The Impact of Two-Terminal Traveling Wave-Based Transmission Line Protection in the Distribution Power System Voltage Sag

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***Abstract*—A fast protection method increases the power system reliability, decreases costs and can mitigate power quality (PQ) problems, such as voltage sag. This paper evaluates and compares the voltage sag behavior in a distribution subsystem due the distance protection and the two-terminal traveling wave-based transmission line protection performance. The tested power system is based in the IEEE 230 kV transmission power system and in the IEEE 30 bus power system, and contains a transmission, sub-transmission, and distribution systems. In order to provide more reliable data, the power system lines were modeled at distributed parameters. The results were obtained by means of computational simulation and indicate that a fast protection can significantly decreases the voltage sag intensity.**

***Index Terms*—Power quality, voltage sag mitigation, IEEE power system, transmission line protection, traveling waves.**

I. Introduction

Researches related to PQ has been increasingly developed in recent years. These works are motivated by the need for more efficiency of the power system and for reducing damages to the system and economic lost. Furthermore, it is growing the interesting by the customers for solving PQ problems. Many others PQ study motivations may be enumerated [1, 2].

When a disturb occurs on the power system, such as a fault, the voltage and current signals suffer distortions, impacting the power system. The industry and the small consumer are directly affected, since electrical machines, power electronic devices and electronic devices may be damaged or lose efficiency [3].

According to the Institute of Electrical and Electronics Engineers (IEEE), a voltage sag occurs when the absolute voltage level is between 10% and 90% of its nominal value. The voltage sag is one of the most commons PQ problems and can be generated by faults, overload, and the starting of large motors [4], being the faults the main cause [5], generating voltage sag at loads positioned at hundreds of kilometers away [4]. The residual voltage level and the duration are the main voltage sag characteristics [6]. Therefore, it is possible to reestablish the voltage by disconnecting the segment where the fault is located, considering that the rest of the system will remain powered by a source. In other words, the voltage sag duration is mainly determined by the time in fault clearing by the protection scheme [2], then, how faster the protection, smaller will be the fault intensity and, consequently, less severe the voltage sag [4]. Reference [7] presents typical values of faults clearance to different voltage levels. For 230 kV, it varies from 50 to 133 ms with 83 ms of average value.

A fast transmission line protection increases the voltage sag mitigation velocity in sub-transmission and distribution electrical subsystems, reducing the system damages. Currently, the fault clearing time occurs after some fundamental wave cycles passed from the fault inception time, which, in large part, it is due to fault detection delay, that occurs through protection schemes based on fundamental frequency phasorial estimation. In order to provide high velocity protections, several reliable protection schemes were developed [8].

When a fault occurs in a transmission line, traveling waves (TW) propagate toward the line terminals with a velocity close to the light's one, causing high frequency electromagnetic transients in the voltage and current signals at the line ends. When these TW arrive at the line terminals, they reflect back toward the fault point where are refracted and reflected back toward the line terminal, resulting in several coexistent TW due to the wave superposition principle. The TW can be detected by a relay connected to a line terminal using wavelet transform coefficients or other high-pass filtering process, with no need of phasorial estimation [9], enabling a fast fault detection.

Many works have developed fault location technics in transmission lines using TW [10–12]. Reference [13] developed a directional protection technique using TW, [14] proposed a bus protection using the TWs amplitudes. A phase-to-ground protection technique in distribution systems using TW was proposed in [15]. Recently, [16] proposed a two-terminal line transmission protection method based on TW, where the first wavefront time in each line terminal are used to the correct protection performance.

This work evaluates the effects of the two-terminal traveling wave-based protection and the traditional impedance scheme protection in voltage sags at the distribution system when a fault takes place on the transmission line. The modeled system was based in a 230 kV transmission system of the IEEE connected to another one based in the IEEE 30 bus distribution system. All the system was modeled with its lines at distributed parameters. The results were obtained by means of computational simulation and indicate that a fast protection can significantly decreases the voltage sag intensity.

II. Two-Terminal Traveling Wave-Based Line Transmission Protection

When a fault occurs on the transmission line, high frequency electromagnetic transients come up to the current and voltage signals. These transient signals are called traveling waves, and propagates close to the light's velocity. The TW travel toward the line terminals and, arriving there, high frequency perturbations, i.e., wavefronts, can be detected at the bus end.

