Traveling Wave Relays for Distribution Feeder Protection with High Penetrations of Distributed Energy Resources

Preprint

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Traveling Wave Relays for Distribution Feeder Protection with High Penetrations of Distributed Energy Resources

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***Abstract*—Increased penetration of power electronics interfaced Distributed Energy Resources (DER) like PV, electric vehicle and battery storage in the distribution system (both in numbers and sizes) may cause bi-directional power flows under normal operation. In addition, they contribute low fault current under short circuit conditions. These two changes can impact the proper operation of legacy protection systems. This can add additional challenges during weak grid and islanded operation. In this research, traveling wave (high frequency) signature based protection scheme is proposed for future distribution systems. Simulations are performed under different transient scenarios to provide insight into the high frequency signatures to show the traveling wave behavior. Finally, this paper discusses the importance of sensing and digital processing requirements for traveling-wave protection in distribution system.**

***Index Terms*—Distributed energy resources, distribution system protection, high-frequency signature, inverters, power distribution, power system protection, traveling wave.**

I. INTRODUCTION

Electric co-operatives (co-ops) in the U.S. are member-owned non-profit entities that provide reliable and affordable electricity directly to the customers. These co-ops are the backbone of rural electrical power systems. Today, there are a total of 897 co-op members, out of which there are 834 distribution co-ops and 63 generation and transmission (G&T) co-ops. G&T co-ops provide power to distribution co-ops through their own generation and/or by purchasing power at wholesale. Distribution co-ops purchase power from the G&Ts. Co-ops own 42% of U.S. electric distribution lines, and serve 13% of the U.S. load [1]. Co-ops strive to meet the electric demand through diverse portfolio of fuels at a reasonable cost, while serving the rural communities reliably and meeting member expectations for environmental sustainability.

About 8% of the electricity sold by co-ops was generated from non-hydro renewable resources in 2017, similar to the national average [1]. Due to the drop in prices and improved technology, distributed generation from inverter based sources are becoming cost-effective. Since 2010, renewable energy capacity in co-ops has increased from 4 GW to 9.7 GW and a significant portion of this capacity is from solar [1]. As the future grid evolves into a more complex system with higher penetration of inverter based distributed energy resources (DERs), there are new challenges faced by the co-ops [2]. These challenges impact the planning, operation, and protection of the rural electric power systems.

Legacy rural electric power systems are designed to operate in the radial configuration with uni-directional power flow from source to the load. Higher penetrations of inverter based DERs may cause bi-directional power flow and impacts standard power system operations, such as voltage and frequency regulation, reclosing, and protection [3]. Protection requires more attention because it can limit the penetration level of DERs. Inverter based DERs provide only 1-2 pu fault current. Simple legacy over-current (OC) schemes may fail to detect the fault. Existing fuse-recloser co-ordination utilizes both OC (for the operation of fuses) and uni-directional (co-ordination between fuse and recloser) nature of the distribution system for fault protection. Bi-directional power flow and highly varying fault current contributions from the inverter based DERs may cause unwanted mis-operations [4], [5]. Finally, the new interconnection standards for DERs (IEEE std. 1547-2018) can dictate the performance of the DERs under abnormal grid conditions [6].

Since, co-ops use long overhead lines and underground cables to serve the sparsely populated service territory, they need reliable protection schemes for faster detection, and location of low impedance faults (LIFs), and high impedance faults (HIFs). This aids in safe operation of the system and in reducing the customer outage time. Current contribution from DERs during both LIFs and HIFs have the same order of magnitude. HIFs are more common in distribution system and are generally difficult to detect under 15 kV distribution voltage level [7] even without the presence of high penetration of DERs.

A smart protection scheme that can alleviate the challenges

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is proposed in this paper. This concept uses the high frequency signatures generated during fault or other transient events to detect and locate the faults. The rest of this paper is organized as follows. Section II briefly discusses the drawbacks of other protection approaches. Section III introduces the traveling waves (TW) concept and their application in the power systems. It also addresses the challenges in the distribution system. In section IV, TW characteristics under different system conditions are explained using the simulated models of test system in EMTP-RV. Section V discusses the frequency response requirements of current transformers (CT) and potential transformers (PT), and signal processing requirements of intelligent electronic devices (IEDs) to capture the high frequency signatures of the transients in distribution system. Finally, future work and conclusions are discussed in sections VI & VII respectively.

II. CHALLENGES OF LEGACY DISTRIBUTION PROTECTION

Legacy distribution systems are designed under the premise that the distribution system has only one source of fault current. But, increased penetration of inverter based DERs at the distribution level introduces multiple sources that contribute typically 1-2 pu fault current. Combined contribution from the DERs to the fault current varies depending on the system operating conditions and the location of the faults.

