Experimental Test Bench for Traveling-Wave-Based Methods Evaluations

R. L. S. França, M. M. Leal, M. S. R. Leal, M. R. Marques, F. B. Costa, R. L. A. Ribeiro

***Abstract*—This work presents an experimental test bench, with the purpose of to enable the generation and measurement of traveling waves in order to support the developing and evaluation of detection, localization, and protection methods based on traveling waves for educational and research goals. The experimental test bench was performed by means of a real cable, which ensures the wave propagation, voltages and currents transducers, impedances, and an oscilloscope for data acquisition. The traveling waves were generated by means of manually controlled fault switchings. Difficulties in the measurements of high-frequency transients are discussed and solutions presented. The evaluations were performed off-line. The results are compatible with the traveling waves theory and demonstrate the feasibility of evaluating methods based on traveling waves by means of the presented assembly.**

***Keywords*—Experimental test bench, traveling waves, fault location, transmission line protection, fault detection.**

I. Introduction

The transmission line is an important component of the power system since it connects the load centers to the power plants. This connection is performed through long distances, thus the transmission line is exposed to weather conditions and vandalism, which may explain the high fault incidence in the transmission system. According to [1], 50% of the faults on the power system occur on the overhead transmission lines. Therefore, a fast transmission line protection operation is crucial for the entire power system reliability, improving its stability margin [2]. Furthermore, an accurate fault location technique can improve the power system availability since it helps ground patrols to identify damages on the transmission line and to reestablish it.

Several studies have been developed in order to improve the transmission line protection speed and the fault location accuracy [3], [4]. Methods based on traveling waves have the potential for being the fastest and most accurate for transmission line protection and fault location. These new techniques work on the time domain, i.e., do not require phasor estimation. According to [3], the protection operation time of the traditional frequency domain techniques is about one to one-and-a-half power cycles, due to the filtering necessary for phasor measurement, whereas a mean operating time of 2.5 ms was reported for a transmission line protection technique based on traveling waves [5]. Traditional frequency domain methods for fault location present accuracy of 0.5 to 2% [4]. For instance, for a 300 km long transmission line, an error of 1% represents 6 km, which means a section of about 20 tower spans to be patrolled. On the other hand, methods based on traveling waves can perform the accuracy of a tower span (about 300 m) [4].

The field evaluation of the methods based on traveling waves for transmission lines is an important evaluation step since simulation evaluations represent the field environment with limitations. However, this is not a simple task since the access to the transmission system is highly restricted. Thereby, the performance evaluation of these methods is normally limited to computational and Hardware-in-the-Loop (HiL) digital real-time simulations. In this way, experimental test benches would be a quite relevant step for the evaluation of these methods, within certain limitations, which could be performed after the digital simulations and before a field evaluation. In addition, experimental test benches could support the demonstration of the traveling wave principals and the operation of traveling-wave-based methods in a very visual and didactic way for both educational and research purposes.

Several works based on traveling waves have been proposed over the years. Most of them propose fault location techniques and, recently, the attention has been focused on the transmission line protection. The majority of these works perform computational simulations for the method evaluations [6]–[12]. Digital real-time simulations were performed in [13]. In [5], the evaluations were performed by means of HiL digital real-time simulations. In [14], voltages and currents were simulated by an Electromagnetic Transients Program (EMTP) and were input into a protection prototype through amplifiers. A few works present field evaluations [14], [15], which normally is not an available strategy for most researchers. None of these works performed experimental evaluations without using digital simulators. In [16], a hardware-based laboratory with real DC cables, which should ensure wave propagation, is presented. However, no traveling wave evaluation was performed.