Fig. 1 depicts the general idea of the two-terminal traveling wave-based transmission line protection. The traveling-wave based relay contains basically four stages: the anti-aliasing filtering, the analog to digital conversion, the wavefront arrival time detection, and the internal fault detection. The phasor estimation is not required at this protection method.

According to [16], after the first wavefront detection, the relay send to the another relay a signal indicating a fault detection. When the relay detects a fault and receives the signal from the another relay, a trip signal is sent to the breaker by a communication device. Therefore, it is necessary a synchronization scheme between the two relays, normally provided by a GPS connected to both relays. The communication device provided in [16] has a non-deterministic time delay. For instance, in [16] the average time delay was 0.712 ms. The information transfered between relays occurs using an optical fiber communication channel. The wave propagation velocity, v_c, associated to such communication channel is fairly constant and its typical value is $v_c \approx 0.6814c$ [17].

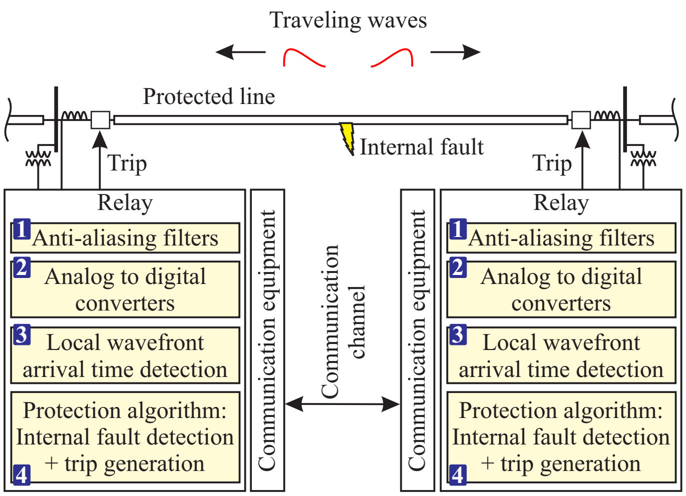

Fig. 1. General idea of the two-terminal traveling wave-based transmission line protection

III. The System

The modeled system was a modification based on two IEEE power systems: the 230 kV transmission power system described in [18] and the 30 bus power system described in [19], containing a 132 kV sub-transmission subsystem and a 33 kV distribution subsystem. The main modification done in these original systems was regarding to the line parameters, which were modeled at distributed parameters to a frequency of 50 Hz.

Fig. 2 depicts the final system used in this work. The 230 kV transmission subsystem contains four transmission lines, where the lines 2 and 3 are disconnected, and two generators, where just the generator G3 is connected and defined as a PQ bus with 100 MW. The 132 kV sub-transmission subsystem and the 33 kV distribution subsystem were based on the IEEE 30 bus system and contain a swing bus, represented by the generator G1, and a PV bus, represented by the generator G2, delivering 40 MW and -40 MVAr to 50 MVAr. The 30 bus IEEE system represents a section of a real American electrical system in December 1961 and was originally modeled at concentrated parameters, therefore, its technical information are scarce. In order to be possible to model the 30 bus system in distributed parameters, it was necessary to follow technical directions to design transmission lines [20, 21] and use typical line parameters used by the Companhia Hidro Elétrica do São Francisco (Chesf). All the distributed line parameters are specified in Tables I and II. Due to the computational limitation of the simulator, only one line was modeled at concentrated parameters, the one connected between buses 21 and 22, in which parameters are specified in the Table III. All the transformers and loads were modeled according to the original systems.

IV. Voltage Sag Mitigation

In this section, a voltage sag in the distribution subsystem, caused by a three-phase fault on the line 1 of the transmission subsystem, is analyzed. The fault was applied 40 km away from the bus 31, and has 3 ohm of fault resistance. The voltage sag mitigation in the distribution subsystem happens when the protection of the line 1 acts, as soon as possible, reducing the voltage sag duration on the distribution system. The protection strategies applied at the transmission line under fault were the traditional impedance based on Fourier phasor estimator and the two-terminal traveling wave-based protection. It was assumed that the breaker takes two cycles then the relay trip. The voltage sag on the bus 16 was estimated for a traditional one cycle Fourier phasor estimator with a 1 kHz sample frequency, which yields 20 samples per cycle.