Traditionally, transmission systems with multiple sources use directional, and distance protection schemes to detect and locate faults [8], [9]. Since transmission systems are mostly balanced under steady state operation, directional and distance protection principles rely on changes in zero and negative sequence components during fault conditions. Under fault conditions, the magnitude of zero and negative sequence components are highest near the fault location and are lower in magnitude at locations farther from the fault. In addition to the magnitude, the angles of the negative and zero sequence quantities are also used for distance element polarizing and fault identification logic [10].

These directional and distance protection schemes are being implemented as potential solution for distribution systems with multiple sources such as grid and DERs. In addition to these approaches borrowed from the transmission system, adaptive settings based protection schemes have also been proposed to account for topology changes in the distribution system. Since challenges in using over current protection has been discussed a lot in the literature, the following subsections focuses on the challenges in using directional, distance and adaptive setting based schemes in future distribution systems.

A. *Challenges in the use of directional element*

Directional elements utilize primarily the zero and negative sequence fault currents to detect and realize the fault location. It is challenging to utilize this in a distribution system because these sequence components are present during non-fault conditions such as open pole, load unbalance, and transformer saturation. These conditions may result in elevated levels of normally present zero and negative sequence quantities. In this situation, protection settings would need to be higher than it would be for balanced system. This limits the effectiveness of directional OC protection in an unbalanced distribution systems. In addition, inverter based DERs produce low or no sequence currents at the terminals because these sources are controlled differently than a conventional rotating machine based resources [10].

B. *Challenges in the use of distance element*

Distance protection measures impedances to detect and realize the fault location. These impedance measurements in distance protection are affected by the presence of taps and DERs between the fault location and the relays. These apparent impedances seen by the relays can underreach or overreach due to the infeed from DER and outfeed of load current in the feeder taps. In addition, increased DER penetration and dynamic loading conditions will also aggravate the relay reach problems. Moreover, distance protection approach also uses sequence components to identify the faulted phase and select the polarizing signals [10]. As discussed in the section II-A, sequence quantities are not dependable in an unbalanced systems and in the presence of the DER. Finally, the distance relays are restricted to the three phases networks due to their dependence on sequence components and non-faulted phase quantities for polarization.

C. *Challenges in the use of adaptive settings*

In adaptive settings based protection, the settings used in the protection schemes are varied to adapt to the network conditions. Different types of adaptive schemes both offline and real time are discussed in [11]. These schemes require communication channel to monitor the changes in the network and update the relay settings, which is very expensive. Increasing penetration of DERs require the algorithms to continuously study the models and update the settings. In offline approach, it is difficult to identify the critical operating conditions and determine the optimal relay settings. To overcome the protection challenges caused by DER, travelling wave based protection which has been primarily used in transmission for the past 40 years has been proposed for distribution protection. There are challenges to design a protection scheme based on travelling waves due to their behavior across different components in the distribution system.

III. BACKGROUND ON TRAVELING WAVES PHENOMENON

Any disturbance in the network such as lightning strike, faults, opening and closing of a circuit breaker, and interruption of steady-state conditions will result in the initiation of a TW or surges. This resulting TW propagates away from the event location in both directions. Under a fault, voltage and current waves are generated at the fault point, traveling at a very high speed. These generated waves are independent of the fault type, network topology, and the location of fault. But, some of their characteristics are dependent on the characteristic impedance of the line in which they are traveling. The propagation velocity of the wave and wave shape depends on the line parameters: resistance (R), inductance (L), capacitance (C), and conductance (G). These line parameters are dependent on the physical aspects of the line design, such as structure geometry, type of conductor, and conductor spacing.

Fig. 1 shows the initiation of TWs at a fault point. Waves are also induced on the non-faulted phases as shown in Fig. 1, due to the mutual impedance between the conductors. As the propagating TWs reach the first impedance mismatch, they are transmitted and reflected based on the relative values of the characteristic impedances of the line in which the waves originated and the adjacent lines or network components. The TWs also attenuate as they propagate along the line. When a fault occurs, voltage waves with equal magnitude are launched at the fault point. These waves propagate away from the fault location. TWs recorded at any time on the line terminals are the summation of all incident & reflected voltage and current waves. Fault generated transients are effected by the Thévenin voltage source at the fault point [12] and it is negative of the pre-fault point on wave as shown in Fig. 2 [12]. Presence of multiple sources and the load flow prior to the fault, establishes the initial conditions for the Thévenin source.

