Closed-Loop Traveling-Wave Relay Testing (TWRT) using RTDS Real-Time Simulators

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***Abstract*— This paper presents a methodology to perform closed-loop Traveling Wave Relay Testing (TWRT) for transmission lines in power systems using RTDS real-time simulator. The Traveling-Wave Relays (TWRs) have a high sampling rate, e.g., around 1MHz, therefore, one requirement for TWRT is that the simulator operates at a small time-step, i.e., in the order of one microsecond. The TW-based protection elements operate based on current and voltage TW signals that are derived from the High-Frequency (HF) response induced by faults on the transmission line. This paper shows that employing inaccurate line models in a simulator can result in incorrect TW signals. Therefore, another requirement for TWRT is to use accurate line models. Fulfilling these requirements requires high computational power and introduces challenges to real-time simulators for the TWRT application. This paper presents two real-time simulator approaches for TWRT: (i) an FPGA-based and (ii) a multi-core CPU-based approach. The proposed approaches are employed to test commercially available TWRs and the results are reported.**

***Index Terms*-- Hardware-In-the-Loop, Real-time, Traveling-wave, Relay testing.**

I. Introduction

Recent technological advancements have realized Traveling-Wave (TW)-based protection elements [1][2]. These elements are based on a short window of the High-Frequency (HF) response of the power system following a fault. AC TW-based protection is utilized for applications in which traditional phasor-based protection is inapplicable or does not meet the performance requirement. These include fast tripping to improve system stability, protection of hybrid underground and overhead lines, protection of series (over) compensated lines [2], active distribution systems [3], and distribution systems where the zero-sequence current magnitude is very small [4].

One approach for Traveling Wave Relay Testing (TWRT) is the use of an open-loop scheme where a generated HF TW signal is super-imposed on a low-frequency system response to create an overall system response. This does not accurately replicate the dynamic behavior of the line and requires challenging synchronization of equipment. Therefore, a closed-loop scheme is necessary for reliable and robust testing of TWRs. This paper focuses on closed-loop TWRT in the background of AC transmission systems, but the methodology described is applicable to other power systems.

TWRs derive TW signals from the measured line voltage and current waveforms. These signals are primarily a function of the system HF response and are the inputs to the TW-based protection elements. Thus, in a HIL test environment, it is important to ensure the fidelity of the HF response of the simulated system. Nevertheless, to ensure the correct load flow and functionality of the other protection elements, e.g., phasor-based, it is critical to retain the fidelity of the LF response of the system. Therefore, TWRT requires model fidelity over a wide frequency range. This paper shows how using different line models for TWRT, namely Bergeron- and Frequency-Dependent Phase Domain (FDPD) models [5], affects the TW signals. It also shows that employing Bergeron model, which is not accurate over a wide frequency range, results in incorrect TW signals, and therefore should be avoided for TWRT. However, simulating precise FDPD line models with a time-step in the order of one microsecond (required for TWRT) is an unprecedented requirement for a real-time simulator. To address this requirement, this paper introduces an FPGA-based- and a Multi-core CPU-based real-time simulator approach, both of which successfully test the available TWRs.

The remainder of the paper is structured as follows. Section II briefly reviews the process of deriving TW signals and the TW protection elements TW87 and TW32, which operate based on these signals. Section III elaborates on the power system component (Electromagnetic Transient) EMT model for TWRT and compares the TW signals obtained from Bergeron and FDPD line models. Section IV presents the two real-time simulator approaches for TWRT, which are employed to test available TWRs, and discusses the testing results. Section V summarizes this paper.

II. TW-BASED PROTECTION

Figure 1 shows a block diagram for the data acquisition of the T400L TWR from SEL [6], which is used in this paper for discussion and testing. This relay features TW differential-(TW87) and dirrectional (TW32) protection elements.

