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A Review on the Application of the Time Reversal Theory to Wire Network and Power System Diagnosis

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***Abstract*—Transmission lines are the backbone structures of electrical systems. They play a primary role in energy and signal distribution where their reliable functioning is of critical importance. The fault location problem has been thoroughly studied due to the importance of safety and reliability aspects. Among various methods, time reversal (TR), which is an adaptive focusing technique employed to focus waves in space and time, has been lately applied with success to transmission line fault diagnosis. Its unprecedented performance has been demonstrated for precisely locating soft and hard faults in simple and complex topologies in both power and communication networks. This paper provides an overview of the state of the art TR techniques and their applications in communication and power networks.**

***Index Terms*—Wiring networks, transmission lines, fault detection and location, time reversal, power grids.**

I. Introduction

The last century has witnessed an enormous growth in world population from 1.6 to 7.7 billion during which the fourth industrial revolution broke through [1]. This was accompanied with a fast development in technology and a vast reckoning on electrical energy. Electrical cables and transmission lines are the fundamental elements that enable reliable transfer of energy and information. The rapid development of complex and large systems or power grids has necessitated more and more wires and cables in electrical systems to transmit power and control signals.

These wires and transmission lines are always prone to faults and failures due to several internal and external conditions (manufacturing anomalies, thermal stress, lightning strikes, etc.). In general, the above-mentioned disturbances can cause counteractive effects on the quality of power supply leading to problems ranging from voltage sags and swells, insulation deterioration, or even blackouts. Therefore, in power transmission networks, fault location functionality is needed for the identification of the faulty line and the adequate reconfiguration of the network to prevent severe cascading consequences. However, fault location in distribution networks is more associated with the quality of service in terms of duration of interruptions when permanent faults occur. In this respect, the problem of fault location has received great attention with the aim of developing methods to protect power lines and cables.

On the other hand, cable networks are not only important for power delivery, but also form the backbone of communication in buildings and transportation systems, where they often provide the main support for transmitting control and safety signals. The criticality of these applications becomes apparent in transportation systems, where the inability to detect the presence of faults can lead to dramatic consequences, as experienced in past railway and air flight accidents. While hard faults (open or short circuits) clearly represent the most critical situation, severing a network into two separate parts with no possible transmission, soft faults do not appear immediately as a threat, because of their weak reflectivity and minor impact on signal propagation. Most soft faults are local modifications found along a cable that can go from light chafing to partial removal of coatings or conductors, but may evolve into more critical faults, and ultimately hard faults. Therefore, guaranteeing a trustworthy employment of wiring and preventing their exposure to jeopardy necessitates the development of reliable fault detection and location techniques.

Although wire diagnosis has been widely studied in the literature for many years and numerous methods have been proposed [2], time reversal (TR) based methods have been recently extensively investigated and applied. Time reversal has emerged as a very interesting remote-sensing technique with potential applications in various fields of engineering [3]. It has received great attention in recent years, particularly in the field of acoustics for the detection and location of scatterers [4], [5]. In the past decade, the technique has also been used in the field of electromagnetics and applied to various other areas of electrical engineering [6], [7]. In particular, the technique has been successfully applied in the fields of electromagnetic compatibility (EMC) and power systems, leading to mature technologies in source-location identification with unprecedented performance compared to classical approaches [3]. It is expected that the fields of application of electromagnetic time reversal (EMTR) will continue to grow in the near future.

The application of the EMTR has been extended to fault location problem in wire networks, thanks to the close relationship that exists between the problem of scatterer detection in radar and fault detection in cable networks [8]–[10]. In fact, TR can ensure a maximization of the fault-related echos by maximizing the energy impinging on the fault position with respect to the rest of the network under test (NUT). Thanks to the invariance feature of the wave equations in transmission lines, it has been shown that if the time-reversed signals, that are originated by the fault, are back-injected to the system, they will converge to the source location. It is noteworthy that re-transmitting the time reversed signals is a kind of matched filtering for the time-invariant components, while it is a kind of energy spreading for the time-varying components.

