only uses current measurements and needs limited communication. A simple exchange of binary signals with neighboring terminals is required along with local current measurements. The lack of any voltage measurements makes this scheme immune to any loss of voltage. The simple binary signal also makes it more robust to loss of communication channels. The proposed method is verified on IEEE 34 Bus system using EMTP-RV. Reference [30] proposes a TW-based protection method that can detect high impedance single-phase-to-ground faults. The scheme uses DWT and modulus maxima. It identifies the fault by comparing it to a non-faulted feeder. The paper simulates the proposed method on a 35 kV distribution system using EMTP.

The work in [116] proposes a method for short circuit fault detection in low-voltage distributed systems. The method is termed morphology-wavelet filter and is based both on wavelet transform and MM. In [36] a method for detecting high impedance faults (HIF) in distribution systems using TFA is proposed. The distribution used is the CWD. The method removes the fundamental component before using the TFA and then the dimensionality of this information is reduced using PCA. The fault detection is based on SVM. Reference [37] is a continuation of [36] to propose a fault location scheme for distribution systems that is active and in which a Chirp-like signal is injected in the system. Both works use PSCAD/EMTDC simulations. The work in [117] presents a method to detect HIF in distribution networks. The method uses DWT for feature extraction of current and voltage waveforms. A nearest neighbor clasifier is used on the RMS values of the DWT to differentiate between normal operations and HIF. In [45] a method based on MM is proposed for the detection of HIF. The specific operator used is the closing opening difference operator and is performed only in voltage waveforms. The paper argues that the distortion in voltage waveforms (caused by TWs) is more consistent than in current waveforms. This work uses PSCAD/EMTDC simulations.

It should be noted that most of the work at the distribution-level has been tested and validated with simulations and sometimes with hardware in the loop platforms. There is still a need for experimental setups to help validate and advance these techniques to real-world applications.

3) AC MICROGRIDS

In [118], a TW-based distance protection for microgrids with inverter-based distributed generators is proposed. This paper also focuses on the fault characteristics of inverter-based distributed generations. The paper uses DWT for TW identification. Using Chaari complex wavelet, this paper proposes a mother wavelet construction method that creates mother wavelets based on the characteristics of signals. The proposed method is verified on a low voltage microgrid with the operating voltage of 400 V. The microgrid is simulated in Matlab/Simulink.

B. DC POWER SYSTEMS

In the following, the existing protection schemes based on traveling waves for High Voltage DC (HVDC) and Medium Voltage DC (MVDC) power systems are reviewed.

1) HVDC SYSTEMS

The fast tripping protection schemes in HVDC systems are proposed in [119]–[126]. In [119], the frequency characteristics of TWs is used to develop an HVDC line protection scheme. The proposed method utilizes the first locally measured TW and focuses on the frequency component and polarity of TW rather than its arrival time. This method accommodates the primary operating time of less than 0.5 ms. It is also sensitive to high-resistance faults. The proposed method is verified on a 400 kV DC system using PSCAD/EMTDC. In [120], a TW-based protection technique is proposed which accounts for the power developed by both the forward and backward TW. The amount of power generated by these TWs can be used to determine if the fault is external or internal. This method will rely on taking both current and voltage measurements in order to calculate TW power. The proposed method is verified on a 400 kV DC system using PSCAD/EMTDC.

Reference [121] proposes a method for TW-based backup protection of a transmission line in an HVDC system. This paper analyzes the characteristics of TWs for internal and external fault currents and uses the characteristic differences to develop a backup protection scheme. The advantages of this method are a reliable way to detect high resistance faults and low computational burden. The proposed method is verified on a 400 kV DC system using PSCAD/EMTDC.

Reference [122] proposes a TW-based protection scheme for a line-commutated converter-based-high-voltage DC transmission line. The proposed method can detect high resistance DC line ground faults. A TW propagation calculation method is developed that reduces the impact. A normalized voltage change rate factor introduced which is utilized for identifying internal faults from external faults. The proposed method is verified on a 800 kV DC system using PSCAD/EMTDC.