A. Voltage Sag During the Traditional Impedance Protection

A traditional impedance protection relay was connected on the bus 31 in order to protect the transmission line 1 presented in the Fig. 2. The anti-aliasing filter utilized was the second order Chebyshev II. The relay sampling frequency was 1 kHz, and the phasor estimator was the traditional one-cycle Fourier.

Fig. 3 depicts the overcurrent behavior on the bus 31. The fault inception time occurred at 26.5 ms, the trip relay occurred at 56 ms, and the fault clearance occurred at 96 ms. Therefore, the trip to the traditional impedance protection relay took 29,5 ms, around 1.5 cycle, and the complete fault interruption took 69.5 ms, around 3.5 cycles.

The traditional impedance protection is subject to the fault impedance calculus delay. Fig. 4 depicts the impedance estimation during the fault and after the fault clearance. The fault impedance calculus took several samples to converge into the

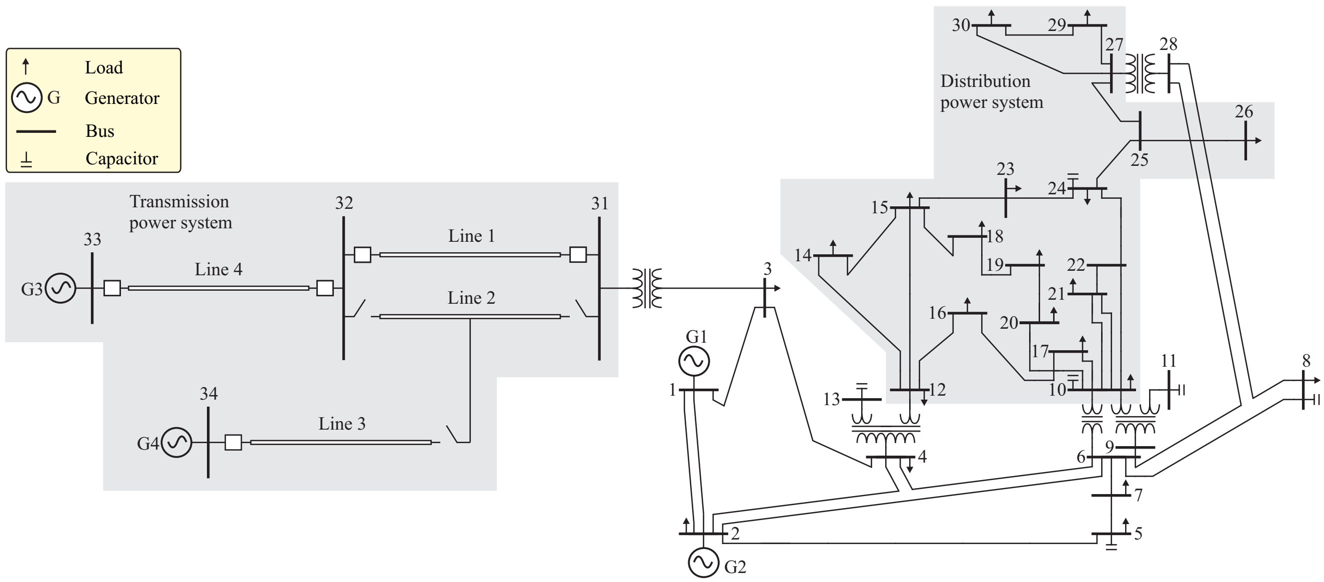

Fig. 2. Final system based on IEEE power systems.

TABLE I
DISTRIBUTED LINE CONSTANTS.