The concept of TWs has been used in the power systems field for decades. Utilities perform transient studies to understand the insulation failure, and surge protection design. These studies are also performed to protect the power systems components from failing due to the temporary over voltages caused by transient events like circuit breaker switching, lightning strikes, and recloser actions [13]. The use of TWs in transmission system protection has been reported since 1940s. Recently, TW methods have re-emerged as a reliable form of protection because of advancement in high speed sampling technology, digital signal processing techniques, high speed fiber communications, time stamping, and synchronization techniques [14].

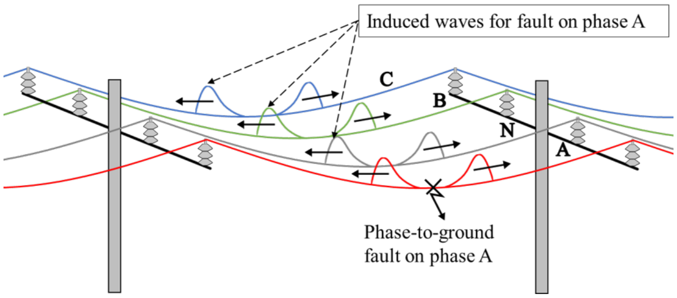


Fig. 1: Traveling waves in multi conductor line during phase-to-ground fault

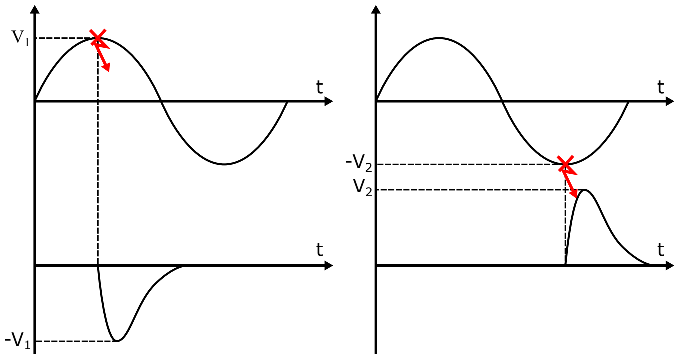


Fig. 2: Induced voltage waves at the instant of fault

Use of TWs to analyze transient events in distribution systems have significant challenges. For example, TW propagation is confined typically to the lines in the transmission. But in distribution, the TWs may travel through or attenuate by different distribution system components like unbalanced short lines, underground cables, frequent taps (point of discontinuities), transformers, change in conductor size, voltage regulators, and capacitor banks along the travel path. In addition, the TWs may also decay in short duration.

IV. Simulation Cases for Comparing Traveling Wave Characteristics and Results

This section describes the test networks that are simulated in EMTP-RV to present the characteristics of TWs under different transient events and the results from the simulation scenarios. The following are the two networks that are simulated:

- Four bus transmission network
- Five bus distribution network

Since there are plenty of literature on TWs in transmission system, only one test case is simulated in this paper. But, for the distribution network, four different scenarios are simulated. The focus is to provide a clear understanding and characterization of TWs using generic representative features of the distribution system under different system topology.

A. Test Network Characteristics

The test network for transmission simulation scenario is shown in Fig. 3. This test network is a four bus (buses U, S, R, and T) 230 kV system with two sources at buses U, and T. Lines are characterized by long and short lines with 25 miles of line length between buses U-S, and R-T, and 190 miles of line length between buses S-T.

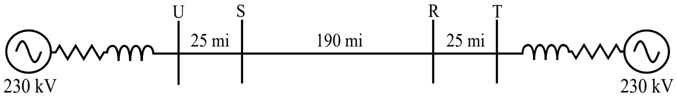


Fig. 3: High voltage 230 kV 4-bus transmission test network

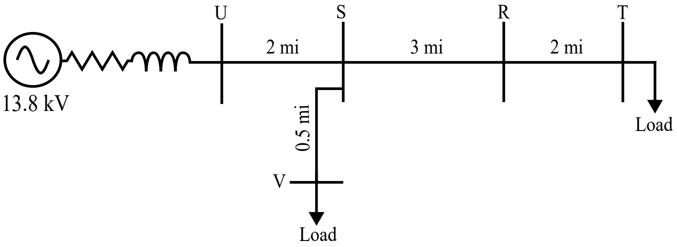


Fig. 4: Medium voltage 13.8 kV 5-bus distribution test network

The test network for distribution simulation scenario is shown in Fig. 4. This test network has five buses U, S, R, T, and V. The line length between the five buses are shown in Fig. 4.