In [123], another approach for the protection of line-commutated converter-based-high-voltage DC is proposed that accounts for the electro-magnetic coupling effect between double circuit HVDC transmission lines. This paper proposes a modal transform-based scheme that considers the wave front magnitude of modal voltage traveling waves. The proposed method accounts for the linear combinations of modal components rather than each independent modal component. The proposed method is verified on a 500 kV DC system using PSCAD/EMTDC.

In [124], a TW-based protection scheme for multiterminal HVDC systems is proposed. Continuous wavelet transform is utilized to calculate the arriving time of first TWs at all converter stations. In this method, the multiterminal HVDC system is modelled by a graph and a low memory demanding technique is proposed to identify the portion of graph that is faulted. The proposed method is verified on a 110 kV DC system using PSCAD/EMTDC.

In [125], the surge arrival time difference between the ground mode and line mode TWs is used for the fault detection on multiterminal HVDC systems. This paper uses mathematical morphology for the detection of surge arrival time difference. The proposed method is verified on 500 and 800 kV HVDC systems.

Reference [126] proposes a multiterminal differential protection for HVDC systems which is verified in PSCAD. The proposed protection scheme combines fault detecting and locating principles, fault isolating tools, and fault current limiting technologies. Derivative-based wavelet transform is utilized with db4 and Harr as mother wavelets is used to extract the high frequency fault components. In [127], a hybrid TW/distance protection for HVDC transmission line is proposed. The proposed method is based on monitoring the phase angles of characteristic harmonic impedance values. Moreover, the WT is utilized to detect faults in the regions that are not covered by the harmonic impedance monitoring technique. The proposed scheme is verified by simulating Hydro-Quebec HVDC benchmark in Matlab/Simulink. In [128], the transient current increments and its distribution over the line are calculated to detect and locate faults on an HVDC system. The proposed method is verified by simulating a 500 kV HVDC system in RTDS. In [129], a directional pilot protection for a multi-terminal HVDC system is proposed that utilizes the transfer function and specific characteristics of the TW currents. The proposed method is verified by simulating a 400 kV HVDC system in RTDS. In [130] a method to discriminate faults in HVDC systems based on the WT is proposed. The approach relies on analytical analysis to determine the parameters of the WT. It has an important discussion on the selection of the mother wavelet. The approach is validated initially with PSCAD simulations and then in hardware in the loop using RTDS. A real-time fault protection strategy for multiterminal HVDC systems is proposed in [131]. This strategy is based on the real-time boundary wavelet transform (RT-BWT) and it uses only local measurements. It was tested using real-time simulations.

Reference [132] proposes a high speed phaselet-based distance relaying scheme. The proposed method is implemented on an FPGA and uses IEC 61850 as the communication Sampled Value and Generic Object Oriented Substation Events (GOOSE) protocols. The Full-cycle discrete Fourier transform (FCDFT) and half-cycle DFT are too slow and have issues with harmonics. The phaselet scheme achieves a fast sub-cycle response. The algorithm runs a lot of parallel phaselet calculations, so a FPGA is proposed over the digital signal processor for faster implementation. The proposed method is experimentally tested on a 400 kV transmission system using RTDS.

2) MVDC SYSTEMS

MVDC microgrids are emerging at the distribution level due to their improved efficiency compared to AC systems. Moreover, they facilitate the effective integration of distributed energy resources with DC nature (e.g., photovoltaic and battery energy storage systems) by avoiding redundant energy conversion stages. However, the protection of DC microgrids is a challenging task due to the unique signature of DC fault currents, which is their high magnitude right after the fault occurrence and fast attenuation of the peak current in a couple of milliseconds. The high magnitude of fault currents can enable the internal protection of power electronic converters, used to integrate distributed energy resources (DERs), to save their internal power electronic switches that in turn results in the outage of DERs and loss of the integrity of DC microgrid. Therefore, designing a fast operating protection scheme that satisfies the fault-resiliency of DC microgrids is of paramount value. Moreover, the protection schemes are preferred to be communication-independent to effectively operate under communication network outages [7]. In [6], a TW-based method for MVDC microgrids is proposed. This method is unique in that it only needs to look at the first locally measured TW and focuses on its waveshape properties and polarity rather than its arrival time. The proposed method accommodates a TW capturing unit as well as a time constant estimation unit. Once the TW is captured, it's time constant is estimated to locate the fault. The response speed of this method is within a few microseconds. The scheme also does not require any communication and solely relies on local measurements. The proposed method is verified on a 2.5 kV DC microgrid using PSCAD/EMTDC. Reference [133] uses wavelet transform and artificial neural networks (ANN) to detect and classify faults in MVDC shipboard power systems. The features of different faults are extracted using wavelet transform multiresolution analysis (with db10 as mother wavelet) and Parseval's theorem which relates the energy of the fault signal to the energy of wavelet coefficients. This paper uses ANN to classify faults after the fault current features are extracted. The proposed method is tested on a 2.5 kV DC shipboard power system using RTDS.