Line (Bus-Bus)	Positive Sequence Parameters			Zero Sequence Parameters		
	Resistance (ohm/km)	Inductance (mH/km)	Capacitance (nF/km)	Resistance (ohm/km)	Inductance (mH/km)	Capacitance (nF/km)
1-2	0.1916	1.421	8.221	0.3934	3.870	5.646
1-3; 2-4; 2-5; 2-6; 3-4; 4-6 5-7; 6-28; 6-7; 6-8; 8-28	0.1913	1.332	8.728	0.5009	4.730	5.779
10-17; 10-20; 10-21; 10-22 12-14; 12-15; 12-16; 19-20	0.1702	1.031	11.407	0.3418	2.877	5.355
14-15; 15-18; 15-23; 16-17; 18-19; 22-24; 23-24; 24-25; 25-26; 25-27; 27-29; 27-30; 29-30	0.4263	1.129	10.374	0.7276	3.345	5.051
31-32	0.0526	1.253	9.354	0.1917	4.070	5.557
32-33	0.0526	1.253	9.337	0.1917	4.070	4.850

TABLE II
LENGTHS OF THE DISTRIBUTED LINES.

Line	1-2	1-3	2-4	2-5	2-6	3-4	4-6	5-7	6-28	6-7	6-8	8-28
Length (km)	14.25	41.67	40.08	44.62	39.67	8.53	9.32	26.1	13.48	18.45	9.45	45
Line	10-17	10-20	10-21	10-22	12-14	12-15	12-16	19-20	14-15	15-18	15-23	16-17
Length (km)	1.78	4.4	1.58	3.16	5	2.75	4.18	1.43	3.71	4.06	3.75	3.59
Line	18-19	22-24	23-24	24-25	25-26	25-27	27-29	27-30	29-30	31-32	32-33	
Length (km)	2.4	3.32	5.01	6.11	7.05	3.87	7.71	11.19	8.41	100	100	

protection zone of the impedance relay, due to the imprecision of the absolute value from Fourier.

Fig. 5 depicts the voltage sag behavior in the distribution subsystem, on the bus 16. Considering that the voltage sag occurs when the absolute value of the voltage decays below 90% of its nominal value, the voltage sag started at 30 ms. After that, the line protection cleared the fault in the transmission subsystem and the voltage value at bus 16 returned to a nominal value. The voltage sag was mitigated at 118 ms. Thus, the voltage sag at bus 16 took 88 ms, around 4.4 cycles.

TABLE III
CONCENTRATED LINE PARAMETERS

Line (Bus-Bus)	Resistance (ohm)	Inductance (mH)
21-22	0.0116	0.7512

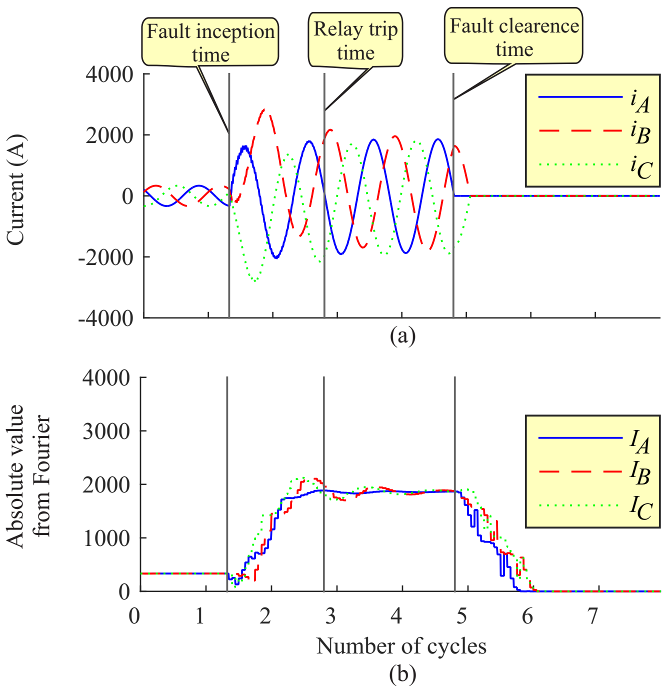

Fig. 3. Overcurrent on the bus 31 of the transmission system: (a) currents; (b) absolute currents.

