Propagation Time Estimation of Transmission Lines using Time Domain Reflectometry

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***Abstract*—This paper proposes a novel time domain reflectometry method to estimate the propagation time of transmission lines in medium-voltage (MV) networks. In the proposed method, a single travelling wave detector (TWD) unit is installed at the zone substation where a switching action is performed. The subsequent recorded transients are then matched to the arrival times and amplitudes of expected transients corresponding to characteristic paths in the network. A combinatorial approach is proposed to mitigate interference from multiple-paths reflected transients. The matching method generates a list of possible propagation times from which the one that best fits the measurements is selected. The performance of the proposed method is evaluated on multiple branched networks. The results exhibit accurate estimation of propagation times for test networks.**

***Index Terms*—Branched transmission lines, time domain reflectometry, propagation time.**

I. Introduction

High voltage lines are the building blocks in power grids. Reliability of these lines is of major importance to energy providers. One of the long-lasting challenges in power networks is fault detection and location. When there is a fault on the line, service to customers is disrupted for an extended period of time. It is therefore beneficial for them to locate and fix the fault in the shortest possible time. New emerging techniques make use of electromagnetic transients in order to locate fault along the lines (e.g. [1]). However, these techniques also require accurate values of the propagation times of the lines in order to precisely locate the fault [2].

In the literature on parameter estimation of distribution lines, multiple techniques have been proposed that either directly or indirectly estimate the propagation time of transmission lines. In [3], the lengths of the transmission lines are determined based on the dispersion characteristics of an injected signal. Having measured the time the signal takes to propagate along the line, its length can be determined using the known velocity of propagation. The main drawback is that injection of an arbitrary signal cannot be readily achieved in the existing infrastructure. Scattering parameters (*S*-parameters) are also used in determining cable lengths [4]. N-port networks are considered with measurements taken at all the edges of the network. The lengths of the transmission lines can then be estimated from the *S* coefficients. The cost of installing measurement devices at all buses in distribution networks limits the applicability of this approach.

Other techniques that transform the time domain signal into the frequency domain have also been proposed (e.g., [5]–[11]). The Fourier transform (FT) is used in [5] to estimate the lengths of lines. However, FT does not work well with non-stationary signals where the frequency is dynamic, which is the case for the measured transient. Another method based on wavelet analysis is proposed in [6]. It is employed to determine both the length of transmission line and the fault location. While wavelet analysis is particularly useful in identifying the location of the fault, it is difficult to extract information related to multiple branches, given the attenuation happening at the junctions. By calculating the time difference in arrivals of transients, the cepstrum can also be used to extract the propagation times [8]. However, the cepstrum does have some limitations for branched networks. Due to the non linearity introduced by the log function in cepstral analysis, it can be hard to interpret the transformed signal. A quarter wave length approach that estimates the propagation velocity along a cable is presented in [12].

Time domain reflectometry (TDR) methods have also been proposed to estimate the propagation times of transmission lines. A Newton based TDR optimization problem is presented in [13] that estimates the lengths of cables in a known branched network. The same authors augment their developed approach with a genetic algorithm to estimate the lengths of cables in an unknown branched network in [14]. In [15], an orthogonal multi-tone time domain reflectometry combined with a genetic algorithm is proposed to reconstruct the topology of a network. The applicability of TDR methods is low since interference from transients reflected from multiple paths makes it hard to identify the useful ones.

Compared to the aforementioned papers, the proposed method:

- estimates the propagation times from measurements obtained from a single travelling wave detector unit located at the root bus;
- employs combinatoric expressions to efficiently reduce the interference from multiple-paths reflections.

The rest of this paper is organized as follows; Section II presents a brief overview of the transient analysis. In Sec-

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tion III, the novel method of estimating the propagation times is proposed. Section IV presents the results of the performance evaluation. Finally, concluding remarks are outlined in Section V.