This work proposes an experimental test bench, with real cables, in order to enable traveling-wave-based method evaluations for educational and research goals. The hardware

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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Paper submitted to the International Conference on Power Systems Transients (IPST2019) in Perpignan, France June 17-20, 2019.

components are detailed described. The methodology for fault applications is demonstrated, as well as difficulties in the measurements of high-frequency transients were discussed and solutions presented. In addition, fault parameters such as resistance and inception angle may be variated, which is not possible in field evaluations. The results demonstrate that the experimental test bench provides traveling wave phenomenon, which are able to be used for developing and assess traveling wave-based methods.

II. General Idea of the Methods Based on Traveling Waves

When a fault takes place on the transmission line, high-frequency electromagnetic transients on the voltages and currents propagates from the fault point toward the line terminals, as traveling waves. When a wave reaches a line terminal, information can be measured from the traveling wave, such as the wave polarity and its arrival time at the terminal. This information can provide several estimations for the fault conditions as, for instance, the fault location and its directionality. The complete theory of the traveling wave can be found in [17].

Fig. 1 depicts the lattice diagram for a fault on the transmission line distanced d_F from bus 1 and $l - d_F$ from bus 2, where l is the line length. The voltages and currents are measured on buses 1 and 2 by IEDs (Intelligent Electronic Devices), with a fixed sampling frequency (f_S). The fault takes place on the transmission line in the fault inception time (t_F). At this instant, traveling waves propagate from the fault point toward the line terminals with a velocity close to the speed of light. Due to the sampling process, the continuous wavefront arrival times on buses 1 and 2 (t_{F1} and t_{F2}) are unknown and replaced by the discrete wavefront arrival times (k_{F1}/f_S and k_{F2}/f_S), where k_{F1} and k_{F2} are the number of the samples.

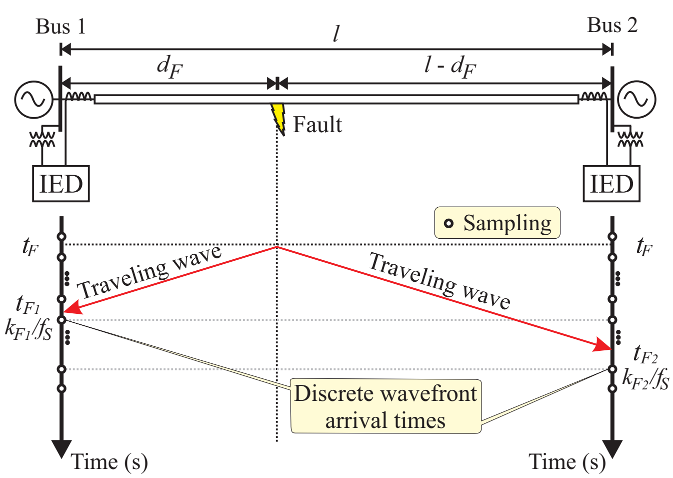

Fig. 1. Lattice diagram for a fault distant d_F from bus 1 and $l - d_F$ from bus 2.

Methods based on traveling waves usually require the discrete wavefront arrival times on one or both line terminals. The polarity of the traveling waves may also be used. This information are used for protection, location and fault classification purposes.

A. Fault Location Estimation

The fault location can be estimated by the detection of the first wavefront arrival time at both line terminals, which is done by communication techniques and data synchronization between both line terminals. Traditionally, the fault location estimation based on traveling waves using two terminals is given by

$$d_F = 0.5[l + (t_{F1} - t_{F2})v], \quad (1)$$

where v is the wave velocity. However, due to the sampling process, t_{F1} and t_{F2} are unknown and the fault location estimation is given by

$$d_F = 0.5\left[l + \left(\frac{k_{F1} - k_{F2}}{f_S}\right)v\right]. \quad (2)$$

III. Experimental Setup

Fig. 2 depicts the complete experimental test bench for traveling wave evaluations. The assembly is composed by: a 127 V single-phase generation source provided by the electric grid (V_S); a 1 km long four-wire polypropylene-type flexible copper cable (PP cable), with transversal section of 1 mm^2; a 100 Ω load impedance (Z_L); a 33.33 Ω fault impedance (Z_F); a push button for fault switching; an access point in the PP cable for fault applications; an oscilloscope for data acquisition; transducers for voltages and currents measurement.