In the literature related to the application of the EMTR to the fault location in wired networks, two different applications could be distinguished. The first one exploits the TR property for locating faults in power networks. The fault in this case is considered active, i.e, electromagnetic transients originate from the fault itself [9]. A fault event is associated with an injection of a step-like wave initiated by the fault occurrence. The fault-generated waves travel along the lines of the network and get reflected at the line extremities where they are recorded within a specific time window. EMTR is then applied on these recorded waves. Promising results have been obtained for both hard and soft faults in simple point-to-point and complex branched networks.

On the other hand, the second category investigates the application of the EMTR for detecting faults in communication networks. In this context, faults are passive and are characterized by a change in the characteristic impedance of the line at the location of the fault, i.e an impedance discontinuity. TR is here applied to the recorded waves at the extremities of a NUT resulting from echoes reflected at the faults' positions due to testing signals injected to the testing ports of the network. In this case, only soft faults are investigated in both simple and complex NUTs. Besides, two approaches have been studied within this application, the first employs TR as a matched-filter signal processing tool to ensure the highest fault-related echo with respect to a given injected energy. The method referred as the matched pulse (MP) approach using a single testing port has shown remarkable results with an increasing network complexity and in the presence of noise [8]. The same concept was also adopted in [11] to enable precise cable aging detection. In another development, two TR variants have been deployed, DORT standing for the french acronym of the decomposition of the time reversal operator and TR multiple signal classification known as TR-MUSIC [8], [10]. For instance, they allow the simultaneous analysis of all NUT multi-port data leading to energy focusing on the position of soft faults in an imaging manner.

This paper presents a review of the current and recent state of the art applications of the EMTR in the field of wired network and power system diagnosis, and is organized as follows: after an overview of the basic concept of EMTR in sec. II, sec. III will present the latest results obtained with the application of TR to power cables. The transposition of EMTR to soft fault detection, location and characterization in communication networks will be reviewed in sec. IV. The last section concludes this paper by addressing the final remarks on the performance EMTR for wire diagnosis.

II. BASIC CONCEPT OF THE EMTR

The basic idea of the EMTR when applied to guided wave propagation along transmission lines is to take advantage of the reversibility in time of the wave equation. The transients observed and recorded in specific observation points of a network (usually extremities) are time-reversed and transmitted back into the system. The time-reversed signals are shown to converge to the fault location.

Thanks to the reversibility in time of the Telegrapher's equations, EMTR has been successfully applied to the fault location problem. Noteworthy, telegrapher's equations are invariant under a time-reversal transformation for lossless lines. However, electromagnetic propagation involving a dissipative medium is not rigorously time-reversal invariant unless an inverted-loss medium is considered for the reverse time [12].

In what follows, we will briefly examine the properties of the transmission line wave equations under time reversal. The voltage wave equation for a multi-conductor, lossless transmission line (for simplicity) is given as:

$$\frac{\partial^2}{\partial x^2}U(x,t) - LC\frac{\partial^2}{\partial t^2}U(x,t) = 0 \tag{1}$$

where $U(x,t)$ is the phase voltage at position x and time t, while L and C are the per-unit-length matrices of the inductance and capacitance of the line, respectively. Applying the time reversal operation on eq. (1) yields

$$\frac{\partial^2}{\partial x^2}U(x,-t) - LC\frac{\partial^2}{\partial t^2}U(x,-t) = 0 \tag{2}$$

Therefore, under the reversibility in time of the wave equation if $U(x,t)$ is a solution of the wave equation, then $U(x,-t)$ is a solution too. Noteworthy, the EMTR in the time domain is applied in the frequency domain as follows ($U(x,-t) \mapsto U^*(x,f)$) where (*) is the complex conjugate.

As mentioned earlier, the first application of the EMTR for wire diagnosis will be dedicated to locating transient originating faults in power cables and overhead lines as will be explained in the following section.

III. EMTR FOR FAULT LOCATION IN POWER NETWORKS

Fault detection and location is a critical process in power transmission and distribution networks as the performance of the process directly affects the security and reliability of the electricity supply.