II. Review of Transient Analysis

Sudden changes in the operating point of a grid due to circuit switches or faulty lines lead to high frequency transients that propagate along the lengths of the transmission lines. As they propagate, these transients are reflected and transmitted at branching and terminal points in the network. The amplitudes of the reflected and transmitted waves depend on the differences between characteristic impedance values of the lines. In this paper, *lossless* transmission lines are considered. The transients in a lossless transmission line are governed by Telegrapher's equations. For lossless lines, the resistance and the shunt conductance of the line per unit length is zero and the travelling wave equations only consists of the inductance, L and capacitance, C per unit length. This leads to a factor of $\sqrt{L/C}$, also called the characteristic impedance of the line, Z (in ohms).

Consider a transient wave propagating through a line with characteristic impedance Z_C, source impedance Z_S and terminated with an impedance Z_R. When the transient is incident on the terminal, part of the wave gets reflected back to the source. The amplitude of the reflected wave depends on the reflection coefficient, Γ_R, at the terminal. The reflection coefficient is related to the ratio between the terminal impedance and the line characteristic impedance. If a second line is connected to the terminal point, part of the wave also gets transmitted through the second line and its amplitude depends on the transmission coefficient, T. The reflected waves moving towards the sending source will cause additional reflections determined by the reflection coefficient of the source, Γ_S.

Given the line has a length l and a round trip propagation time t_o, a travelling wave detector (TWD) installed at the source will detect the transient at time $t_1 = t_{\text{ref}} + t_o$, where t_{ref} is the reference time when the transient was generated. Let the amplitude of the initial voltage transient be denoted by V_o. The magnitude of the measured voltage at time t_1 is $V_o(1 + \Gamma_R + \Gamma_R\Gamma_S)$. The next transient will be detected at time $t_2 = t_{\text{ref}} + 2t_o$. The propagation time of the line can be estimated by calculating the time difference Δt between the arrivals of the transients. If the propagation velocity v is known, then the length of the line can also be estimated as

$$l = \frac{v\,\Delta t}{2}. \tag{1}$$

The measured voltage signal consists of a sum of step functions as new voltage waves arrive at the measuring point after travelling along different paths in the network. The set of all such paths is denoted $\mathcal{H}$. The measured voltage at time t is the sum of all incident and reflected voltages until the time t,

$$V_t = (\sum_{t_{\text{ref}}}^{t} V_{\text{previous}}) + V_{\text{incident},t} + V_{\text{reflected},t}\,. \tag{2}$$

The voltage difference between consecutive arrivals, that is, at every recorded step change, is just the summation of the incident and reflected voltages,

$$\Delta V_t = V_{\text{incident},t} + V_{\text{reflected},t}\,. \tag{3}$$

This also corresponds to the decay the voltage transient experiences as it propagates through the network.

Let γ_i be the decay corresponding to path i from the source back to the TWD as the voltage transient propagates through the network, including the last reflection that happens as the transient gets reflected at the source. Then, (3) is synonymous to the measured difference in voltage at time t_i,

$$\Delta V_{t_i} = \gamma_i\, V_o\,. \tag{4}$$

Borghetti et al. [6] make use of characteristic frequency that is associated with each path in the network. Similarly, in the proposed approach the objective is to match the measured transients' amplitudes to corresponding characteristic paths in the known network. A characteristic path for bus a consists of the links connecting the source bus to bus a. Once matched, the propagation times of individual segments can be estimated from the measured arrival times of the matched transients.

III. Propagation Time Estimation Algorithm

In this section, the proposed method of estimating the propagation times of transmission lines based on multiple recorded reflections is presented.

A. Overview

A transient signal is generated through a switching action at the source (where the travelling wave detector is located) at time t_{ref} and the subsequent voltage transients are measured. The time differences, τ_i, between t_{ref} and other transient arrivals t_i is calculated, as is the corresponding amplitude differences ΔV_i. Assuming the network consists of homogeneous lines (Γ and T are known), the expected decay, γ_i, corresponding to a characteristic path $h_{sa} \in \mathcal{H}$ between the source, s and bus a, can be calculated. The algorithm seeks to match the expected decay, corresponding to a characteristic path, to the list of measured ΔV. The τ corresponding to the transient with the lowest error between the expected decay and measured decay is fitted to the path h_{sa}. The overall procedure gets repeated until all characteristic paths in $\mathcal{H}$ is identified, thereby also returning the τ of individual segments. If the propagation velocity is known, the lengths of the segments can be estimated by (1).