The over head lines, and underground cables in the transmission and distribution test networks are modeled using the frequency dependent modeling approach known as Universal Line Model (ULM). The tower structure and conductor spacing were modeled using the rural utility standard (RUS) 1724E-200 based on the voltage level. Because of this frequency dependent modeling approach in EMT, the transmission and distribution test networks are valid over a wide band of frequency. Finally, the sources used in both the test networks are modeled as voltage source behind equivalent Thévenin impedance. The impedance values are calculated from fault MVA at power frequency.

B. Simulation Scenarios

This subsection describes the transient scenarios simulated in EMTP-RV using the test network systems to provide the characteristics of TWs under different network and system conditions.

1) Scenario 1 - phase-to-ground fault in overhead line section between buses S and R in the test transmission network: In this scenario, a phase-to-ground fault was simulated in the test transmission network. The fault was simulated in phase A at the overhead line section between buses S and R. The fault was simulated at approximately 50 miles from bus S, and 140 miles from bus R respectively. This is shown in Fig. 5. In this research, this scenario is used as the benchmark for studying TW behavior in a simple transmission system.

2) Scenario 2 - phase-to-ground fault in overhead line section between buses S and R in the test distribution network: In this scenario, a phase-to-ground fault was simulated in the test distribution network. The fault was simulated in phase A at the overhead line section between buses S and R. The fault was simulated at approximately 1 mile from bus S, and 2 miles from bus R respectively. This is shown in Fig. 6. In this research, this scenario is used as the benchmark for a studying TW behavior in a simple distribution system.

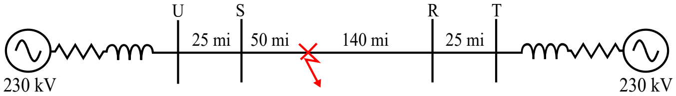


Fig. 5: Scenario 1 - phase-to-ground fault in overhead line section between buses S and R in the test transmission network

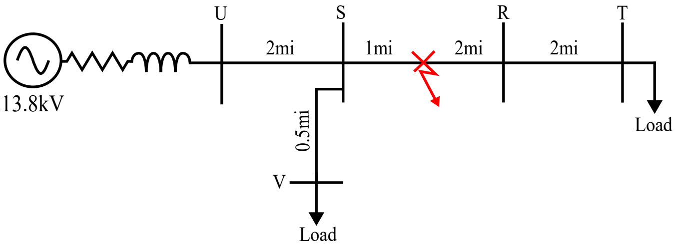


Fig. 6: Scenario 2 - Phase-to-ground fault in overhead line section between buses S and R in the test distribution network

3) Scenario 3 - phase-to-ground fault in underground cable section between buses S and R in the test distribution network: Similar to scenario 2, a phase-to-ground fault was simulated between buses S, and R. But, the overhead line section between S and R was replaced with an underground cable section and the test scenario is shown in Fig. 7. The results from this scenario are compared with scenario 2 to show the impact of the presence of underground cable in the distribution system on TWs.

4) Scenario 4 - energizing capacitor bank between buses S and R in the test distribution network: The goal of this scenario is to show the difference between a fault generated transient and a capacitor energizing based transient. Fault transient event in scenario 2 is replaced by a capacitor bank energizing event. This scenario assumes that the capacitor bank is energized in the same location as the fault in scenario 2. That is, the capacitor bank was energized between buses S and R at 1 mile from bus S and 2 miles from bus R. This scenario is shown in Fig. 8. The reasoning behind the location of the capacitor bank is to show the difference in the frequency

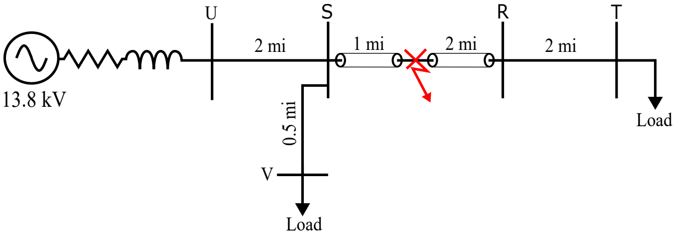


Fig. 7: Scenario 3 - Phase-to-ground fault in underground cable section between buses S and R in the test distribution network

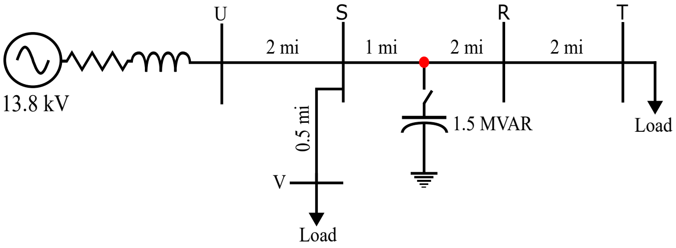


Fig. 8: Scenario 4 - Energizing capacitor bank between buses S and R in the test distribution network

