Real-Time Closed-Loop Traveling-Wave Relay Testing (TWRT) in the Environment of Multi-Machine AC Power Systems

R. Mirzahosseini, S. Arunprasanth, E. Tara, U. Samarasekera, Y. Zhang

***Abstract*—Deployment of Traveling-Wave Relays (TWRs) in AC power systems promises enhancement of transmission system capacity and improvement of system stability margins by reducing the fault clearing time. As compared to traditional phasor-based relays, TWRs have more advanced hardware platforms and communication means to carry out Traveling-Wave (TW)-based protection algorithms. These algorithms are based on high-frequency responses of power systems after inception of a fault. A closed-loop scheme, where TWRs are interfaced with the realistically emulated system response prior and subsequent to the fault detection, is necessary for rigorous testing prior to installation. Closed-loop TWR Testing (TWRT) is enabled by real-time simulation of accurate power system models using a simulation time-step in the microsecond range. This paper presents a Control Hardware-In-the-Loop (CHIL) simulation to verify the stability margin enhancement of power systems with the use of TWRs. It elaborates modeling requirements of power system components in TW studies and presents two case studies on single-machine and multi-machine power systems. The CHIL simulation studies are conducted by connecting commercially available TWRs with a Digital Real-Time Simulator (DRTS). This paper (i) proposes a CHIL approach for TWRT for AC systems and (ii) verifies that TWRs improve the Transient Stability (TS) of power systems.**

***Keywords*—Traveling-Wave Relay Testing, CHIL, Real-Time Simulation, Transient Stability**

I. INTRODUCTION

TRAVELING wave based protection schemes for power systems are based on a short window of the high-frequency response of the system followed by a fault. Current and voltage waveforms in this window contain information about the source of disturbance, which is valuable in applications where the traditional phasor-based protection is inapplicable or does not meet the performance requirement. TW-based protection for Medium-Voltage (MV) to High-Voltage (HV) AC [1] and HVDC fault locator [2] has been introduced. Other applications of TW-based protection include single-phase to ground fault detection of AC distribution systems where the zero-sequence current magnitude is very small [3] and protection of active distribution systems, where traditional relays are not applicable due to the low fault current contribution from inverters [4]. Nowadays, with the technology advancement in electronics and communication, TWRs with differential elements are available [5]. These relays have recently received attention for HVAC application where they enable fast fault clearing to increase energy transfer capacity and also to improve the TS of power systems. This paper focuses on closed-loop TWRT and the application of TWR based protection for HVAC power systems. However, the TWRT methodology proposed in this work is general and applicable to other power systems.

One proposed approach for TWRT is the use of an open-loop scheme where a TW response is generated by using a signal generator. High-frequency TW signals are super-imposed on a low precision system response to create the overall TW response. This requires challenging synchronization of equipment and does not accurately replicate the dynamic behaviour of the line. Therefore, a closed-loop scheme is necessary for robust testing of TWRs where they are interfaced with a DRTS in a Control Hardware-In-the-Loop (CHIL) setup to receive accurate and realistic current and voltage waveforms prior and subsequent to a fault detection.

Firstly, this paper presents a closed-loop TWRT approach using precise real-time digital simulation to emulate the Electromagnetic Transients (EMTs) of the power system. A multi-core parallel processing approach is employed to achieve a simulation time-step in the microsecond range in the DRTS to meet the resolution required by commercially available TWRs. The system modeling approach towards TWRT for the application of HVAC systems including synchronous generators is explained and the choice of each component model is discussed.

Secondly, this paper considers two power system simulation test cases to show the TS improvement when using TWRs for line protection. The first test case is a single-machine AC system in which transmission lines are used to connect the machine to an infinite bus. The second test is carried out on a benchmark multi-machine AC system proposed in [6]. The CHIL test results are presented to demonstrate that fast fault detection using TWRs ensures transient stability in heavily loaded power systems (first test case) and helps to improve the power transfer capability in lightly loaded power systems (second test case). Thus in general, a fast fault protection system improves the TS of the power system.

The rest of this paper goes as follows. Section II explains the requirements of the CHIL TWRT setup and explains the methodology adopted in this work. Section III elaborates the power system modeling requirements for this type of test and Section IV presents the proposed TWRT CHIL case studies

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and test results. Section V concludes this paper.

II. Requirements of Testing TWRs

This section discusses the requirements of different elements in a closed-loop TWRT set-up and presents the approach adopted in this study.

A. AC Traveling-Wave-based Protection

The single diagram of a transmission line in an AC system, shown in Fig. 1(a), is used to explain the TW based protection. Soon after the inception of a fault, TWs are launched towards both ends of the line, as shown in Fig. 1(b). At the fault point, TWs have high rate of change and get attenuated when they travel along the line as illustrated in Fig. 1(c). This attenuation depends on factors such as tower configuration, line length, conductor configuration, and ground resistance. Once a TW arrives at any point with a new characteristics impedance, it gets partially reflected and partially transmitted. This back and forth process, shown in Fig. 1(b), continues until the TWs damp out. The process happens in a relatively short time window after the inception of the fault after which the lower frequency response of the system dominates the system response.

AC TW-based protection schemes primarily use current TWs due to better flat high-frequency response of Current Transformers (CTs) compared to Potential Transformers (PTs) [7]. AC TWRs extract high-frequency current TW variables from line currents using a filter-like process at a relatively high sampling rate (200 kHz - 1 MHz) [8] compared to conventional relays (around 10 kHz). Wavelet transform [3] have also been used to extract TW variables. These TW variables are used to detect the type and/or location of the fault [8]. Therefore, a major requirement of an CHIL TWRT scheme for AC systems is to correctly emulate line current waveforms, so that the TWRs can be tested in conditions close to the field conditions.