C. POWER SYSTEMS WITH RENEWABLE ENERGY INTEGRATION

The integration of clean renewable resources, such as wind and solar, typically interfaced with the grid via power electronics converters, is changing the operations of power systems and their associated protection mechanisms. The work in [134] presents a good overview of the challenges faced by the protection community with a high penetration of renewable energy. The works on TW protection for power systems with renewable energy penetration can be roughly divided in two categories: those for hybrid transmission lines and those for microgrids.

Hybrid transmission lines are those composed of overhead lines and underground lines. This type of transmission system is common for interconnecting certain types of renewable sources such as offshore wind power plants. The work in [135] proposes a fault-location technique for hybrid multi-terminal transmission lines. This work uses the differences in arrival times of the TWs for fault location. The arrival times are determined using the DWT to the first mode of the Clarke transformation of the voltages. This work uses EMTP-RV simulations for testing. Reference [136] proposes a single-ended method based on TWs for fault location on transmission lines where overhead lines are combined with underground cables. It uses the DWT to analyze the aerial mode, using the Clarke transformation for fault location and identification. Reference [137] is an applied work on extending TW fault locating techniques from two-terminal homogeneous lines to multiterminal and hybrid transmission lines. The work in [138] proposes a method for fault location in hybrid transmission lines using TWs. The differentiating factor of this work from previous research is that the fault location is performed without any assumption regarding the velocity of propagation of the TW. In related research, [139] proposes a technique for fault location and detection of a TCSC-compensated two terminal line that connects a wind power plant. The method uses the fast discrete S-transform to analyze modal information of the three phase current for extracting TW information. This information is used for fault detection by analyzing the times of arrival. Each of these methods is able to improve the integration of renewable resources that connects to the system via hybrid transmission lines.

In the microgrid and distribution systems space some work has been devoted to TWs as a solution for integrating additional renewables. In [140] a model-based method for fault detection for inverter dominated microgrids is proposed. The method does not require communications and is intended to overcome the two type of errors that protection systems can have: breakers not tripping when they should, called blinding in this work, and breakers tripping when they should not, called nuisance tripping. The work in [46] is also for an inverter dominated microgrid and uses MM filters to extract information on TWs. The approach proposed in this work is tested with simulations conducted in PSCAD/EMTDC for a 20 kV microgrid. Reference [141] proposes a TW based scheme to isolate single-line-to-ground faults in distribution networks including distributed generation. The scheme uses WT to analyze TW information and is tested using the ATP/EMTP software platform. Other works have been cited previously like work [6] in IV-B2, and the works for distribution systems [113]–[115] in IV-A2.

V. REVIEW OF PATENTED AND MANUFACTURED TW-BASED PROTECTION SCHEMES

A. TW-BASED PROTECTION PATENTS

In [142], [143], a variety of different techniques for calculating fault location using TWs in an intelligent electronic device (IED) are disclosed. The IED includes different modules including a TW detection module and a fault location estimation module. The fault location estimation module uses the arrival time of the first TWs at both ends of the power line to calculate the fault location. In [144], a TW-based protection scheme for HVDC transmission lines is disclosed. This patent includes methodologies for estimating the amplitude of TW at the fault location, calculating the fault resistance, estimating pre-fault voltage value at the fault location, and calculating surge impedance of power line. Using voltage measurements at both sides of the line, the proposed methodologies can estimate the TW magnitude and pre-fault voltage at the fault location. The patent also discloses a fault detection device that comprises the above-mentioned estimation and calculation algorithms. Reference [145] discloses a fault sensing system using TWs. The proposed method is based on estimating at least one TW of current or voltage at each position and comparing them against some determined TW thresholds. In [146], the TW-based protection is performed using a Rogowski coil and a processor. The Rogowski coil is placed on the power system to detect the TWs resulting from faults on the transmission lines. The output of the Rogowski coil and the original TW signal are used in the processor to identify the fault location. This method is also double-ended and relies on the TW arrival time at both ends of the line. In [147], a time reversal process is proposed which uses electromagnetic waves initiated by faults. This method is single-ended and calculates a time inversion of the measured TWs to identify the fault location.