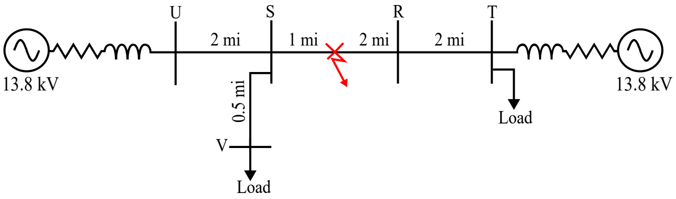


Fig. 9: Scenario 5 - Phase-to-ground fault in overhead line section between buses S and R in the test distribution network in the presence of multiple sources

content between a fault transient event and a capacitor bank energizing event.

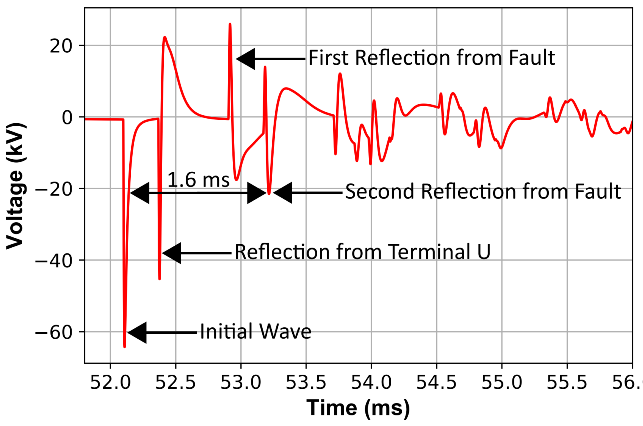
5) Scenario 5 - Phase-to-ground fault in overhead line section between buses S and R in the test distribution network in the presence of multiple sources: This scenario explains the behavior of TW in the presence of multiple sources in the distribution. The model used in the scenario 2 was used with another source added at terminal T as shown in Fig. 9.

C. Results

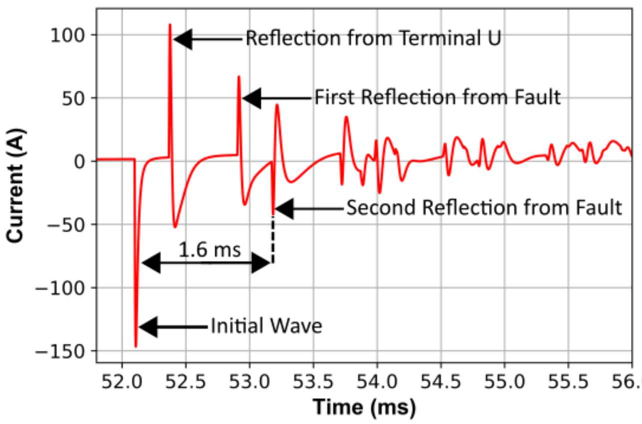
The EMT models are simulated at at a time step of 100 ns. Current and voltage measurements are included in all the terminals and recorded at each time step. The measured voltage and current values are filtered using high pass filters tuned at 10 kHz. In all the simulation scenarios, the simulation is allowed to settle and a phase-to-ground fault on phase A is applied at 51.83 ms (Phase A voltage peak).

1) Comparison between scenario 1 and scenario 2: The filtered voltage and current measurements at bus S for both scenario 1 and scenario 2 are shown in Fig. 10 & 11, respectively. An immediate observation that can be made is the length of the window between these two scenarios. Fig. 10 has a window length of almost 4 ms (52 ms to 56 ms) whereas Fig. 11 has a window length of almost 0.25 ms (51.8 ms to 52.05 ms). This indicates that the waves reflect more times in the distribution system compared to transmission system. This translates to the need for PTs and CTs with wider frequency band of response in distribution system compared to the transmission system. It can be observed that the reflected waves of voltage and current are always of opposite sign which is evident in Fig. 10(a) & 10(b). In scenario 2, as explained earlier, the fault generated waves travel between the point of discontinuities and reflect more in a very short period of time compared to scenario 1. These reflected waves superimpose on each other as shown in Fig. 11(a) & 11(b). This superimposition of TWs makes it challenging to differentiate the reflections between different discontinuity branches that exist in distribution system. This presents the need for advanced signal processing techniques to extract TW information for fault triangulation in distribution.