The fault location problem in power networks has been investigated since the 1950s (e.g., [13]) and numerous methods have been reported (e.g. [14]–[16]). These methods can be classified in two main categories: (i) methods based on phasor (impedance) analysis and (ii) methods based on fault originated travelling waves (TW). Phasor-based methods are, in general, more straightforward to apply and historically have been widely used in real applications. However, their performance might be affected by the pre-fault conditions such as system load flow, fault impedance, and measurement noise. Therefore, TW-based fault location methods have been increasingly used as a suitable alternative to overcome those drawbacks. Nevertheless, these methods, in general, require multiple measurement points and 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.

Recently EMTR theory has received a great attention as an efficient fault location method to overcome above-mentioned limitations. The application of the EMTR for the fault location problem has been first proposed in [17]. The proposed method takes advantage of the time-reversal invariance of the wave equations in transmission lines. In addition, confinement of the waves within the boundaries of the network allows to effectively apply the EMTR process using a single measurement point.

It has been shown that the EMTR method can be equally applied to radial/meshed AC/DC power transmission or distribution networks, and compared to other TW-based methods, irrespective to the size and complexity of the network, the method requires only a single measurement point. Furthermore, the accuracy of the method is robust against fault impedance and measurement noise.

In brief, the proposed EMTR method in [17] is based on the three steps:

1) *Forward propagation phase*: the fault originated voltage transient signals are recorded in a single measurement point.
2) *Backward propagation phase*: as the main unknown in the location of the fault, a number of guessed fault locations (GFL) are defined. The recorded signals are inversed in time and back-injected to the simulated network model from the same measurement points.
3) *Fault location characterization*: The fault current at each GFL is calculated. According to the temporal and spatial correlation properties of the TR theory, the back injected signal will arrive in phase only when the GFL corresponds to the real fault location. Therefore, the fault current signal energy (FCSE) can be used as a metric to identify the real fault location.

Using the FCSE criterion, it has been shown that the EMTR process can be successfully applied to different types of power networks such as inhomogeneous networks and radial distribution grids [17], series-compensated transmission lines [18], and multi-terminal HVDC networks [19], [20]. In addition, practical applications of the method has been demonstrated using a reduced-scale experimental setup realized by coaxial cables [17] and a full-scale experiment in an unenergized 677-m-long, double-circuit 10-kV overhead distribution line [21].

Considerable attention has been recently devoted to the use of EMTR procedure with different norms, and several metrics to identify the real fault location have been investigated. He *et al* studied the use of the norm criteria in the EMTR fault location method [22]. It has been shown that compared to the 2-norm criterion (which is equivalent to the FCSE), the ∞-norm (equivalent to the amplitude peak) represents higher location accuracy in noisy environment. Using properties of the back-injected signals in the backward propagation phase, a so called Maximum Cross-Correlation Sequence metric has been proposed in [23]. This method analyzes the similarity between the signals respectively observed in the forward- and backward-propagation phases.

The proposed method of [17] relies on the inspection of multiple GFLs in the network. Thus, in order to accelerate the process, alternative methods in frequency domain using the argument of the voltage along the line [24] and using mirrored minimum energy property [25] have been proposed. In these methods the transverse branch representing the fault is removed in the backward propagation phase. Thus, the process can be applied using a single simulation of the back-propagation model.

Most recently, the approach presented in [24] has been also extended to locate soft faults [26] and longitudinal defects [27] in transmission lines using the bounded phase property of the TR voltage or current transfer functions, respectively.

IV. EMTR FOR CHARACTERIZATION OF COMMUNICATION WIRED NETWORKS

In this section, the application of the EMTR to communication networks will be investigated. The first part will deal with the matched pulse technique for locating soft faults in complex branched NUTs as well as estimating the cable aging. On the other hand, the second part will present the results obtained with TR imaging techniques namely DORT and TR-MUSIC.

A. Matched pulse to reliably detect soft faults

There has been a growing interest in the last decade in developing reliable means of detecting the presence of soft faults and in particular in monitoring their state, in order to intervene before they risk becoming hard faults. Unfortunately, the difficulties in detecting them with standard time-domain reflectometry are well-known, basically due to their weak reflectivity [28], [29]. Notably, state of art of time-domain reflectometry methods show that they are essentially based on a time-domain approach where a test signal is injected into the NUT and the reflected one is monitored in order to detect the presence, position, and nature of an impedance discontinuity.