In practice, there might not be a single τ with an amplitude close to γ as the measuring device will record transients reflected from multiple paths. The measured Δ of these transients can be close to γ_i of a given path, and if not taken care of, will be erroneously matched to τ_i. Also, some of the recorded transients will be due to other effects termed *superposition* and *collision*. Two paths produce a superposition transient if, for each line in the network, both paths traverse it the same number of times, but the orders of traversal are different. As such, when calculating γ_i, all the possible

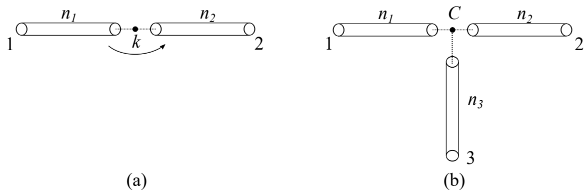

Fig. 1. (a) Two segments in a straight line with n_1 and n_2 traversals, respectively; (b) Junction with 3 branches (T-junction) of n_1, n_2 and n_3 traversals, respectively.

paths $h_{sa} \in \mathcal{H}$ must be considered. Collision transients are harder to identify as these transients can correspond to at least two different τs from different paths in $\mathcal{H}$, which arrive at the source at approximately the same time, causing their transients to overlap. Since the summation of voltage signals is measured, if the impact of superposition and collision is not considered, the error between the expected decay and the measured decay will be significant resulting in a wrong propagation time being assigned to the characteristic path.

B. Mitigating the Impact of Superposition and Collision

The impact of superposition and collision can be reduced if the number of superposed paths are known. Knowledge of the superposed paths allows the calculation of the voltage transient amplitude resulting from these superposed paths. The calculated amplitude can then be located and subtracted from measured ΔV. This also helps with collision transients. Suppose a superposed path collided with a characteristic path and impacted the measured transient voltage. The true transient voltage corresponding to the characteristic path can be obtained by subtracting the interference from the superposed paths. The calculation of the number of superposed paths and their associated decay is as follows.

Corresponding to different paths in $\mathcal{H}$, i.e., summation of segments, there might be different number of paths leading to the same τ. A simple way of calculating those paths would be using a backtracking technique [16] that finds all paths leading to a specific τ. However, backtracking takes time exponential in the number of lines traversed, and quickly becomes intractable. Instead, a recurrence relation was devised to calculate the number of paths that traverse each link a given number of times.

1) Segments connected in a straight path: When the path consists of a single line and the only reflections come from changes of characteristic impedance, no recurrence is required and a closed form expression is possible. If t_1 and t_2 are the round trip propagation times for the two-line model shown in Fig. 1a, transients corresponding to all paths of the format $n_1 t_1 + n_2 t_2$, where $n_i \in 1, 2, 3, \ldots$, for $i \in \{1, 2\}$, will be measured. The number of paths, N_k, for any combinations of n_i can be calculated by counting the number of times the transient passes k times through the connection point. Specifically,

$$N_k = \binom{n_1}{k}\binom{n_2 - 1}{k - 1} \quad \text{for } k \in 1, 2, \ldots \min(n_1, n_2). \tag{5}$$

Given Γ_a is the reflection coefficient at bus a and T_{ab} is the transmission coefficient from bus a to bus b through the intermediate bus K for $a, b \in \{1, 2\}$, the decay corresponding to these N_k paths is

$$\gamma = \sum_{k=1}^{\min(n_1, n_2)} N_k \Gamma_1^{n_1 - 1} \Gamma_K^{n_1 + n_2 - 2k} \Gamma_2^{n_2} \left(T_{12} T_{21}\right)^k. \tag{6}$$

If n_1 corresponds to the traversals across the segment linked with the source bus, the decay term must be multiplied by $1 + \Gamma_1$ to account for the last reflection at the source.

Extending the above formulation to a general r segments, with n_r traversals, connected in a straight fashion, the number of paths the transient passes through the $r-1$ connection points is

$$\begin{gathered} k_1 = \min(n_1, n_2), \ldots, k_{r-1} = \min(n_{r-1}, n_r), \\ N_{k_1, \ldots, k_{r-1}} = \binom{n_1}{k_1}\binom{n_2 - 1}{k_1 - 1} \times \cdots \times \binom{n_{r-1}}{k_{r-1}}\binom{n_r - 1}{k_{r-1} - 1}. \end{gathered} \tag{7}$$

The decay corresponding to r segments can be calculated by multiplying the above expression by the reflection and transmission coefficient terms similarly to (6).