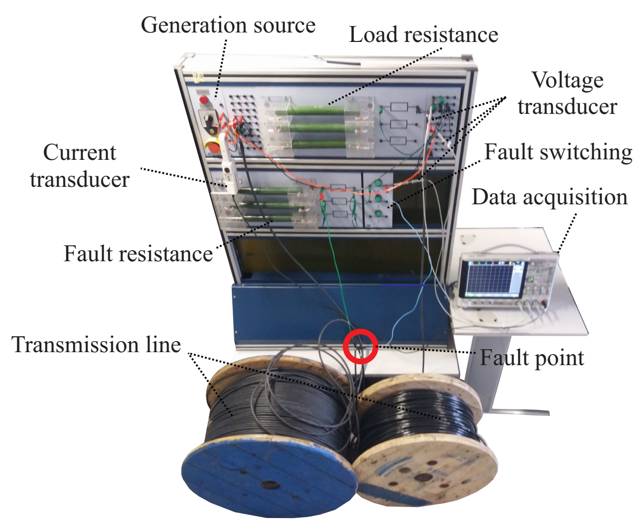

Fig. 2. Complete experimental test bench.

Fig. 3 depicts the equivalent circuit for the complete experimental test bench. One of the four wires connects the single-phase source of the electric grid V_S to the load impedance Z_L, i.e., bus 1 to bus 2. The load impedance is connected to the ground of the source by means another wire. This connection is necessary in order to avoid that transients on bus 1 reach bus 2 immediately, or the opposite. Therefore, two wires of the four-wire PP cable are used in assembly bench. There are three points for voltage measurements, one in bus 1, one in bus 2, and one between the fault switch and the fault impedance. Current measurement is positioned in the bus 1 in order to measure the source current. The fault current is limited by the fault impedance in order to avoid overloading of wires. The PP cable presents a grounded electromagnetic shielding, which reduces the noise and facilitates the traveling waves detection.

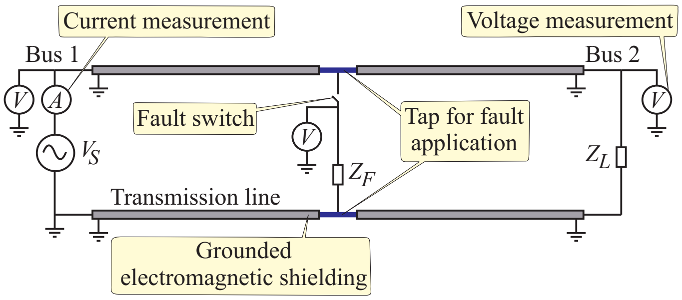

Fig. 3. Equivalent circuit for the complete experimental test bench.

The objective of this experimental test bench is not to emulate a real transmission line, but to enable the generation and measurement of the traveling waves in order to support the developing and evaluation of detection, localization, and protection methods based on traveling waves. Therefore, the PP cable could be wound on a reel in order to raise the capacitance and inductance. Thereby, the wave velocity propagation could be reduced in order to compensate the short length of the cable.

The following subsections describe in detail each component and strategy for the experimental test bench.

A. Fault Applications

Careful measurement of the cable length must be performed since imprecisions on cable length estimation may yield to inaccurate fault location estimation [13] and protection misoperation [5] to methods based on traveling waves. Two wires of the PP cable are used for fault applications, each one with 1 km long. It was implemented 99 access points from 10 to 990 m, with 10 m step, in each wire, which allow fault applications along the entire line. The fault application is manually controlled by means of a push button, which connects the wires through an impedance.