Indeed, weak echoes from soft faults affect their detection in two ways: a) echoes can be significantly smaller than those from other discontinuities, e.g., junctions, and thus go unnoticed; b) power limitations in test signals could lead to echoes not standing out of the noise background. Moreover, as a network grows more complex, the large number of spurious echoes from junctions makes it ever more difficult to sort out the presence of weak echoes.

Time-domain reflectometry using matched pulses (MP) was introduced in [30] as the first application of time reversal principles to fault detection, in order to improve the probability of detecting soft faults in cable networks. Standard TDR methods would use a network-independent test signal $i_{ST}(t)$, producing an echo response $e_{ST}(t)$. MP rather defines an ad hoc test signal $i_{MP}(t) = e_{ST}(T - t)$, with T the duration of $e_{ST}(t)$. According to TR theory, injecting a time-reversed version of the NUT response should result into injected signals partially focusing onto the fault, thanks to the reciprocity of the NUT. In practice, $i_{MP}(t)$ ensures that the maximum possible instantaneous power impinges over the fault, thus producing the strongest echo with respect to any other test signal; by the same token, less energy interacts with the 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.

Moreover, MP was shown in [31] to thrive in complex configurations, where the number of spurious echoes can exceed the hundred. A situation that would make inferring the presence of a soft fault hardly possible with any standard TDR test signal, actually results in a sizeable improvement with MP. The focusing resulting from using TR signals was proven in [31] to result in a detection gain as high as 20 dB, as defined as the apparent amplification of the fault echo, while keeping unchanged the input energy.

As a direct consequence, the amplification of the fault echo results in an effective increase of the signal-to-noise ratio, and therefore a higher probability of detecting the fault's presence.

These results, based on a comprehensive theoretical derivation, plus thorough numerical and experimental analysis in [31], showed that MP is an effective solution to the issue of detecting in a reliable way the presence of soft faults in realistic complex NUTs, where large sequence of echoes typically lead standard TDR methods to fail.

In a recent study, the authors in [32] integrated the MP approach with the multi-carrier reflectometry (MCR) method which successfully enabled online network diagnosis and sensor communication in complex NUTs. Thanks to the multi-carrier signals' capacity to control the signal bandwidth [33].

B. EMTR for cable aging estimation

Aging can be an important issue for cables, especially if they are part of a critical system. As defined by IEEE 1064 standard, aging is the occurrence of irreversible deterioration that critically affects performance and shortens the useful life of a system [34]. Cable aging has become a critical issue for avionics, that led to the creation of the Aging Transport Systems Rule-making Advisory Committee (ATSRAC) in 1999 which delivered a report [35] providing guidelines and recommendations for the detection of defects in cables and bundles.

But aging can also be characterized by the global degradation of the properties of a cable, along its length, either of the insulator or the conductor. Many factors can cause global aging such as: electric field, temperature, moisture, radiations, chemical corrosion, mechanical vibration, etc. Standard reflectometry is not suited to the detection of such an aging phenomenon, even less in its quantization. But the use of EMTR in this context as performed in [36] has proven to be very interesting for cable aging monitoring and estimation. Numerical simulation and experimental measurements have shown the possibility to detect aging and also provide an accurate index for its quantization. The comparison of this estimator with a predetermined threshold can help anticipate timely maintenance of degraded cables.

The proposed EMTR-based cable aging estimator process can be summarized as follows:

- First inject a symmetric signal, such as a Gaussian pulse, in a new cable and record the reflected dispersed (thus no more symmetric) signal. The reflected signal is time-reversed and stored for further use throughout the life of the cable. If it would be injected again in the new cable, it would give rise to a symmetric reflected signal.
- Whenever required during the lifetime of the cable, inject the saved signal and measure the reflected signal from the aged cable.
- Estimate the asymmetry of the measured reflected signal and derive a "skewness coefficient". The comparison of this coefficient with experimentally or theoretically predetermined values enables to quantize the aging.

Notably, the proposed method is based on the fact that dispersion changes the shape of a signal while it propagates in a cable. This phenomenon has a negative impact on standard reflectometry methods as it decreases the location accuracy of the defects. In the context of aging, dispersion is used as an advantage: propagation in an aged cable will see the dispersion change when compared with its value when the cable was new. Thus, comparing the signal's dispersion in an aged cable with the dispersion in a new cable shows the effect of aging.