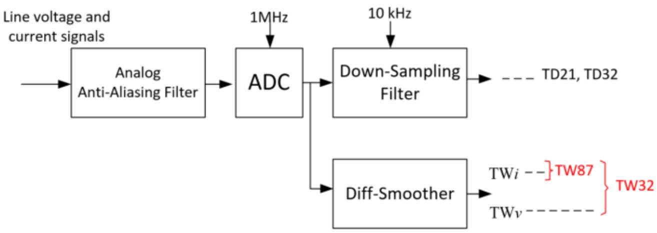

Figure 1. Data acquisition diagram of T400L [6].

The first step in TW-based protection is extracting Traveling-Wave using a Differentiator Smoother (DS) block [6]. During a short time window after a disturbance inception and resulting from the subsequent launch and reflection of waves, the line voltage- and current waveforms contain multiple time-shifted, step-like components. The DS block extracts the HF content of these waveforms, leading its output signals to be in the form of multiple pulses. Figure 2 depicts the functionality of the DS module [7]. A high-bandwidth low-pass filter (smoother) is first used to eliminate the relatively high-frequency noise before the output TW signal is obtained using derivative operation. Other methods such as Wavelet have also been used to obtain TW signals [4].

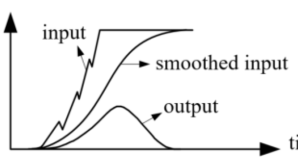

Figure 2. Differentiator Smoother (DS) typical signals [7].

TW signals are the inputs to TW87 and TW32 protection elements. After a TW event, each TW current/voltage signal contains a sequence of pulses. The operation principle of TW87 is solely based on current signals [6] shown in Figure 3, which is due to the significant higher bandwidth of current transducers (CTs) compared to that of voltage transducers (PT or CVT) in power systems. For an external fault (black), the time interval between the peak of the local current TW signal- (TWIA) and the remote current TW signal (TWIAR) pulses is equal to the travel time of the waves along the entire length of the line. However, for an internal fault (red), this time interval is less than the length of the line.

Figure 4 shows the operation principle of TW32. The operating torque (green) is the product of the sign-inverted voltage TW signal and current TW signal, which results in positive torque for forward faults [1]. TW32 detects a forward event if the integrated torque after the event is greater than a specific threshold [1].

TW87 and TW32 elements use current and voltage TW signals. The characteristics of the TW signals, i.e., amplitude, width, timing and the number of the pulses, affect the performance of these protection elements. TW-based fault location is another feature of the TWRs, which in some applications is used for adaptive reclosing [2]. The TW-based fault location principles are also dependent on the characterisitics of the TW signals [7]. TW signals are primarily a function of system HF response. In fact, the DS block acts as a high-pass filter. In most disturbances, the amplitude of the TW steps are relatively small, as compared to the low-frequency components. Therefore, rather than using the voltage and current waveforms, this paper uses the TW signals for comparisons and evaluating the fidelity of line models for TWRT.

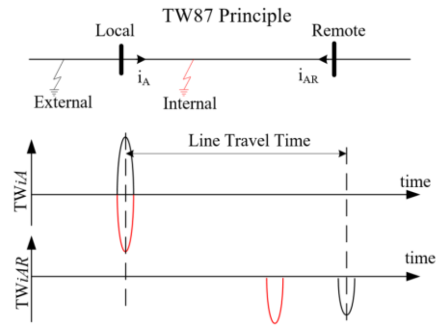

Figure 3. TW87 Principles. Local (TWIA) and remote (TWIAR) current TW signals for an internal (red) and an external (black) fault.

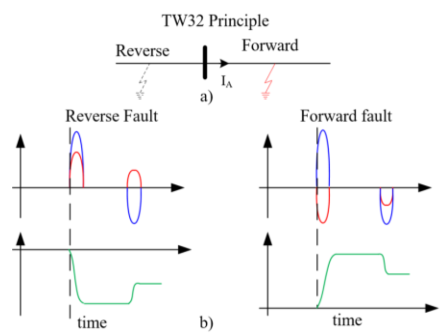

Figure 4. TW32 Principles. a) Forward and reverse faults. b) Voltage (blue) and current (red) TW signals, and TW32 integrated torque (green).