2) Comparison between scenario 2 and scenario 3: Compared to transmission system, distribution system have more underground cables to serve the densely populated areas. The

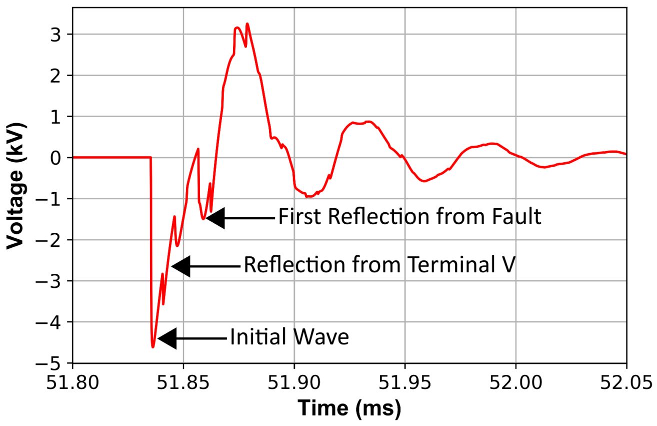


(a) Voltage TW observed at terminal S

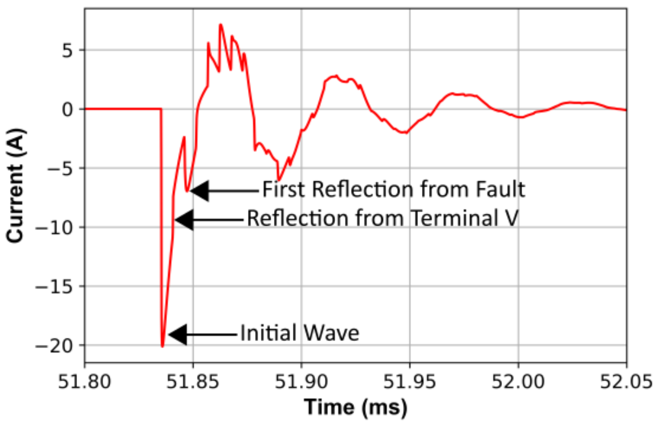


(b) Current TW observed at terminal S

Fig. 10: Voltage and current TWs for a phase-to-ground fault in transmission test network between terminals S-R



(a) Voltage TWs observed at terminal S



(b) Current TWs observed at terminal S

Fig. 11: Voltage and current TWs for a phase-to-ground fault in distribution test network between terminals S-R

characteristic impedance of a underground cable is approximately 10 times lower than that of overhead lines. The fault generated TWs will experience different mediums of propagation when they travel through under ground cables and overhead lines. In an underground cable, TWs travel at about 50-60% of speed of light. This is much slower than that of overhead lines. In scenario 3, when the fault is simulated at 51.83 ms, voltage and current waves are launched (similar to scenario 2), moving away from the fault point towards buses S and R. A comparison of the voltage TWs between scenario 2 and 3 is shown in Fig. 12. The reflections take much longer time to arrive back (even though the distance traveled by the waves are the same in scenario 2 and 3). Voltage signals at terminals S shown in Fig. 12 move slower through cables compared to the overhead lines. Energy in the wave lasts longer in the underground cables due to the lower resistance in underground cables compared to overhead lines. The slower rate of propagation as well as the different characteristic impedance will affect the frequency signature of the TWs generated and/or propagating through underground cables in distributions systems. Understanding this difference can help in detecting and triangulating faults in distribution systems with a mix of overhead lines and underground cables.