C. TR imaging methods

Although the MP approach ensured a higher sensitivity to the presence of soft faults than reflectometry methods, ambiguity in the interpretation of their results was encountered as soon as the NUT becomes complex (multiple branches).

Consequently, TR imaging methods were transposed to guided-wave propagation in wire networks. They allowed two major differences with respect to existing MP and TDR based techniques: 1) Multiple testing ports are used thus allowing the simultaneous analysis of all multi-port data; 2) the signals applied to the NUT no longer aim at directly locating the fault but, rather, are meant to characterize the propagation of signals through the NUT. The eventual presence of a fault is subsequently inferred from the scattering matrix of the NUT rather than from echoes.

To access the benefits of the TR imaging methods, it is first necessary to approach the basic operations and properties involved in their use; the interested reader should refer to [37] for more details. When dealing with an NUT displaying N testing ports and M soft faults, its scattering matrix $\mathbf{S}$ of dimensions $N \times N$ allows a direct computation of the output signals generated by any testing signal applied to one or more of its N testing ports.

As such, TR imaging methods applied to fault detection are based on the availability of this matrix, which can be measured either by simulation or by means of a vector network analyzer (VNA). As it is often the case when dealing with soft faults, the procedure requires a baselining approach, i.e., taking the difference between the response of the NUT, containing potential faults ($\mathbf{S}_f$), and a reference response of a healthy version of it ($\mathbf{S}_h$) [38]. This operation ideally removes the spurious echoes generated by impedance discontinuities like junctions, leaving only those echoes initially generated by the interaction between the testing signals and the faults. The NUT response after baselining is thus $\mathbf{S} = \mathbf{S}_f - \mathbf{S}_h$, which can be shown to result in an equivalent description where a fault acts as a secondary source.

For TR-imaging methods, the analysis of the TR operator (TRO) is fundamental [39]. The TRO is computed as $\mathbf{K} = \mathbf{S}\mathbf{S}^\dagger$ where $\dagger$ stands for the Hermitian transpose. Particularly, the eigenvalue decomposition of the TRO forms the basis for both the DORT and TR-MUSIC methods. These two approaches allow TR-based imaging via the use of complementary subspaces of $\mathbf{K}$. They do so by computing the eigenvalue decomposition of $\mathbf{K}$ according to $\mathbf{K} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^\dagger$, which is also equivalent to the singular value decomposition of $\mathbf{S}$ where the number $M < N$ of the non-negligible eigenvalues hints at the number of potential faults found in the NUT.

The quantity Λ is a real-valued diagonal matrix containing the eigenvalues, while $\mathbf{U}$ is the eigenvector matrix. In fact, $\mathbf{U}$ can be divided into a signal space $\mathcal{S}$ and a noise space $\mathcal{N}$; the latter can be seen as an approximation of the null space of $\mathbf{K}$. $\mathcal{S}$ is identified by the eigenvectors associated with the most significant eigenvalues, with respect to a threshold λ_{th}, i.e., $\mathcal{S} = \mathrm{span}\{\mathbf{u}_i : \lambda_i > \lambda_{th}\}$, whereas $\mathcal{N}$ is formed by the remaining eigenvectors deemed to have negligible eigenvalues $\mathcal{N} = \mathrm{span}\{\mathbf{u}_i : \lambda_i < \lambda_{th}\}$, with λ_i and $\mathbf{u}_i$ are the eigenvalues and their corresponding eigenvectors, respectively; λ_{th} is set by analyzing the scree plot of the eigenvalues of $\mathbf{K}$.

Specifically, DORT employs the signal subspace $\mathcal{S}$ whereas TR-MUSIC employs the null subspace $\mathcal{N}$.

1) DORT for fault location: The properties of the DORT implementation in free-space propagation show that sets of input signals can be defined, such that when injected through the testing ports they will lead to waves focusing onto each fault. On the other hand, the transposition of DORT to guided wave propagation in transmission lines as first introduced in [37] was shown capable of only locating the most compelling (severest) fault in the NUT. It does so by monitoring the propagation of input signals whose Fourier spectra would be defined by the scalar components of $\mathbf{u}_i$ corresponding to the largest λ_i. This operation can be carried out by means of a numerical simulator for transmission lines, modeling the layout of the healthy NUT; the fault's position would be found by looking for maximal energy focusing [37].