B. Voltage Sag During the Two-Terminal Traveling Wave-Based Protection

Traveling wave-based relays were connected on the buses 31 and 32 of the transmission subsystem. The sampling frequency of both relays was 20 kHz, which is considered a low sampling frequency compared to the useful sampling rate of several MHz used in traveling wave detection. However, 20 kHz is completely possible with the current technology and the protection is still very fast. The utilized anti-aliasing filter was the second order Chebyshev II, and the mother wavelet was the Daubechies 4 (db4), since this one provides an accurate detection of the fast transients in power systems [22]. The communication channel was provided by the optical fiber and the wave propagation time delay associated to such communication was 0.49 ms, considering a line length of 100 km. The communication device used was the one provided in [16] and was assumed that the time processing delay of this device was 0.712 ms.

Fig. 6 depicts current i_A behavior at buses 31 and 32 during the fault, that occurred at 26.469 ms. It was necessary around three relay sampling time to the first wavefront arrives at bus 31 and four to the bus 32. The traveling waves were detected using the wavelet coefficients in the consecutive relay sampling after the wavefront arriving at the buses, therefore the wavefronts were detected at 26.650 ms in the bus 31 and 26.70 ms in the bus 32. Thus, the traveling wave-based relay at bus 31 detected a fault transient after about 0.18 ms. Thenceforth, the relay trip occurred after the communication device processing and the wave propagation associated to the communication channel, resulting in time delay.

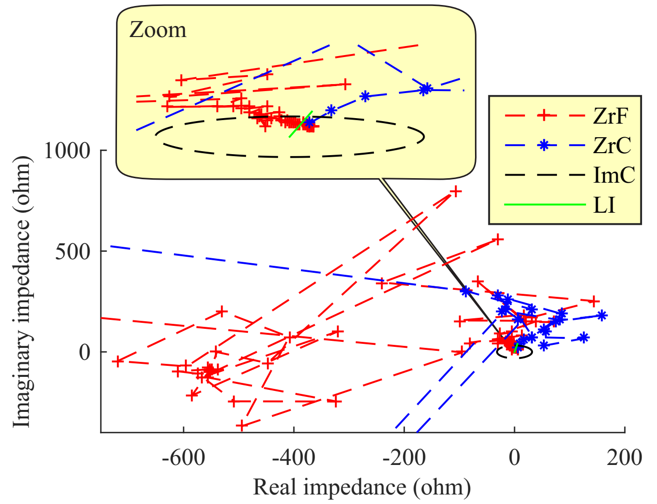

Fig. 4. Impedance estimation, where: ZrF is the estimated impedance (Zr) during the fault; ZrC is Zr after the fault; ImC is the impedance circle to 80% of the line impedance; LI is the line impedance.

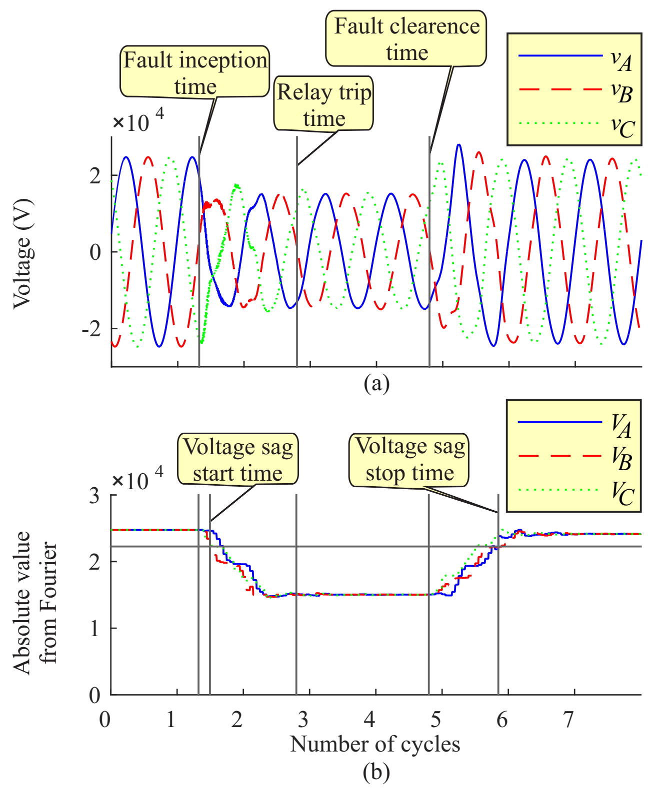

Fig. 5. Voltage sag on the bus 16 to a traditional impedance transmission line protection: (a) voltages; (b) absolute voltages.