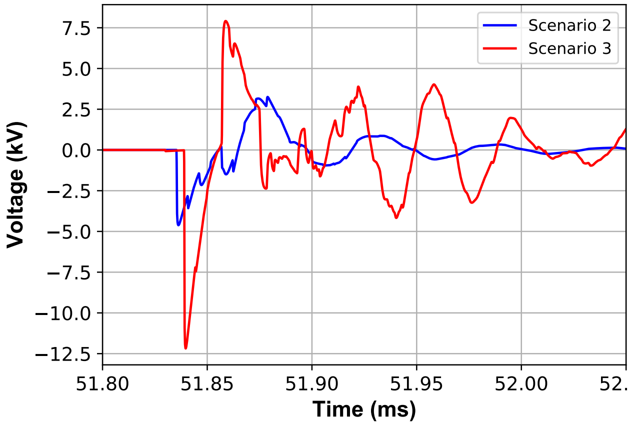
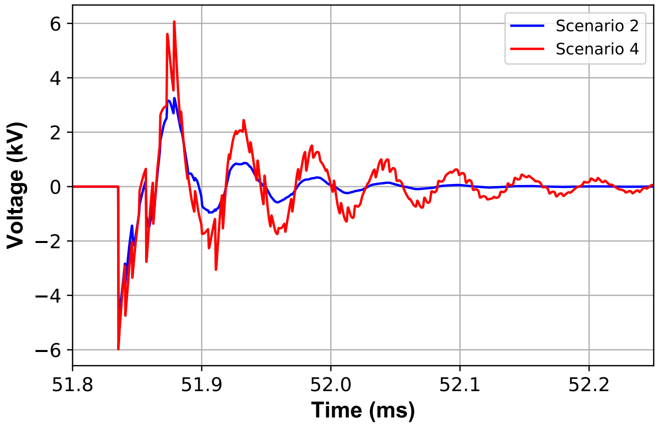
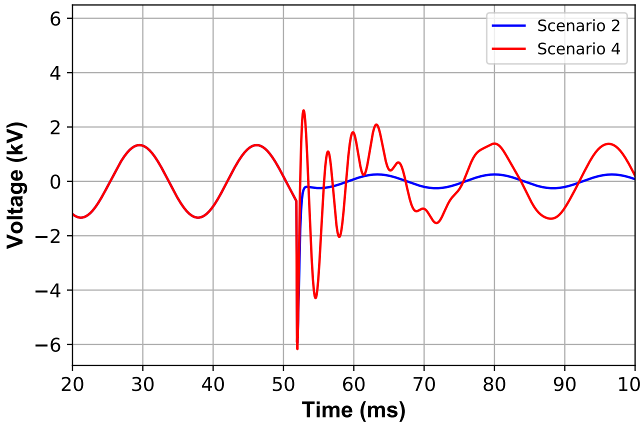


Fig. 12: Voltage TWs observed at terminal S for scenario 2 and 3



(a) High frequency voltage transient



(b) Low frequency voltage transient

Fig. 13: Capacitor switching and phase-to-ground fault generated voltage TWs observed at terminal S

3) Comparison between scenario 2 and scenario 4: Capacitors are predominantly present in distribution systems to address the power factor and voltage regulation issues. Utilities switch the capacitors during peak loads and remove them when the load drops [15]. These capacitor switching causes transient surges that are similar to the ones generated during fault. In order to understand the behavior of TWs during capacitor bank switching, the system shown in Fig. 8 is simulated with a capacitor bank of 1.5 MVAR. High frequency transients initiated by the switching of the capacitor bank are similar to the fault initiated waves. This comparison as observed at terminal S is shown in Fig. 13(a). Transients generated while energizing capacitor bank also lasts longer than the fault generated transient and contain more energy in the wave. In addition, capacitor bank energization creates signatures in frequencies that are non-existent during the phase-to-ground fault. Fig. 13(b) shows the presence of low frequency signatures in the capacitor bank transients caused by the inrush current originating from the source during capacitor bank switching. Band pass filter tuned to 1 kHz is used to extract 295 Hz low frequency in Fig. 13(b). The frequency of this inrush transient depends on the system inductance and the capacitance of the capacitor bank installed. The low frequency can be calculated as explained in [16]. This can help in characterizing the transients generated by energizing a capacitor bank.

4) Comparison between scenario 2 and scenario 5: Finally, the comparison between the scenario 2 and scenario 5 is shown in Fig. 14(a) & 14(b). It is evident from Fig. 14(a) that the presence of source at the terminal T does not affect the behavior of the waves. At terminal R, presence of source in Fig. 14(b) shows the oscillatory signal has higher voltage magnitude due to the pre-fault voltage support from the source. This is of significant advantage for the future distribution systems which will have variable penetration of DERs during a day that will affect the source strength, fault current contribution from the sources.

V. REQUIREMENTS FOR FIELD IMPLEMENTATION OF TW APPROACH IN DISTRIBUTION SYSTEM

TW based protection approach offer faster detection of transient events in the distribution system. There are challenges in the use of legacy sensing equipment for TW based protection approach. Instrumentation devices like CTs and PTs are not typically designed for wider band frequency measurements. Furthermore, IEDs that process these instrumentation measurements may not have faster processing capabilities or GPS time synchronization capabilities that are crucial for TW analysis.