2) Junctions with α branches: Distribution networks also consists of junctions with the smallest possible number of branches being 3 (T-junction). Junctions are more complex than the straight paths in the previous paragraph, since the transient propagates along multiple branches. For example in the T-junction shown in Fig. 1b, the three segments have propagation times t_1, t_2 and t_3 respectively. A transient with delay $\tau = t_1 + t_2 + t_3$, can either propagate along the path 1 c 2 c 3 c 1 or 1 c 3 c 2 c 1, where c is the centre node.

For junctions, it becomes more efficient to calculate the number of times the wave would jump from one branch to the other. This is computed by recursive calculation of a variable $C(n, e)$ defined for the $T-junction$ as follows. A path is said to "visit" a line once when it enters the line, and is reflected back and form multiple times and then leaves the line. Let n be a 3×3 matrix where n_{ii} is the number of times line i is visited, and n_{ij} is the number of times taking the path $i \to c \to j$. Then $C(n, e)$ is the number of paths that take a path with the given n and ending at line $e \in \{1, 2, 3\}$. Since the transient starts on edge 1 before any turns have been made, $C(n, e)$ is initialized as $C(O_3, e) = \mathbf{1}_{e=1}$ where O_3 is the 3×3 zero matrix, and $\mathbf{1}_E = 1$ if expression E is true, and 0 otherwise.

Then, $C(n, e)$ is defined recursively as $C(n', e') + C(n'', e'')$ where e' and e'' are the two elements of $\{1, 2, 3\} \setminus \{e\}$. The matrix n' is defined as $n - A_{e',e} - A_{e,e}$ where A_{ij} is the 3×3 matrix with zeros everywhere except for $a_{ij} = 1$, with n'' defined analogously. For each path, C considers the number of times the transient changes branch. The number of orders in which the transient can change branch is expressed in terms of binomial coefficients that choose when among the traversals of branch i the transient jumps out. The number of paths for a particular n is then

$$N_c = C(n,1)\binom{n_1}{n_{11}}\binom{n_2-1}{n_{22}-1}\binom{n_3-1}{n_{33}-1}. \tag{8}$$

Given T_{ab} is the transmission coefficient for a transient propagating from bus a to b through the centre node, Γ_a is the reflection coefficient at bus a for $a,b \in \{1,2,3\}$ and Γ_c is the reflection coefficient at the centre node, the decay corresponding to the T-junction is given by

$$\gamma = N_c\left(\prod_{(a,b)\in\{1,2,3\},a\neq b} T_{ab}^{n_{ab}}\right)\left(\prod_{a\in\{1,2,3\}} \Gamma_c^{n_a-n_{aa}}\Gamma_a^{n_{aa}}\right)\Gamma_1^{-1}. \tag{9}$$

If n_1 corresponds to the traversals across the segment linked with the source bus, the decay term must be multiplied with $1+\Gamma_1$. For junctions with α branches, the same process can be repeated with $e \in 1,2,3,\ldots,\alpha$.

3) General Tree Structure: Usually, distribution networks are radial tree structures that consist of multiple junctions. The paths, $\mathcal{H}$, in the network can consist any combination of straight line segments and junctions. Any given path in the tree is broken down into β sub-trees that consists of either independent straight line segments or independent junctions. The expressions (6) and (9) are used to return the decay corresponding to all β. Then, given the independent expressions for the sub-trees, the overall decay of the path is calculated as the product of the decay values corresponding to each β sub-tree. This works since the paths in each β are independent, with the order in which the transient change from one β to another taken care of by the k and $C(n,e)$ terms in (6) and (9) respectively.