When the push button is fired, a singularity occurs in the fault point, generating traveling waves that propagates toward the line terminals, as depicted by Fig. 4. The traveling waves are simultaneously generated in upper and lower lines and travel d_F to reach bus 1, and $l - d_F$ to reach bus 2. Switching transients may precede the wave arrival, which may interfere with the correct traveling wave arrival time detection. These transients can be identified by its low amplitude and opposite polarity when compared with the traveling waves. All the evaluated fault cases in the results were visually inspected in order to discard the ones where switching transients interfered the correct traveling wave arrival time detection.

Without the lower line, the transients generated on the fault point would reach buses 1 and 2 instantaneously, as depicted by Fig. 5 since the distance between the common ground and the line terminals would be irrelevant. This strategy is important for an experimental test bench because the ground

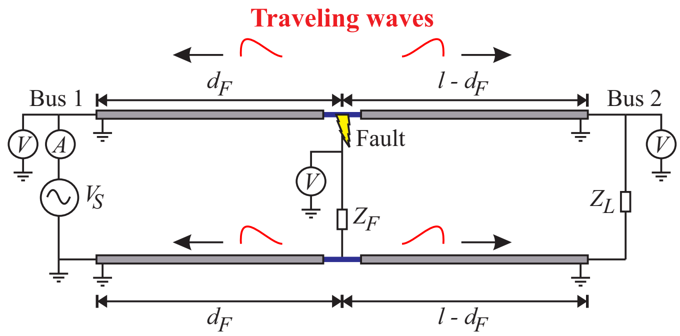

Fig. 4. Traveling wave propagation due to the push button firing.

is common for both buses, whereas in a real transmission line there is no common connection between the line terminals. Therefore, transients coming from the uniform earth-return path are not avoided and certainly interfere in the transducers measurement. However, they do not arrive at the line terminals before the expected traveling waves. In addition, in an actual transmission line, inhomogeneities in the grounding resistance along the system yield variation in the transmission line parameters [10], which do not occur by adopting a uniform earth-return path. However, inhomogeneities in the transmission line can be emulated by connecting in series lines with different electrical parameters [10].

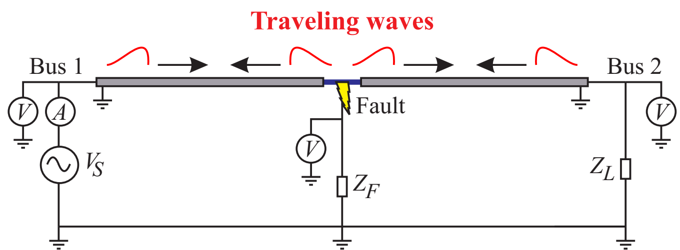

Fig. 5. Traveling wave propagation due to the push button firing, without the lower line.

B. Transducers

Three voltage and one current transducers are used in the experiment. The voltages are measured at buses 1 and 2 in order to detect the arrival time of the traveling waves at the line terminals. A voltage measurement is also performed between the fault switch and the fault impedance, thus the fault inception time may be detected. The source current at bus 1 is measured in order to trigger the data storage by the oscilloscope since its memory is limited. Therefore, only a small quantity of samples after and before the fault inception time are stored in the internal oscilloscope memory.

The voltage transducer used in the experiment is the Agilent N2894A probe with 700 MHz bandwidth. The current transducer used is the Keysight 1146B probe with 100 kHz bandwidth. Due to the better frequency response of the voltage transducer, the traveling wave detections are only performed in the voltages.

C. Data Acquisition

The oscilloscope used on the experimental test bench for data acquisition presents a 200 MHz bandwidth, a maximum sampling frequency of 5 GSa/s, and a maximum memory depth of 4 Mpts. It has four analogical channels, which are all used for voltage and current measurements.

The channel-to-channel isolation of the oscilloscope is equal or greater than 40 dB from DC to maximum specified bandwidth, which is 200 MHz. However, it was observed in the acquired oscillographs that, to sampling frequency greater than 5 MHz, the channel-to-channel isolation may not be suitable for high-frequency transients.