III. EMT MODELS FOR TWRT

The test system in Fig.5, which is a 160.9km 500kV line between terminal S and R, is employed for analysis and testing in this paper. To perform TWRT it is important not to simplify the external circuit to each terminal of the protected line to a voltage source behind an impedance. This would create unrealistic TW reflections at the line terminal. Therefore, in addition to a voltage source behind an impedance, a 40.22km line segment is used to represent the external system at each end of the protected line.

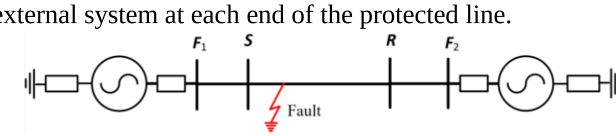

Figure 5. Test system 1.

TW-based protection operates primarily 1based on the HF response of the system measured at the line terminals. This response is determined by the characteristics of the transmission lines, faults, breakers, and current/voltage measurements. Therefore, accurate representation of these components in the real-time simulator is critical for TWRT.

In EMT studies, faults and breakers are commonly represented using variable resistance model, which results in a time-variant admittance matrix and therefore renders the real-time simulation of the power networks (using a small time-step) into a challenging task. To perform fast real-time simulation by retaining time-variant admittance matrix, a switch representation with small inductance (L) and small capacitance (C) was proposed [8]. However, the fictitious inductors and capacitors introduced by this model interfere with the line model and create unrealistic system responses. Therefore, the variable resistance model is employed for faults and breakers.

Current Transformers (CTs) are commonly represented by non-linear inductors. This model, however, cannot represent CT behavior in the presence of TWs as these lumped inductors create a high-impedance path at high frequencies and attenuate TWs in secondary windings. This differs from the experimental results, which suggest that CTs do not exhibit such an attenuation at high frequencies. To achieve accurate high-frequency representation, capacitors should be added to the CT model [9]. However, this modeling approach would require experimental results to obtain the capacitance values. CT saturation occurs for large line currents. In fact, even for worst-case three-phase faults, fault currents would take several milliseconds to become large enough to cause CT saturation, allowing TW transients of the line to be damped out by then. Therefore, as a simple solution, CTs are modeled using gain blocks, which would sufficiently represent the CTs for TW studies.

In modeling the system for TWRT, modeling of the transmission lines is very critical. Lumped element line models, e.g., PI section, should be avoided since they do not represent the TW phenomenon. Bergeron line model represents TW phenomenon and has a low computational burden, making it easier to achieve real-time simulation of the system using small time-steps. However, Bergeron line can only be tuned for one frequency (usually the fundamental frequency to satisfy the load flow operating point), so it does not provide accuracy over a wide range. It also fails to model the frequency-dependent attenuation of waves as they travel along the line.

On the other hand, FDPD line model accurately represents overhead lines and underground cables over a wide frequency range, regardless of their configurations. However, to be adopted in real-time simulation with small time-steps, it requires relatively large computational power.

To understand the effect of the line model on TW signals, the system depicted in Fig. 5 is simulated using Bergeron line and FDPD line. An internal phase A to ground fault at 8km is applied and the short time window of the system response is shown in Fig. 6. The pre-fault steady state currents from the two models match since the Bergeron line frequency is set to the fundamental frequency. However, the HF content of transient responses are different. Figure 7 shows the phase A current TW signals for the local- (TWIA) and remote (TWIAR) terminal using FDPD- and Bergeron model. The number, magnitude, and attenuation of the consequent pulses in the current TW signals obtained from Bergeron model are different from the ones obtained from FDPD model.