C. Practical Implementation

An algorithm that uses this information to match observed steps to paths is given in Algorithm 1. It starts with the source bus and iteratively proceeds towards the most downstream bus whilst matching the propagation times to expected decay of characteristic paths. Let the mapping of propagation times onto edges of the network be denoted as $\mathcal{E}$. The propagation times of lines are stored in $\hat{t}$ while e, formally defined in a later part, is the error for a given $\mathcal{E}$. In the initialization step (line 1), $\mathcal{E}$ and $\hat{t}$ structures are initialized with "NaN" tuples which signify incomplete matching, while e is initialized as ∞. These variables are appended to a priority queue variable $\mathcal{Q}$. The algorithm begins with the first incomplete mapping in $\mathcal{E}$, which corresponds to the segment between the root bus and it's direct descendant. The segment to-be-matched is stored in the variable $link$ (line 5). The decay of the characteristic path pertaining to $link$ is returned using the `Decay` subroutine (line 6). It makes use of (6),(9) and calculates the expected γ of all paths, up to the matched link, in the network.

To account for collisions, all propagation times whose amplitudes' are within $\pm 30\%$ of the γ corresponding to the characteristic path, are considered as possibilities, hereafter referred as candidates (line 7). The `matching` subroutine returns all the possible propagation times that could be mapped to $link$. For each possibilities, γ with $n \in 1,2,\ldots 5$ is subtracted from the measured amplitudes (line 9)

$$\Delta V = \Delta V - \gamma_i V_o. \tag{10}$$

Any $n > 5$ will result in negligible γ and is thus not considered. For selecting the candidate to expand, the error, e, in time and expected amplitude of the second order multiple of the selected link is calculated using `mismatch` (line 10). For example, referring back to Fig. 1a, having identified $\hat{t}_1$ and $\hat{t}_2$, e in time and amplitude of $\tau = \hat{t}_1 + 2\hat{t}_2$ is calculated. All terms are then pushed onto $\mathcal{Q}$. Following that, the candidate with the lowest error is expanded first. The algorithm resumes until $\mathcal{E}$ is fully mapped. The mapping is stored in the candidate set, $\mathcal{L}$ (line 15). The overall approach is repeated until all the candidates are generated.

1) Candidate Selection: Once all the candidates are generated, the one that best fits the measured signal is returned as the output propagation times. For determining the fitness of each candidate, the energy of the residual signal is used, $E = |\Delta V|^2$. As the higher order multiples are being subtracted from the original signal, a decrease in the energy of the signal is expected. Consequently, the candidate for which most of the higher order multiples are accounted for, i.e. with the lowest energy, serves as a better fit for the model. If the database of the propagation times is known, then the candidate selection process can be applied on the sub-group of candidates that first fits the database within an acceptable threshold.

IV. Performance Evaluation

The performance of the proposed method is evaluated on three networks with sizes 4 (T-junction), 6 and 10. The results exhibit accurate estimation of propagation time across networks of all sizes.

A. Base Case - T junction

In this section, the base case and associated results are presented. The T-junction network is simulated using the EMTP software. The zone substation transformer is connected at one end of the model and MV/LV transformers are connected on the two other ends of the model. A simplified high-frequency model for transformers have been used, i.e., they are modelled as resistors with high resistance values. Constant parameter line models, with similar characteristic impedance are used for the transmission lines, and the lengths of the lines are chosen from independent random uniform distributions between 1 km and 8 km. A switch is closed at the zone substation and the subsequent transients are measured, and then given as input to the algorithm.

The simulation is repeated 100 times with different lengths of lines sampled from the aforementioned uniform distribution. Overall, in 100% of the instances, the propagation times are correctly matched to the true values. The percentage error in the estimated propagation times of cables, across all instances is shown in Fig. 2. The worst error is around 0.1%. In terms of the computation time, the major benefit comes from using the

Algorithm 1: Propagation Time Matching

Input: List of measured propagation times τ,
list of amplitudes, ΔV
the adjacency matrix, A,
the reflection coefficients, Γ, and
the transmission coefficients, T.