The oscilloscope provides a standard USB 2.0 connectivity. Therefore, the acquired data may be transferred to a PC for offline evaluations. The waveforms can be exported as XY data pairs in a comma-separated values format (*.csv) which facilitates the data analysis in the Matlab software, for instance. The data exportation through the USB port is limited to about 60000 points when the four channels are used. Therefore, it is important to define correctly the length for the horizontal axis before the data exportation, in order to export all the sampled points.

IV. Limitations of the Experimental Test Bench

As aforementioned, the main purpose of this experimental test bench is not to emulate an actual transmission line, since there are limitations such as:

- Ideal time synchronization between the line terminals, since the proposed experimental setup uses only an oscilloscope for measurements.
- The used current transducers in this experimental test bench did not present saturation for any evaluated situation. However, the operation of the method based on traveling waves is expected to occur prior to the saturation of the current transformer [12], [14].
- The steady-state and fault currents must be limited to the PP cable tolerances in order to avoid damages to the system. Therefore, fault resistance and load impedance variations must respect their limits. In addition, no time-varying arc was reproduced.
- The presented experimental test bench can only be used in order to evaluate two-terminal traveling-wave-based schemes since further validations must be performed regarding wave polarity and reflections.

V. Results

By means of repeated attempts and visual inspections, the faults were applied with inception angle about 90^o in order to provide a high incidence of electromagnetic transients and facilitate the traveling wave detections.

Fig. 6 depicts the voltages on buses 1 and 2, and on the fault location, for a fault on 300 meters from the bus 1 and 700 meters from the bus 2, considering a sampling frequency equal to 5 MHz. Transients can be seen on the voltages at the line terminals some samples after the fault inception time. The first wavefront arrival times at buses 1 and 2 are different, in accordance with the traveling waves theory.

Fig. 7 depicts the voltages on buses 1 and 2 for the same fault depicted in Fig. 6, but with a 10 ms window. Fig. 7(a) depicts an evident singularity on the voltage on bus 1, at about

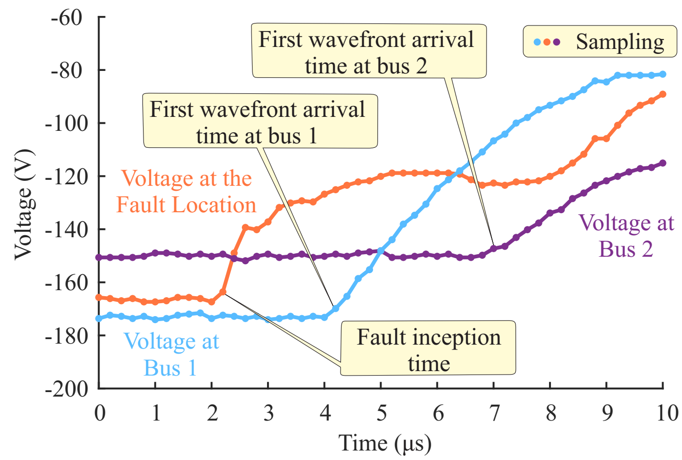

Fig. 6. Oscillograph for a fault distant 300 meters from bus 1 and a sampling frequency of 5 MHz.

4 ms. After 1 ms, no evidence of the fault can be perceived since the voltage level is reestablished. However, the arriving of the traveling wave on the bus 1 is responsible for the fast transient in the voltage at 4 ms. Fig. 7(b) depicts a similar singularity on bus 2, at about 4 ms, which indicates the arriving of the traveling wave. Since bus 2 is not directly connected to a power source, a voltage sag is evident after the fast transient.