Fig. 7 depicts the overcurrent behavior at bus 31 of the

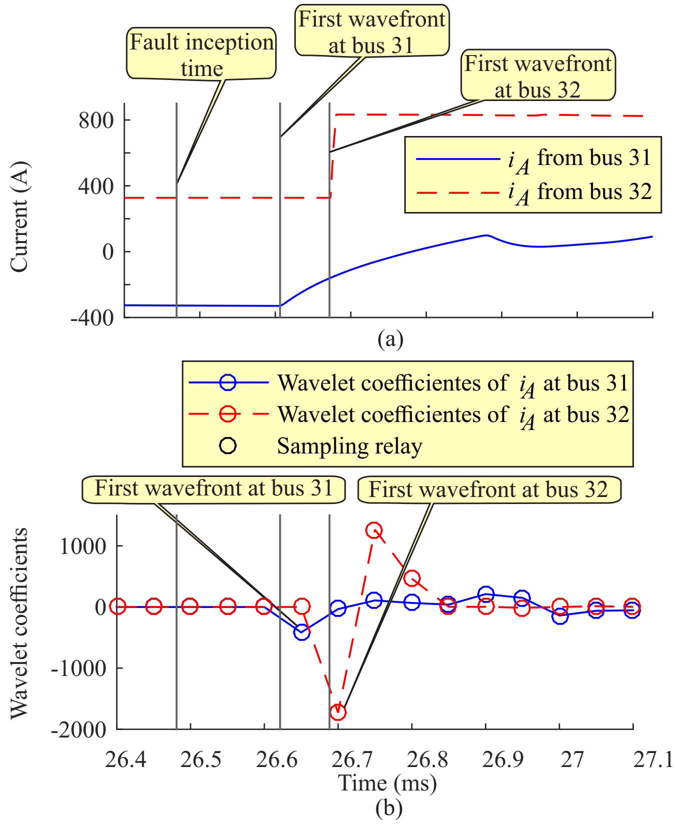

Fig. 6. First wavefront on the bus 31 and bus 32: (a) currents; (b) wavelet coefficients of i_A.

transmission subsystem. The trip relay happened at 27.950 ms, and the complete fault clearance at 67.946 ms. Therefore, the trip to the traveling wave-based relay at bus 31 took 1.48 ms, around 0.074 cycle. The complete fault interruption took 41.477 ms, around 2.07 cycles.

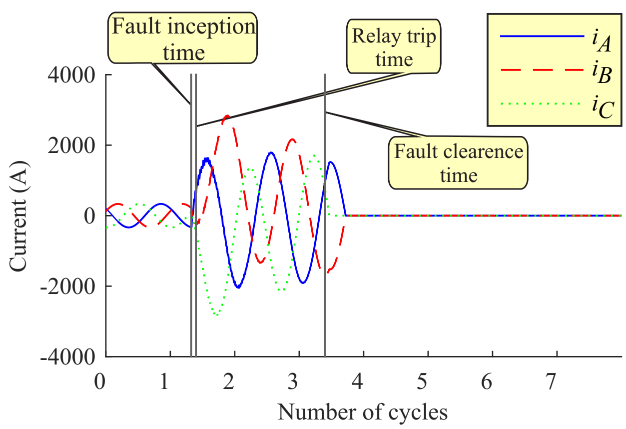

Fig. 7. Overcurrent on bus 31 of the transmission system.

Fig. 8 depicts the voltage sag behavior in the distribution subsystem, at bus 16. The voltage sag started at 30 ms, after that, the line protection cleared the fault in the transmission subsystem and the voltage value in the bus 16 returned to a normal landing place. The voltage sag was mitigated at 88 ms. Thus, the voltage sag at bus 16 took 58 ms, around 2.9 cycles.