B. MANUFACTURED TW-BASED PROTECTION RELAYS

Even though there are many research articles available that address fast-tripping fault location using TWs, only a few of TW-based relays are commercially manufactured. In [101], [102], the smoother-diffrentiator technique discussed in Section III.A and the patent disclosed in [142] are utilized to create time-domain fast-tripping protection relays. In these manufactured relays, a TW-based differential element, an incremental-quantity distance element, and a TW-based transfer trip scheme are incorporated to detect faults within 1 to 5 ms. Using ultra-high sampling of measured current and voltage values, [103] calculates the arrival time of TWs at both terminals of a power line to identify the fault location. [103] can find the fault location with an accuracy of less than 50 m in a few milliseconds. This solution can effectively work for AC and DC high voltage power lines.

In recent years, there have been some pilot projects verifying TW-based protection in both AC and DC systems. The time domain technology in [101] has been commissioned and employed by an electric power utility as mentioned in [148]. The manufactured relay in [103] has been also verified through some pilot projects [149]. Some TW-based protection pilot projects for HVDC systems in Canada and Germany are discussed in [150].

VI. REVIEW OF SIMULATION TOOLS FOR TW-BASED PROTECTION SCHEMES

Given the specific signature of high frequency components of fault currents, the tools utilized for the simulation and study of protection schemes should accommodate a high-fidelity simulation of fault scenarios. To this end, this paper reviews and compares the existing commercial software packages that are suited for studies of protection schemes.

A. DESCRIPTION OF COMMON SOFTWARE PACKAGES FOR ASSESSING PROTECTION SCHEMES

1) EMTP-RV AND ATP

The Electromagnetic Transients Program (EMTP) originated in the seventies from the Bonneville Power Administration and its theory and usage are well documented in the EMTP 'Theory Book' [151] as well as in the proceeding of the International Conference on Power System Transients [152]. In the '90s, various groups, such as Manitoba Hydro(PSCAD/ RSCAD) [153], Development Coordination Group (EMTP-RV) [152], and others, began to commercialize the EMTP code, while the original code was remained in the public domain under the name 'Alternative Transients Program' (ATP). Other tools such as Matlab/Simulink's Simpower/Simscape [154] also use many of the models originally created for ATP. ATP Draw was developed as a public domain graphical user interface by the European EMTP_ATP user's group [155].

ATP was originally developed to study switching transients in long, extra- and ultra- high voltage (EHV, UHV) transmission lines. ATP uses the simple trapezoidal rule and the method of companion networks [151], to solve the differential equations that apply to a power system model. Nonlinear elements are most commonly accommodated via compensation techniques, which may require special treatment [151]. EMTPR-RV [152] uses an iterative solution for nonlinear elements. As with any simulation method the user must carefully understand and model not just the main elements in a system, but all parasitics as well. Over the last fifty years, the code has grown to include the modeling of rotating machines, transformers, substation equipment, power electronics and control systems. Some key features include nonlinear models (e.g., saturation), frequency dependence models, corona and arc models and statistical analysis. Some of these models involve simplifying assumption that the user must understand. A large library of models, many of which have been field tested, is available. ATP normally is used on a multicore desktop or workstation, but has been compiled to run on Graphical Processor Units(GPU) [156] and real-time implementations have also been reported (e.g., [157]).