The difference in the number of pulses is due to the definition of the delays in the Bergeron line model. If a mode delay is different from the other modes, when a fault occurs, the simulated TW signal arriving at the line terminal can exhibit two distinct steps with a time difference equal to the difference between the mode time-delays. This would create two pulses in the TW signals instead of one. The difference between the amplitude of the pulses in Fig. 7(a) and (b) is due to the fact that Bergeron line contains a simplistic representation for the propagation function of the transmission line, therefore, it fails to correctly simulate the TWs as they travel and reflect between the line terminals and the faulted point. As a result, the pulses in the TW signals have different amplitudes.

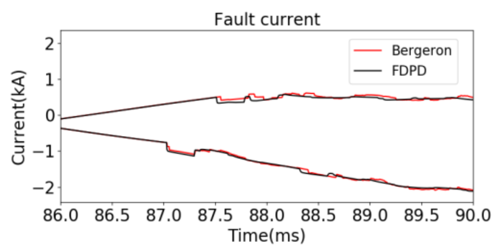

Figure 6. Simulated system response to a phase A to ground fault, using Bergeron (red) and FDPD (black) line model.

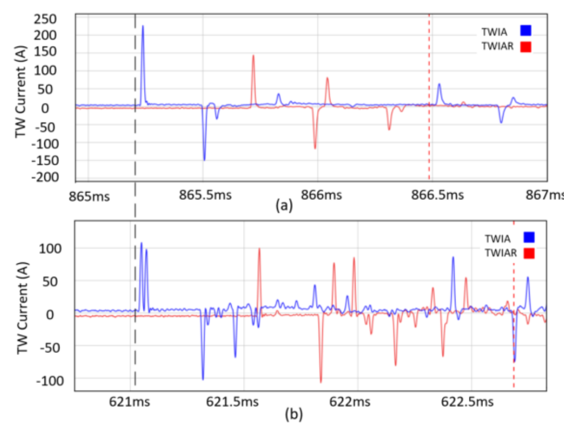

Figure 7. Phase A current TW signals for local (blue) and remote buses (red), using (a) FDPD model and (b) Bergeron model. The time reference of (a) and (b) are different.

The spurious high frequency response, created by the Bergeron model, results in spurious TW signals and renders the model unfit for TWRT applications. For instance, it was observed that the fictitious repeated TW pulses, as shown in Fig. 7 (b), can mislead the T400L and prevent the tripping. To ensure the correct simulated responses for the TWRs under testing, FDPD is employed for modeling the transmission lines.

IV. HIL PLATFORM FOR TWRT

The TWRT HIL platform in this paper includes the RTDS simulator connected to the TWRs using IO cards. Current amplifiers are avoided and the connection is established through the low-level interface of the TWRs. This is primarily due to the relatively limited bandwidth of current amplifiers for the TWRT application. Two real-time simulation approaches, both using time-steps in the order of one microsecond, are used to enable the challenging real-time simulation of the system based on the FDPD line model and the variable conductance fault/breaker model. These approaches are both explained as follows.

A. *FPGA-based (GTFPGA unit)*

The first approach is to use a Giga Transceiver FPGA (GTFPGA) unit, which is a VC707 FPGA board from Xilinx connected to the RTDS simulator using a fiber optic cable, as shown in Fig. 8. The RTDS simulator acts as the host to the FPGA-based simulator and simulation of the system is carried out on the GTFPGA unit.

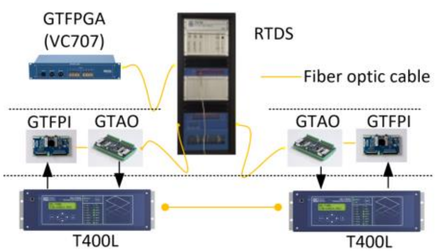

Figure 8. The FPGA-based real-time simulation approach for TWRT.