1) Current Transformers and Potential Transformers: Distribution system disturbances generate signatures that cover a wide band of frequencies [17]. CTs and PTs used in the distribution system are optimized for nominal 60 Hz operation. Generally, CTs have a frequency response in the range up to 100 kHz and with a 10% of error representation between 100-500 kHz [18], [19]. Due to the limited literature available on the frequency bandwidth of PTs used in the distribution system, it can be assumed that the frequency response is similar to the CTs. The proposed protection approach characterizes the high frequency signatures of different transient event to detect a fault. Thus, the proposed approach requires the CTs and PTs to accurately reproduce the transients in their secondaries. To capture the wide frequency band transients, especially TW signatures, instrumentation devices are required to have frequency bandwidth upto several MHz.

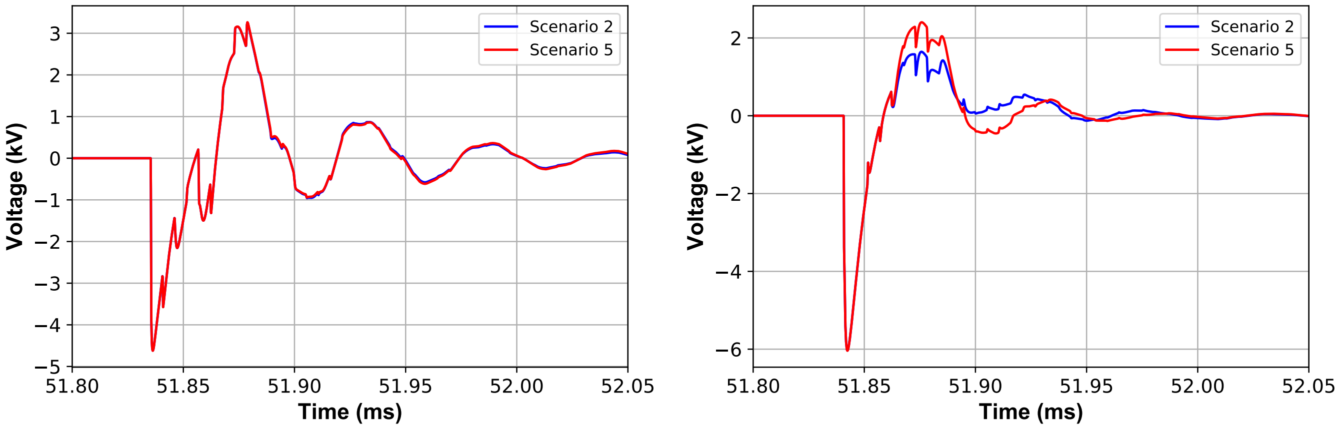
2) Digital Signal Processing and Time Synchronization Requirements: In distribution system, the sampling rate and the time step of the IEDs that performs the digital signal processing need to be greater than the highest frequency under study [20]. This rate is significantly higher than the rate of the IEDs used in the transmission system (1 MHz). This requirement is due to the shorter line length and the superposition of reflected and transmitted waves [21]. For the proposed protection approach, IEDs with high processing power and high sampling rates may be required to extract TW signatures in real time. In addition to the signal processing requirements, TW signatures based transient characterization also need high fidelity time stamping. Due to the reflections at impedance mismatches, accurate time stamping of TW signatures will reduce any errors in the triangulation of fault location.

VI. FUTURE WORK

The characteristic behavior of TWs presented in this paper are the observations made from small test networks. But, distribution networks are more complex than the test systems studied here. More studies should be performed to completely understand the TWs in distribution system. The research presented here will be extended to larger and more complex distribution networks. Finally, advanced signal processing techniques that can extract traveling waves in real time will be developed and tested in simulation.

VII. CONCLUSIONS

Increased penetrations of inverter based DERs in the distribution system causes bi-directional power flow, variable fault currents, and changing system conditions. In this paper, limitations on the use of legacy over-current, distance, directional, and adaptive protection in such systems are discussed. This paper introduced the use of TW signatures for systems with high penetration of inverter based DERs. TW relays has been proven to be effective in the transmission system for detecting and locating faults. However, using them in the distribution network has challenges. Simulation of simple test systems are performed to compare the TWs generated during different transient events. The results show that the TW signatures are not heavily influenced by the source type and strength. It is also shown that switching transients generated with capacitor bank can be differentiated from fault based on the frequency spectrum. This paper also addressed the CT & PT requirements to capture high frequency waves and the



(a) Terminal S

(b) Terminal R

Fig. 14: Voltage TWs for a phase-to-ground fault between terminals S and R in test system with one source and two source

need for IEDs with digital signal processing capabilities and GPS time synchronization. This TW based protection approach has the potential to overcome the challenges caused by high penetration of inverter based DERs and help facilitate the DER integration into distribution systems owned and operated by co-ops.

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