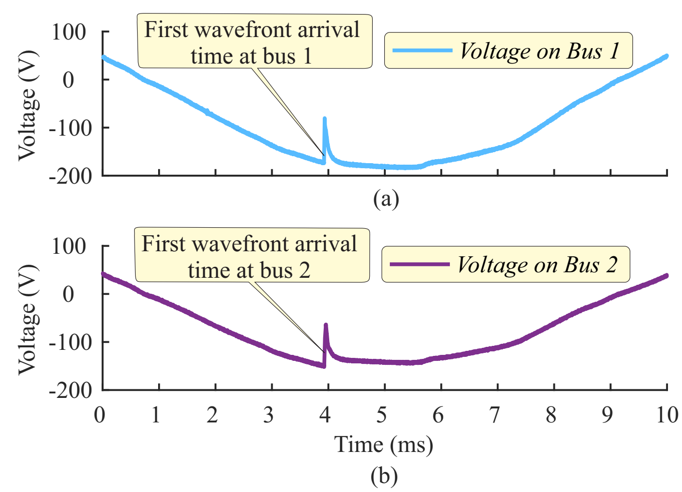

Fig. 7. Voltage signal for a fault distanced of 300 meters from bus 1, on: (a) bus 1; (b) bus 2.

A. Channel-to-Channel Isolation Failure

Fig. 8 depicts the oscillograph for a fault on 300 meters from bus 1, considering a sampling frequency of 10 MHz. Artificial transients can be detected on buses 1 and 2 in the fault inception time, due to a channel-to-channel isolation failure. The wavefront arrival times of the traveling waves on buses 1 and 2 may be incorrectly detected, due to these undesired transients. How greater the sampling frequency, greater the probability for the channel-to-channel isolation failure. However, these simultaneous fast deformations on the signals can be easily discarded automatically from an offline analysis performed. Moreover, by adopting sampling frequencies equal to or smaller than 5 MHz, this failure almost never occurs.

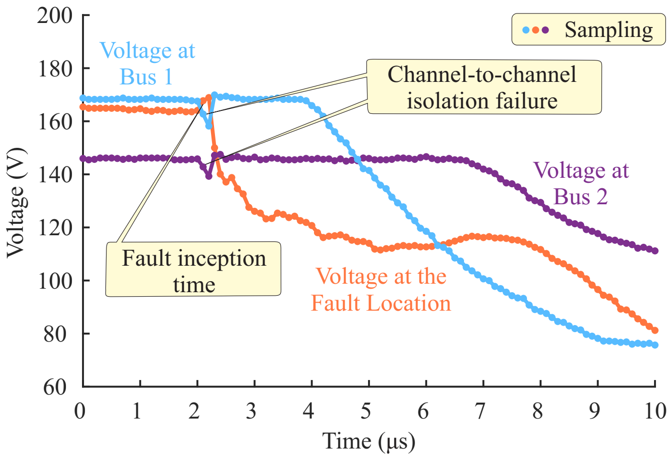

Fig. 8. Oscillograph for a fault distant 300 meters from bus 1 and a sampling frequency of 10 MHz.