To achieve small time-steps, the parallel processing capabilities of the FPGA and the parallelism in the EMT simulation algorithm are exploited. This means component models (i.e., FDPD line, branch, fault and breaker models) and the network equations are solved using dedicated hardware modules on the FPGA. Four parallel FDPD modules are considered to enable simulation of system representations similar to that of Fig. 5. The FPGA-based design is based on 175MHz clock frequency, with a simulation time-step of 1.54μs. Further details of the FPGA-based implementation are out of the scope of this paper and therefore not discussed here.

The HIL test is conducted for the scenario of an internal phase B to ground fault at 56.31km from the local terminal (S). The fault resistance is 0.1Ω. The results are reported in Fig. 9. The TWs reach the local terminal (S) earlier since the fault location is closer to this terminal. TW32 is asserted after around 0.1ms, as it only requires the data from the local terminal. Around 1ms after the fault inception, TW87 is asserted and the relay issues a trip signal. The breaker operation time is considered to be 1.5 cycles. Therefore, as Fig. 9(a) shows, phase B current is interrupted at the next zero crossing.

Another function of the TWRs is finding the fault location. To examine this functionality, a series of tests are conducted as follows. The internal single-phase to ground fault test is carried out for different fault locations. Each fault is repeated three times and the fault locations found by the relays are recorded. Fig. 10 (a) shows the error in the fault location found by T400L relays. Using this approach, similar testing on a 100km line has been conducted on the TWRs developed by an anonymous University (A). Figure 10(b) shows the error in the fault location found by that TWR. The fault location precision results from the relays are different because they are based on different algorithms. Fig. 10 interestingly suggests that the fault location error for both of the relays is smaller for faults closer to the middle of the line.

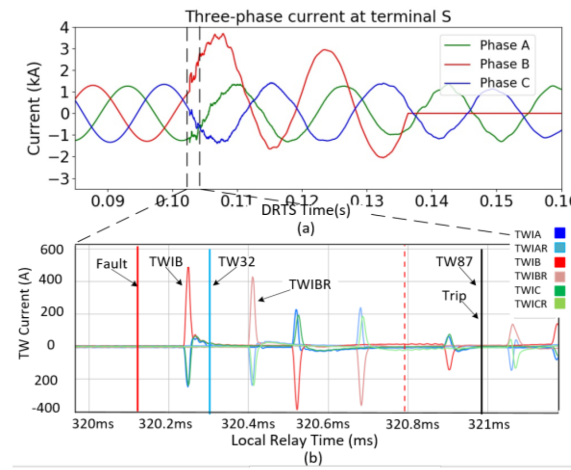

Figure 9. HIL results for T400L, using the FPGA-based simulator: (a) three-phase current at local terminal, (b) the TW signal recording of the local TWR.

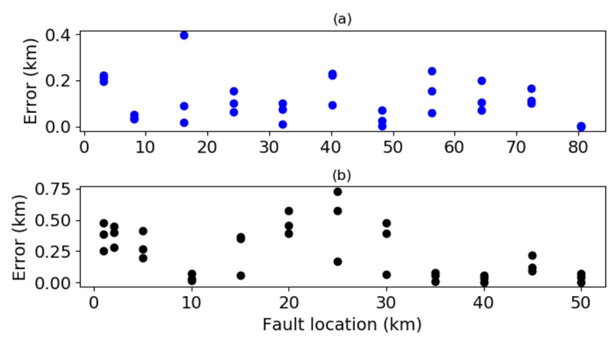

Figure 10. TWR fault location error for (a) T400L from SEL and (b) TWR developed by University A

B. *Multi-core CPU-based (NovaCor)*

In the second approach, NovaCor, a multicore CPU-based simulator based on IBM power8 processors operating at 3.5GHz, is employed. The connections for this approach are shown in Fig. 11. This approach is based on modeling-level partitioning of the system equations using the block diagonal form of the Dommel admittance matrix. One or a few blocks of the admittance matrix and the corresponding component models are assigned to each processor core to maximize the parallelism and therefore reduce the time-step. The "sub-step" feature of the RSCAD software is employed to achieve this partitioning of the system model to exploit the parallelism.