Output: Estimated propagation times of segments, $\hat{t}$

Initialization Priority queue, $\mathcal{Q} = \{(\mathcal{E}, \Delta V, \hat{t}, e)\}$, empty candidate set, $\mathcal{L} = \emptyset$.
while $\mathcal{Q} \neq \emptyset$ **do**
  Pop $(\mathcal{E}, \Delta V_{\text{new}}, \hat{t}, e)$ from $\mathcal{Q}$ with lowest e
  while $\mathcal{E}$ *incomplete* **do**
    Find nodes in $\mathcal{E}$ which are yet to be matched to a propagation time and assign it to *link*
    $\gamma \leftarrow$ `Decay` $(A, link, \Gamma, T)$ using (6),(9)
    for $\tau_i \in \texttt{matching}(\gamma, \Delta V_{new})$ **do**
      $\mathcal{E} \leftarrow \mathcal{E} \cup (link, \hat{t} \leftarrow \tau_i)$
      $\Delta V_{\text{new}} \leftarrow \Delta V_{\text{new}} - \gamma V_o$ (10)
      $e \leftarrow \texttt{mismatch}(\Delta V_{\text{new}}, \tau, \hat{t})$
      Push $(\mathcal{E}, \Delta V_{\text{new}}, \hat{t}, e)$ to $\mathcal{Q}$
    end
    Pop $\mathcal{Q}$ with lowest e
  end
  $\mathcal{L} \leftarrow \mathcal{L} \cup (\mathcal{E}, \Delta V, \hat{t}, e)$
end
$\hat{t} \leftarrow$ `Candidate Selection` $(\mathcal{L})$

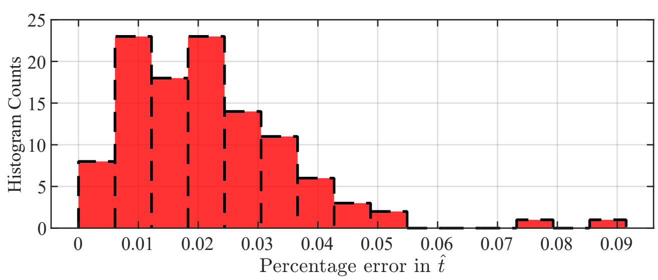

Fig. 2. Percentage error in estimated propagation times for T-junction.

combinatorial expressions instead of a brute force backtracking technique. The time it takes for a backtracking method [16] and the combinatorial expressions to calculate the decay, γ corresponding to all paths $\mathcal{H}$ in the T-junction is compared and shown on a semi-log plot in Fig. 3. It can be seen that the combinatorial expressions are always quicker than the brute-force backtracking approach, with the longest paths calculated around 200 times quicker. On average, the algorithm altogether took approximately 30 milliseconds.

B. Comprehensive Analysis

The algorithm is applied on 3 networks of different sizes ranging from 4 bus (T-junction) to 10 bus networks, shown in Fig. 4. For each network size, 100 instances are generated with the lengths sampled from the aforementioned uniform distribution. The success rate of the algorithm is defined as

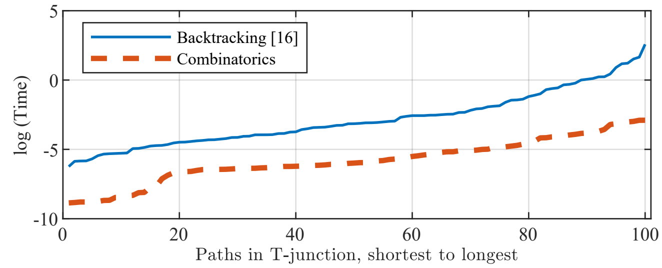

Fig. 3. Comparison between computation times for backtracking [16] and expressions in Section III-B.

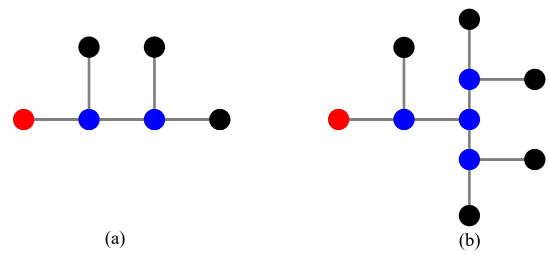

Fig. 4. Network topologies with TWD placed at the root bus (red node). Branching points and terminal transformers are highlighted as blue and black nodes respectively with (a) the 6 bus network and (b) the 10 bus network.

the percentage of instances in which all the propagation times are correctly matched to their true values across the 100 test cases. The results are summarized in Table. I.