2) PSCAD/EMTDC

PSCAD/EMTDC is a robust tool for simulating time domain instantaneous responses and electromagnetic transients in electrical systems. This software solves the electromagnetic and electromechanical systems' differential equations in the time domain. Differential equations are calculated based on a fixed time step basis. PSCAD/EMTDC accommodates the simulation of transients on lines and cables using a frequency dependent (phase) model. The frequency dependent model is built upon a TW model in which all line/cable parameters are frequency dependent. Moreover, the model's internal transformation matrices are all frequency dependent. This facilitates the detailed simulation of different frequency components of TWs. In the frequency dependent model, curve fitting is utilized to approximate the impedance and admittance of line/cable with a N^{th} order approximation. Users can specify a frequency range for these calculations. Another useful component in PSCAD/EMTDC library is its discerete wavelet transformation. This component calculates the wavelet coefficients for different sampling frequencies. Users can choose a variety of mother wavelet functions including Harr, Daubechies, Symlets, and Coiflet [153].

B. LINE/CABLE MODELS USED FOR THE SIMULATION OF FTPS

The most simplistic approach to model a transmission line is using the Π-model. However, this model exhibits considerable shortcomings for the proper simulation of transient phenomena. The first one is that it uses a lumped-parameter scheme, losing sight of the distributed parameter nature of the conductor, which in turn makes it only suitable for short lines (lines that are much shorter than the transient wavelength λ). All transmission line parameters are modeled at a single frequency (e.g., 60 Hz). The second one is that the differential equations used for modeling the voltages and currents in the line (e.g., telegraph's equations) are time-independent, which limit the modeling to a steady-state condition and fails to capture any transient behavior of the line.

The most complete models that capture all of the temporal behavior of lines are the ones that incorporate the distributed nature of the line parameters and that include partial differential equations (in space and time) in order to provide a more complete solution for the representation of voltages and currents at any point in the line at any given time.

Another important feature of these models is the inclusion of the frequency-dependent characteristic (or surge) impedance as well as the propagation constant. This is important because as frequency increases the skin effect and the earth-return current (soil effect) become more prevalent, and it is important to capture these effects on the electromagnetic transient model.

There are two types of frequency-dependent models: the modal domain and the phase domain model. The modal domain model developed by Martí [158], decouples the lines in a multi-phase line by using real-constant transformation matrices. This allows to treat each line independently as an uncoupled mode. This matrix transformation method provides excellent results when dealing with balanced systems, but it becomes inaccurate when the system in unbalanced.

The modal domain model develops the line equations between nodes k and m in the frequency domain. These equations can be synthesized into two equivalent Thévenin circuits with impedance equal to the characteristic (or surge) impedance as a function of frequency, and with voltage sources representing the past history of the transmission line. When converting these equations back to time domain, two convolution integrals need to be performed: one with the characteristic impedance, and the other with the propagation matrix. By fitting the propagation matrix with rational functions in the frequency domain, the integral can be evaluated very efficiently because in the time domain the propagation constant is an exponential. In this way the convolution integral is reduced to what is called a *recursive convolution*. Furthermore, if the input is assumed constant during the time step of the integration, then, an analytical, closed form for the recursive convolution can be obtained [159].

The second frequency-dependent model, the phase domain model, avoids the problems associated with the mode transformation matrices by directly working the formulation in the phase domain [160]. The phase domain model is accurate for all transmission line configurations, even if the lines are unbalanced. This model is the most advanced and accurate time-domain line model, it is considered to be the *universal line model* [161], [162].

If the objective is to capture TWs for fast-tripping protection schemes (FTPS) during simulation, a frequency - dependent model in phase domain should be used. There are mainly four models in the phase domain [160]: the Taku Noda model [163], the Z-line model [164], the idempotent line model [165]–[168], and the Nguyen direct phase-domain model [169].

In the Taku Noda model, the telegraph's equations are manipulated algebraically in the frequency domain to obtain a set of two coupled equations: one for the sending and the other one for the receiving current. The n-conductor transmission line is represented by two independent current sources representing the history of the line and delayed by τ, the minimum traveling time between terminals k and m. Each conductor on each side of the circuit is connected to ground by its characteristic admittance $\mathbf{Y_c}$. Transforming these equation to time domain requires eight convolutions. The computing time of these convolutions can be improved by replacing them with the ARMA (Autoregressive Moving Average) model in the z-domain.

The challenge of superposition of traveling times in the coupled-phase waves in the phase domain modelling is solved in the Z-line approach by the superposition of an ideal wave propagating at the speed of light, and a second wave that is shaped by the parameters of the line which are a function of frequency. The Z-line model consists of two sections of lines connected in series: the ideal section and the section that accounts for the losses [164].