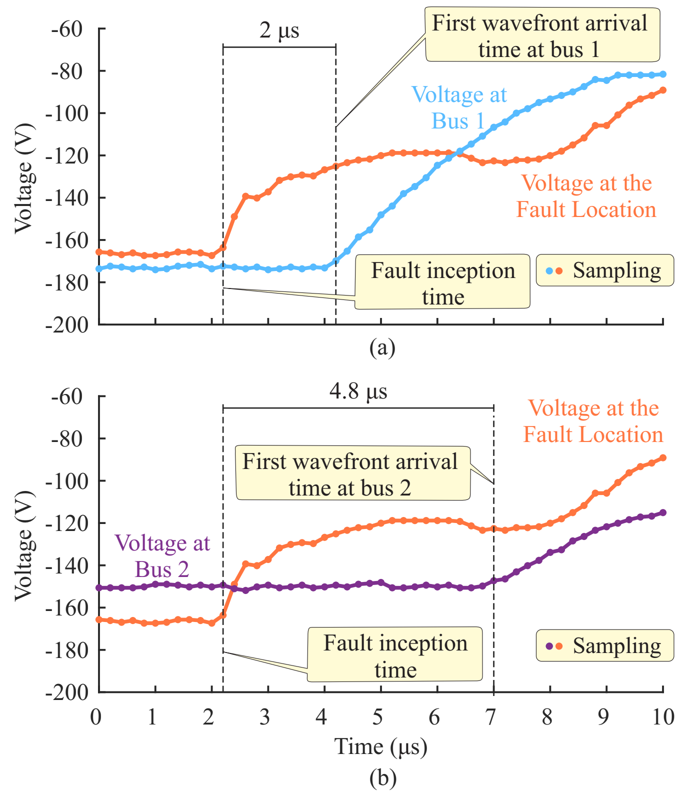

Fig. 9. Wavefront arrival time for a fault distant 300 meters from bus 1 and a sampling frequency of 5 MHz, with measurement on: (a) bus 1; (b) bus 2.

B. *Wavefront Arrival Time*

The wave velocity was estimated statistically by means of several measurements of the cable transit time for the traveling waves. The cable transit time was measured by detecting the instant wherein the traveling wave reaches bus 1 due to switching on bus 2. As the voltage on bus 2 is measured, the switching instant is known. Therefore, by knowing the difference between the instants on both buses, and knowing the cable length, the wave velocity can be estimated. The traveling wave velocity was estimated as v = 1.4286 km/s or v = 0.4762c, where c is equal to the speed of light. A similar method for the wave velocity estimation was reported for field application in [15].

Fig. 9 depicts the wavefront arrival times on buses 1 and 2 for a fault distant 300 meters from bus 1 and 700 meters from bus 2. According to the voltage at the fault location, the fault took place on the cable at 2.2 μs. Considering that v = 1.4286 km/s, it is estimated that the first traveling wave takes 2.1 μs to reach bus 1, and 4.9 μs to reach bus 2. Fig. 9(a) depicts that the traveling wave reached bus 1 2 μs after the fault inception time, which means that the estimation missed by half sample. Fig. 9(b) depicts that the error on the estimation for the first wavefront arrival time at bus 2 was of half sample since the traveling wave took 4.8 μs to reach bus 2.

As discussed in section II, the exact values for the fault inception time and the wavefront arrival times on the line terminals are unknown, due to the sampling process. Therefore, Fig. 9 depicts discrete instants that may not be the correct values, which explains the errors on the estimation for the first wavefront arrival time at the cable terminals. Thus, the results are compatible with the traveling waves theory.

C. *Fault Location Estimation*

The experimental test bench can emulate the evaluation of the methods based on traveling waves for a longer transmission line. For instance, by adopting a sampling frequency of 1 MHz to a 1 km long line, it is equivalent to adopt a sampling frequency of 10 kHz to a line 100 times longer, i.e., 100 km long, regarding the sampling frequency effect. In addition, as the wave velocity propagation was reduced to about half of the typical value for overhead transmission lines (0.98c), a sampling frequency of 10 kHz could emulate the effects of a sampling frequency equal to 20 kHz. The method proposed in [5] was evaluated with a sampling frequency of 20 kHz.

A simple technique for detecting the traveling waves is to compute $x(k) - x(k-N)$, where $x(k)$ is the present voltage or current signal amplitude and $x(k-N)$ is the amplitude of the same signal one wave cycle before. Therefore, in the steady-state regime, $x(k) - x(k-N)$ is ideally zero, but different from zero when a variation on the signal occurs. By using this technique, it is possible to detect the wavefront arrival time whether a threshold is exceeded. Fig. 10 depicts the signals resulting from the application of this technique in the voltages at buses 1 and 2, for a fault distant 300 meters from bus 1, considering a sampling frequency equal to 1 MHz. A threshold could be delimited in order to detect the wavefront arrival time on buses 1 and 2 at 19 and 22 μs, respectively. Therefore, a wavefront reached the bus 2 three samples after the first wavefront reaches the bus 1. From (2), the fault location estimation is

$$d_F = 0.5\left[1 + \left(\frac{-3}{1\times10^6}\right)1.4286\times10^5\right] = 0.28571 \text{ km.} \quad (3)$$

Therefore, the fault location was estimated at 285.71 meters, with an error of 14.29 meters.