While passing from a single scatterer to several is trivial with waves propagating in homogeneous media, it was shown in [40] that in the case of wire networks this is no longer true. Multiple faults cannot be resolved separately, because of their strong coupling via guided propagation. Instead, the authors in [41] introduced an alternative formulation of the DORT (EDORT) based on an updating scheme and proved to allow selective focusing and location of multiple soft faults in complex branched NUTs. The input signals used for imaging the faults defined by EDORT were shown to focus selectively on single faults, allowing a clear identification [41], [42]. Besides, the proposed procedure allowed an accurate estimate of the severity of each fault, a feature of practical interest when monitoring the state of critical cable networks [41].

2) TR-MUSIC for fault location: Although EDORT has shown to be formidable with multiple soft fault wire diagnosis, it relies on the availability of potentially large bandwidths (GHz), in order to create the conditions for spatial resolution as any method based on time-domain analysis [43]. Limitations are thus introduced by the ability of cables in an NUT to support such bandwidths, as in the case of low-frequency networks, such as power grids.

With this background in mind, the authors in [43], [44] studied the possibilities offered by TR-MUSIC. TR-MUSIC shares the same foundations as DORT but follows a distinguished way to translate multi-static data into a fault position by spanning the null space $\mathcal{N}$ of $\mathbf{K}$ instead of $\mathcal{S}$. Under the condition of $N > M$, the positions of soft faults are thus inferred from local maxima in the pseudo-spectrum $\Phi(x, \nu)$, defined as

$$\Phi(x, \nu) = \left(\sum_{\mathbf{u}_i \in \mathcal{N}} \left| \mathbf{u}_i^\dagger \mathbf{g}(x, \nu) \right|^2 \right)^{-1} \tag{3}$$

with $\mathbf{g}(x, \nu) = [g1(x, \nu), ..., g_N(x, \nu)]^T$ being a vector consisting of the N Green functions of the healthy NUT, which are defined as the N spatial distributions, in the coordinate x, of voltages observed along the NUT, when separately excited from each testing port. These distributions can be estimated from a numerical model of the NUT, e.g., based on transmission-line theory.

Experimental validations have shown that this technique is effective in detecting and locating single as well as multiple soft faults in complex branched NUTs while also returning good estimates of faults' reflection coefficients [44]. This has been accompanied by a surprising ability of TR-MUSIC to ensure a sub-millimeter resolution while using relatively low test frequencies when similar performance with TDR of DORT techniques would require much higher test frequencies and wider bandwidths, which may be hampered by attenuation in cables.

A recent submitted but yet unpublished work in [45] has investigated the performance of TR-MUSIC in the presence of noise. A multi-frequency estimator, based on independent single-frequency results was introduced and has reinstated precise super-resolved estimates of fault locations even for signal-to-noise ratios as low as 5 dB, without requiring the use of wide-band signals [45].

V. Conclusion

In this paper, we have provided a summary of the EMTR-based techniques applied to fault location in transmission networks. In particular, we have focused most of the discussions on power and communication networks. The EMTR has shown to be an accurate fault location method for inhomogeneous and complex power networks even using a single observation point. On another hand, EMTR applied to communication networks efficiently succeeded in locating soft faults in complex branched networks through the MP approach. More importantly, it allowed estimating the cable aging.

EMTR-based focusing techniques have shown to provide superior performance compared to TDR methods. As known, these methods require the propagation delay as a direct measure of a fault position, which results in ambiguous predictions as soon as realistic networks are considered, due to their multi-branched structure. DORT (in its standard and extended formulations) has shown a dramatic improvement in the detection rate of faults, similarly to the case of matched-pulse testing, by exploiting the existence of a large number of echoes in order to focus signals onto the fault position. TR-MUSIC, on the contrary, was rather proven a promising method to improve spatial resolution, at the expense of robustness to noise. Moreover, it is of clear interest for optimal frequency allocation of test signals, since it can be based on a discrete set of tested frequencies, rather than a continuous bandwidth as for most TDR methods.

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