The third model, the idempotent model, avoids the problem of using eigenvectors for the treatment of the modal transformation matrices. The use of multiple-choice eigenvector functions becomes more problematic when there are repeated eigenvalues. Instead, this model represents the phase-domain propagation function $\mathbf{e}^{-\gamma_{ph}x}$ (a matrix function) as a linear combination of the natural propagation modes $e^{-\gamma_i x}$ (scalar functions) with idempotent coefficient matrices [165].

By using rational functions for the synthesis of the propagation function, the idempotent matrix, and the characteristic impedance, time-domain exponential functions are obtained as the elements of these matrices. In this way, The computation time of each operation is faster since the exponential functions allow the use of recursive convolutions [160].

Prior methods to Nguyen's rely on real and constant transformation matrices for conversion between the modal and the phase domains. These models become more and more inaccurate as the asymmetry of the line increases. Direct phase-domain modeling techniques address this problem but the numerical stability of the efficiency of the solution could be affected [169].

Nguyen's method, also a direct phase-domain method, removes the stability concern of the solution by employing a different fitting routine. This is a modified version of the fitting routine developed by Martí [158], [170]. Also, the time domain characteristic impedance and time domain propagation function matrices are composed of elements that are linear combinations of exponential functions. In this way the time domain convolutions are evaluated very efficiently using fast recursive methods [158], [170].

Nguyen's direct method is extremely useful when modeling transmission lines with a high degree of asymmetry. It is also a good alternative to analyze induced voltages on railways that run parallel to a three-phase line [160], [169].

C. HARDWARE-IN-THE-LOOP SIMULATION OF FTPS

1) Opal-RT HYPERSIM

Advances in parallel computing are allowing the proliferation of Hardware-in-the-Loop (HIL) real-time simulators. HIL systems provide a testing platform that permits the rapid prototyping of control schemes and their incorporation into simulation environments either in real time or offline. This simulation scheme is referred to as Control-Hardware-in-the-Loop (CHIL). Furthermore, HIL systems also permit the addition of power interfaces, such as power amplifiers or power converters, into the simulation testbed. Such a setup is called Power-Hardware-in-the-Loop and is largely used to

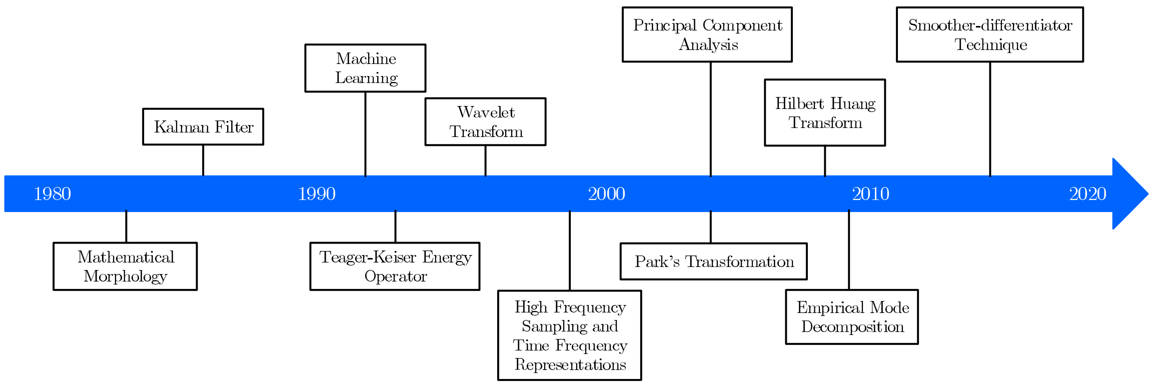

FIGURE 5. **Timeline diagram of surveyed TW techniques.**

test and validate commercially available power conversion devices such as inverters and DC-converters. Hypersim is an EMT-domain simulation environment created by Opal-RT Technologies which allows testing and optimization of control and protection systems used in power grids [171]. With the proper hardware, Hypersim can run real-time simulations with fixed time step resolutions down to 40 μs. Whereas, while working offline, it allows simulation time steps as low as 200 ns. For transient sub-cycle analyses involving TW dynamics, high resolution simulations are crucial in determining arrival times of TWs.