Table I summarizes the estimation of fault location for faults applied from 100 to 900 meters of bus 1, with a step of 100 meters, considering two different sampling frequencies, 1 MHz and 2 MHz. In the total, 18 faults were applied, 9 for 1 MHz

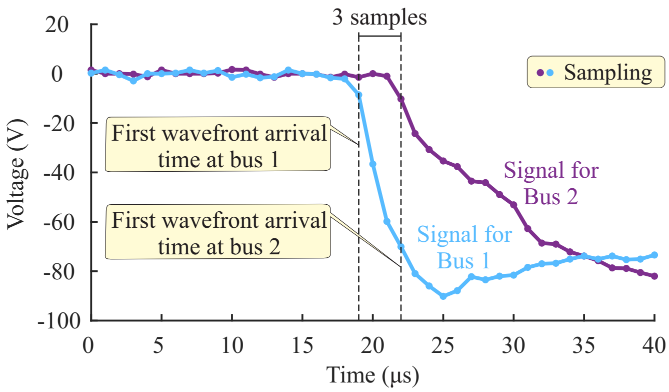

Fig. 10. Wavefront arrival time on buses 1 and 2 for a fault distant 300 meters from bus 1 and a sampling frequency of 1 MHz.

and 9 for 2 MHz. The mean errors for all the applied faults were about 19.05 and 11.91 meters, for the lowest and the highest frequencies, respectively. The higher error occurred in the lowest frequency and, disregarding the error 0, the lowest error occurred in the highest frequency. Therefore, a higher value of the sampling frequency reduced the errors since the discrete wavefront arrival times at the line terminals were closer to the continuous wavefront arrival times, as discussed in section II.

TABLE I
FAULT LOCATION ESTIMATION.

Fault Location (m)	Fault Location Estimation (m)		Error (m)	
	1 MHz	2 MHz	1 MHz	2 MHz
100	71.42	107.14	28.58	7.14
200	214.28	214.28	14.28	14.28
300	285.71	321.43	14.29	21.43
400	428.57	392.86	28.57	7.14
500	500.00	500.00	0	0
600	571.43	607.15	28.57	7.15
700	714.29	678.58	14.29	21.42
800	785.72	821.43	14.28	21.43
900	928.58	892.84	28.58	7.16
	Mean Error		19.05	11.91

VI. CONCLUSIONS

This work presented an experimental test bench in order to support the developing and evaluation of methods based on traveling waves, without requiring digital simulations, for both educational and research purposes. In order to do so, a real cable was used, which enables the wave propagation phenomenon.

Usually, the methods based on traveling waves are evaluated by means of digital simulations since the access to real transmission systems is highly strict. Few works presented field evaluations, which are restricted to a few and uncontrolled events. However, this paper demonstrated the feasibility of an experimental test bench for traveling wave evaluations, with real phenomenon representation of traveling waves.

The described assembly can perform variations on fault parameters such as, fault location, fault impedance, load variation, and fault inception angle, which are completely uncontrollable parameters in field evaluations. The traveling waves were performed by means of fault applications along the real cable. The described methodology for the implementation of the experimental test bench can be easily reproduced.

The measured high-frequency transients attested the feasibility of the experimental test bench in order to enable the wave propagation phenomenon. The traditional two-terminal traveling wave-based transmission line fault location method was evaluated. The results demonstrated that methods based on traveling waves can be properly evaluated by means of the presented experimental test bench, with no need for digital simulations.

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