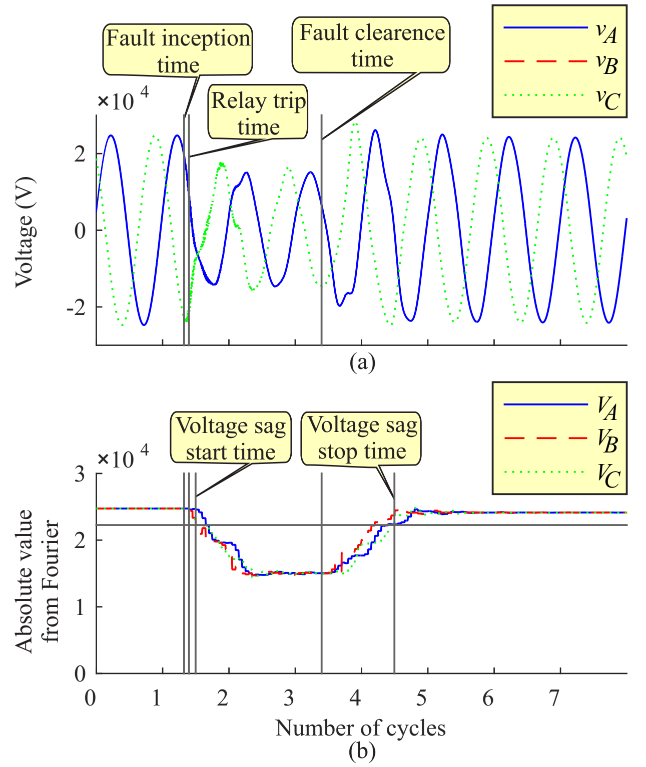

Fig. 8. voltage sag on the bus 16 to a traveling wave-based transmission line protection: (a) voltages; (b) absolute voltages.

C. Impacts of Voltage Sag

Table IV summarizes the obtained results. The voltage sag duration was significantly reduced, what is an important contribution from the power quality point of view.

Voltage sag produces significant impacts on sensitive loads, for example, the tripping of power adjustable speed drives which causes interruption of the manufacturing process several times a year [23]. In addition, a fast voltage sag mitigation reduces the chance of to damage sensitive loads, reducing the economic losses.

According to Table IV, the fault clearance time was significantly decreased to only 5% of the time took by the traditional distance protection. Hence, the voltage sag duration was practically determined by the breaker delay, reducing the voltage sag duration in around 34%.

TABLE IV
RESULTS SUMMARIZED.

Method of Protection	Time Duration (ms) Relay Trip	Time Duration (ms) Fault Clearance	Time Duration (ms) Voltage Sag
Traditional	29.50	69.50	88
Wave-Based	1.48	41.47	58
Percentage Decrease	94.98%	40.33%	34.09%

V. CONCLUSIONS

This paper analyzed the voltage sag behavior in a distribution subsystem due to a fault in the transmission subsystem.

The results were obtained in a system based on a IEEE transmission power system and a IEEE sub-transmission and distribution power system, and was modeled at distributed parameters. The voltage sag was evaluated and compared considering the transmission line under fault was protected by a traditional impedance relay and by a two-terminal traveling wave-based transmission line relay.

The two-terminal traveling wave-based transmission line protection provided a very fast fault clearance. In the fault scenario evaluated, the relay trip of the traveling wave-based relay took only 5% of the time that the traditional impedance relay demands to send a trip to the breaker. Thus, the time to the fault clearance was significantly restricted to the breaker delay, and occurred 40% faster if comparing the traveling wave-based relay with the traditional impedance relay. Regarding the voltage sag duration, the evaluated scenarios demonstrated that traveling wave-based relay reduced significantly the voltage sag in the distribution subsystem from 4.4 to 2.9 cycles.

The non-use of the phasor estimator, that is used for the traditional protection schemes to extract information from the fundamental frequency, was one of the principal reasons to the significant gain in the PQ mitigation time due to its large convergence delay, whereas the fast propagation of the high frequency electromagnet transients is possible to be detected with high-pass filtering in traveling wave-based protection.

The fast voltage sag mitigation provided by traveling wave-based protection and evaluated in this work decreases several power system problems such as the tripping of power adjustable speed drives, which causes interruption of the manufacturing process and may results damages to electrical equipments.

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