2) RTDS

Real Time Digital Simulator (or RTDS) is a similarly attractive platform for fast, reliable, accurate and cost-effective simulation of complex power systems and power electronics devices. RTDS uses parallel processing to accommodate HIL simulation and testing through a set of analog/digital inputs/outputs. The Traveling Wave Relay Testing (TWRT) functionality enables RTDS to be used for testing TW protection relays in an HIL closed loop testbed. To effectively simulate TWs, the convectional Bergeron transmission line models that are simulated at 25-50 μs time step cannot be utilized as they fail to model the attenuation of TWs. However, this tool incorporates frequency dependent phase domain transmission line models that can be simulated at small time steps (1-3 μs) required for TW testing. Users can model multiple line segments to simulate faults at multiple locations as well as physical transposition [172]. TWRT has been used to test a commercial TW relay according to [173].

VII. SUMMARY OF THE STATE OF THE ART

This paper cites works from 1981 to date regarding protection schemes based on different methods to extract information on TWs or distorted waveforms. A timeline diagram of the different extraction methods is presented in Fig. 5. This figure shows that very early on work started with methods such as mathematical morphology and the Kalman filter. More recently, there are works with other methods such as EMD and the smoother-differentiator technique. For research purposes, the WT is perhaps the most popular method for protection applications; work with this method started in the mid-'90s. The cited works use a number of different software to generate data with TW information to test their proposed protection techniques. In addition, some of these works use recordings of actual data. Fig. 6 shows the 12 different software or data categories of the papers cited by this work. These data shows that 9% of the works do not reference the software or the type of data they use. The most popular software is PSCAD/EMTDC with 35% of the cited works using it. ATP/EMTP is second with 20% of the works using it. Matlab/Simulink is used in 11% of the works, while Matlab only is used in 3% of the works. The distinction between Matlab/Simulink and Matlab was done because that is how the papers themselves refer to the software. Around 8% of the works mention using an EMTP-type of software, but they do not mention the specifics. Data generated by real-time digital simulation and actual data from recordings are used around 3% and 2% of the time respectively.

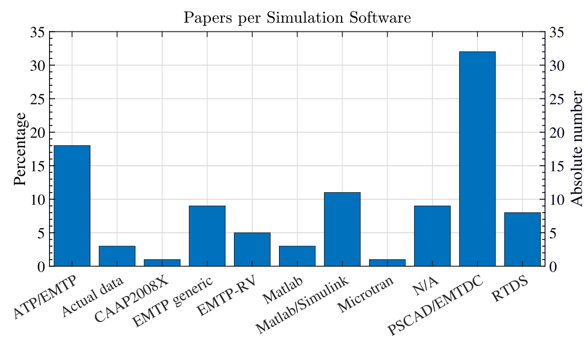

FIGURE 6. **Histogram of the simulation software used by the papers cited in this work.**

Fig. 7 shows the application of the papers referenced in this work. The figure shows that overwhelmingly most works are for transmission level applications with more than 60% of them dedicated to it. The second most common applications are distribution with 16% and HVDC with 9%.

VIII. LIMITATIONS OF TW-BASED FAULT LOCATION

Even though fast-tripping protection schemes often utilize TW-based fault location techniques, there are some

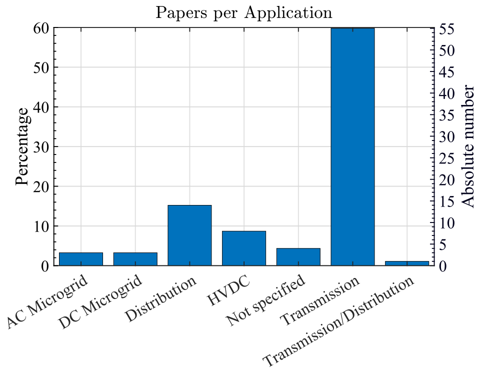

FIGURE 7. Histogram of the application of the papers cited in this work.

limitations that can affect the practical implementation of these schemes. In these cases, the standalone operation of TW-based protection schemes can endanger the reliability of power grids. These limitations are summarized as follows:

1) For lower voltage level power systems, capturing high frequency TWs of currents can be a challenging task. In [174], it is mentioned that for power grids with operating voltages lower than 35 kV, the current TW front value is attenuated, which may make it ineffective for fault location applications. On the other hand, [174] recommends the use of voltage TW for these networks. However, the voltage TW can be highly impacted by the frequency response of the voltage transformers (VT).
2) To effectively capture the TWs in low voltage power grids, ultra high resolution data sampling is required to extract high frequency components of TWs at the expense of increased computational complexity and burden.
3) The presence of tap points on overhead lines impacts the TW magnitude and its arrival time, which deteriorates the performance of TW-based fault location techniques [174].
4) The frequency response of coupling capacitor VTs (CCVT) can attenuate the high frequency components of TWs, which renders inaccurate performance of TW-based fault location schemes [175].

IX. FUTURE SCOPE AND TRENDS

The nature of power systems is evolving to accommodate more and more inverter-interfaced devices. Renewable resources, mainly wind and solar PV, are those primarily responsible for this evolution. In addition, the traditional boundaries of transmission and distribution are going to be blurred in future grids partly because of the widespread installation of inverter-based distributed energy resources (DER). These fundamental changes to the grid will require that protection mechanisms adapt accordingly in order to maintain the secure operation of the system. Fortunately, along with the aforementioned changes in grid configuration, there are new technologies in monitoring and control that can be used to design and implement novel protection schemes.

It is anticipated that protection schemes will make use of data sampled at ultra high resolutions which are necessary to capture the high frequency components of TWs and are of particular importance for fault detection and location in distribution systems. The future grid is going to have more sensing devices and will communicate more data out of them is going to be communicated. These data can be leveraged with machine learning/artificial intelligence methods to develop data-driven protection schemes for fast detection and classification of system faults. Future protection schemes are also expected to be informed by data available in different parts of the system, even remote in areas. Such an idea already exists with synchrophasor data but in the future time synchronized point-on-wave measurements might be available. Because future protection schemes need to be resilient, these schemes will also be adaptive, robust to communication failures, and system changes. At the local level, protection schemes will use all information available, that is, local voltages and currents (and quantities derived from them such as power and frequency). Techniques aimed at predicting the occurrence of faults will also be leveraged in future protective equipment.

Another game changer in future protection schemes is the inclusion of protective and fault detection functions to the power-electronics interfaces of DERs, by making an extended use of all the available local measurements that these interfaces take, such measurements can provide valuable information in helping to discern abnormal grid conditions. In such configuration the protection of the system is distributed with the DER penetration. The inclusion of protection mechanisms to the interfaces of DER can also enable active protection schemes where the *protective equipment* inject controlled and *unnoticeable* signals to the grid to determine the occurrence of faults.

X. CONCLUSION

This paper presents the basic theory of TWs in power systems and how it can be used to design protection schemes that act much faster than traditional approaches. Such schemes are expected to be paramount to maintain the reliability and secure operations in future grids with higher contributions of inverter-based generation. The paper presents the most widely used signal processing methods to extract information of TWs in power system waveforms. The specific characteristics of each method are detailed and they are compared when appropriate. The paper then presents a survey of protection schemes at the transmission and distribution levels for both ac and dc systems. It is shown that protection schemes using TWs have been studied at the transmission level for several decades however at the same type of ideas have only sparsely been explored at the distribution level. The paper also presents a review of the most commonly used tools for performing research in power system protection.

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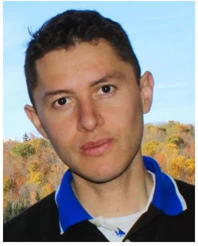

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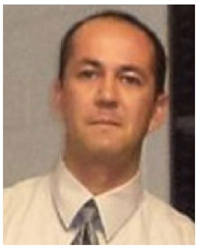

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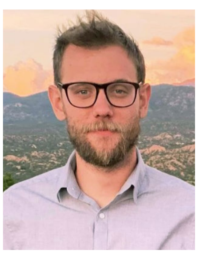

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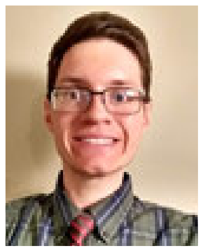

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