As presented, the algorithm can accurately estimate the propagation times of lines. There is a decrease in the accuracy as the size of the network grows. While the algorithm can still match the small propagation times, it can fail to match the large propagation times associated with the branches located further away from the zone substation. The transients corresponding to early arrivals are well sparse compared to the ones arriving at a much later time. The latter transients are more densely packed with other transients originating from multiple paths reflections. These redundant transients also negatively interfere with the ampltiude of the transient corresponding to the characteristic path, and thereby degrades the performance of the matching algorithm.

The computation time of the algorithm for all network sizes is shown in Fig. 5. As the size of the network and the number of branches grows, more candidates are generated by the algorithm. This is due to similar γ being expected for different branches. In order to correctly estimate all branches, all candidates must be processed resulting in an increase in the computation time. Also, due to the attenuation of the signal at junctions, the depth of the network, D, plays a major role in the accuracy of the algorithm. Assuming a network, with depth $D = 7$, consisting only of T-junctions (highest transmission

TABLE I
SUCCESS RATE OF ALGORITHM ACROSS 100 INSTANCES

Network Size	Success Rate (%)
4 bus (T-Junction)	100
6 bus	100
10 Bus	97

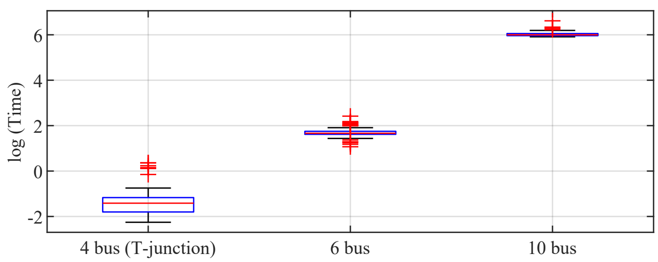

Fig. 5. Computation time across different network sizes on a semi-log scale.

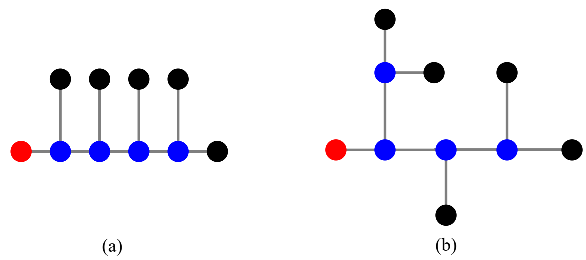

Fig. 6. Variations of the 10 bus network topologies. (a) Single feeder 10 bus network with depth of tree of 5; (b) Branched 10 bus network with a depth of tree of 4.

coefficient, $T = 2/3$), the amplitude of the measured transient corresponding to the longest characteristic path will be a hundredths of the initial transient. The maximum depth, for which the measured transient amplitude is approximately 0, is 18.

C. Impact of Topology Differences

The performance evaluation is extended to the study of topological differences. For this case study, the topology of the base 10 bus model is modified resulting in 2 other 10 bus models as shown in Fig. 6.

Similar propagation times in the 100 instances of the base model are employed in the modified 10 bus models. The average success rate across all the 300 instances is 84%. The instances corresponding to topology 3 are more prone to failures. Upon investigating, the reason for the failures is collision for propagation times corresponding to characteristic paths. While collision on characteristic paths happened 8% of the times across the instances of the base model, it increased to 35% for topology 3. As a result, some of the propagation times are not selected in the candidate list.

This shows that topology, in combination with the propagation times, plays a major role in the occurrence of collision events, with some combinations more prone to collision compared to others.

V. Conclusion

This paper has proposed a method for estimating the propagation times of transmission lines using a time domain reflectometry approach. The measured voltage transient signal is matched to the expected transient of a given characteristic path in the network. Expressions for transients corresponding to all paths in the network, including branching points, is used to mitigate their interference. The proposed method generates a set of possibilities from which the one that best fits the measured signal is selected. The proposed method is evaluated on a range of networks with different sizes. The results show that the proposed algorithm can accurately estimate the propagation times. Further research is being carried on larger networks, together with extending the current approach to lossy lines.

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