Using this approach, the system representation can be expanded beyond the configuration and component models of Fig. 5. For instance, generator and transformer models can also be included if the application requires a complete system representation. The time-step in this approach is equal to the longest computation time between the CPU cores, which depends on the way the system model is partitioned and assigned to the cores. For the case used for this approach, two parallel lines as shown in Fig. 12 represent the external system. The remaining parameters are kept the same as those of the system in Fig. 5. The simulation time-step for this case is 2.33μs.

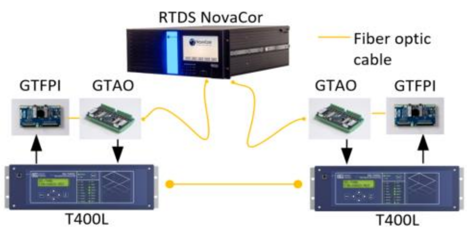

Figure 11. The CPU-based real-time simulation approach for TWRT.

Figure 12. Test system 2.

A test is conducted for the scenario of an internal phase B to ground fault at 56.31km from terminal S, similar to that in Section IV.A. Figure 13 shows the recorded current TW signals in local terminal (S). Following the inception of the fault, TW32 is asserted after around 0.1ms and TW87 is asserted after around 1ms (since it requires the data exchange between the two T400L units). Using this approach, the error in fault location for the T400L and the TWRs developed by two anonyms Universities (A and B) are reported in Fig. 14(a) and (b), respectively. It is evident that this approach can be employed for accurate testing of the TW-based protection elements and the fault location feature of the TWRs.

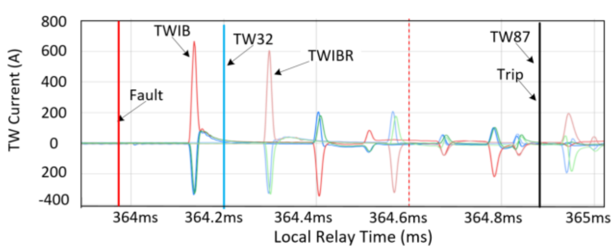

Figure 13. HIL results for T400L: the TW signal recording of the local TWR, using the NovaCor simulator.

V. Conclusion

This paper briefly explained the TW-based protection principle and highlighted the importance of employing real-time simulation approaches that accurately represent the system over a wide frequency range when performing closed-loop testing of the TWRs. Specifically, it was shown that to ensure accurate simulated system response, frequency-dependent line model should be used to represent transmission lines. To address the high computational burden associated with the real-time simulation of the system, two approaches, based on frequency-dependent line model and using time-steps in the order of one microsecond, were presented. The first approach is to use an FPGA-based simulator, which is capable of simulating small-size system representations with a fixed time-step of 1.54μs. The second approach is to use a multi-core CPU-based approach, which is capable of simulating larger system representations with a time-step of around 2μs, depending on the complexity of the system. Both simulator approaches were used to test the TW-based protection elements and fault location feature of the commercially available T400L and TWRs developed by two universities.

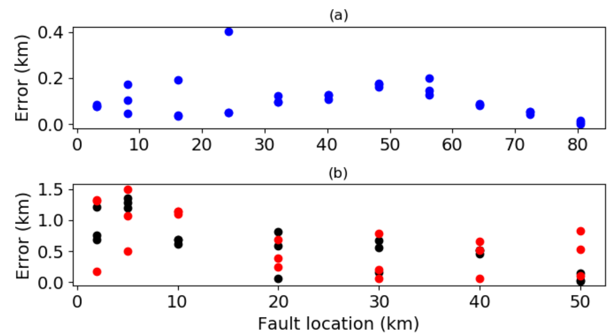

Figure 14. TWR fault location error for (a) T400L from SEL and (b) TWR developed by University A (black) and University B (red).

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