B. Traveling-Wave Relay Testing Setup

The block diagram of the closed-loop TWRT for AC systems considered in this study is shown in Figure 2(a). A pair of TWRs are interfaced with a DRTS. The complete system model including the instrument transformers are simulated inside the DRTS. The DRTS sends current and voltage waveforms to the TWRs and reads breaker signals from the TWRs. The connection between the DRTS and TWRs is established through the low-level interface and therefore, current amplifiers are avoided. This is primarily due to the bandwidth limitation of current amplifiers for TWRT applications. The inadequate bandwidth of amplifiers distorts TW components and interferes with the relay operation. The hardware platform used in this study is shown in Fig. 2(b). A pair of T400L relays [8] are connected to each other via a point-to-point connection using a fiber optic cable. Although this relay has different protection elements including non-TW-based elements, only the TW differential element 'TW87' is tested in this work. The TW87 element uses an input filter with a sampling rate of 1 MHz and an effective bandwidth of 400 kHz [8]. Therefore, the relay demands the DRTS to have a simulation time-step in the microsecond range.

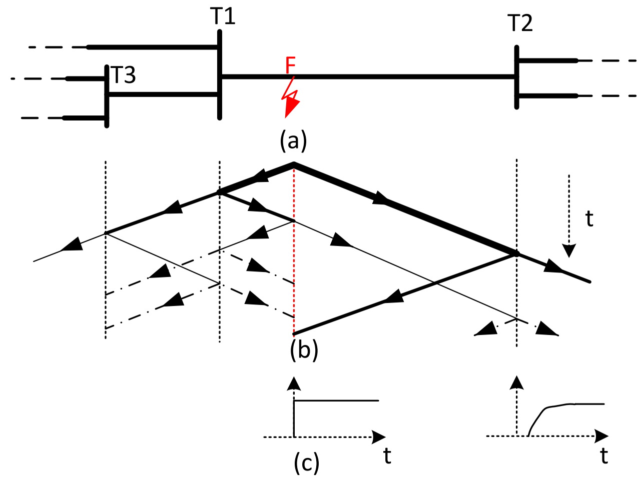

Fig. 1. Traveling-waves in power AC power system (a) Single-line diagram. (b) Wave reflection diagram. (c) Attenuation of the current wave along the line.

NovaCor-based RTDS™, which is a multi-core simulator based on IBM P8 generation processor, is used as the DRTS hardware platform. The RSCAD software, the user interface to the RTDS™, exploits the parallelism in modeling of power systems. Power system computations are mapped onto different cores which are solved in parallel to reduce the real-time simulation time-step as low as 1.5 μs in some cases. To ensure the fidelity of the closed-loop TWRT, components used to build the power system in DRTS must provide accurate results over a wide range of frequency.

III. System Modeling

In computer simulation programs, power system components can be represented using simplified or detailed models. The level of details considered in modeling depends on the type of study. For example, a transmission line can be represented using a PI equivalent (lumped) model for transient stability studies and using a distributed (detailed) model for switching transient studies. TWs exist due to the distributed nature of the transmission lines. Therefore, in order to investigate TWs, it is ideal to model all components of power system using their detailed models. However, there are practical limitations such as the availability of detailed models and their parameters.

A. Transmission Line

TWR is a protection scheme based on high-frequency transient signals. The transmission line model used in TWRT must have the capability to reproduce the voltage and current signals with high fidelity. Currently available line models can be categorized as Bergeron model, Frequency-Dependent (FD) modal-domain model [9], and FD Phase-Domain (FDPD) model. Bergeron model is a single-frequency model normally calculated at the fundamental frequency. Hence, it cannot be used to study the behaviour of TWs, which contains a wide range of frequencies. Modal domain models use frequency-independent matrix to decouple the line equations into modal domain. They can model overhead transmission lines in some cases but has difficulty to model non-transposed overhead line segments and underground cables [10]. The FDPD model is also known as the universal line model and is recognized as the most accurate model available in the EMTP community [11]. However, it has the heaviest computational burden. In some circumstances, overhead lines are physically transposed and each transposition is a TW reflection point. In order to accurately represent the transpositions, it is required to simulate each segment of the line as a separate non-transposed line. For these reasons FDPD is selected in the work of this paper. Although the FDPD line brings the cost of heavy computational burden, we can overcome this problem and model the line in real-time by efficiently mapping the system model on different cores of the DRTS platform.

Continuous-time and discrete-time representations of a FDPD model of a line are shown in Fig. 3. Transfer functions Y and H are respectively the characteristic admittance and propagation functions of the line. The discretized admittance matrices [12] of the two ends of the line, i.e., $\mathbf{G_Y}$s, are decoupled due to the propagation delay and this is the basis for parallel processing used in real-time simulations. The above feature is exploited in RSCAD to map decoupled sections of the system admittance matrix on separate cores of the DRTS for parallel processing.

B. Fault and Breaker

Faults and breakers are commonly represented using variable conductance models. These models result in a time-variant conductance matrix which makes solving the network equation in real time challenging for large networks. A time-invariant conductance respresentation for switch was proposed in a motivation to perform fast real-time simulation [13]. However, the parasitic inductors and capacitors introduced by these models interfere with the line model and create unrealistic TW reflections. Therefore, the variable conductance model is employed for faults and breakers.

C. Current Transformer

Current transformers (CTs) are commonly represented by non-linear inductors. However, this model cannot represent the CT behaviour in presence of TWs as series inductors in the model create high-impedance path at high frequencies and attenuate TWs in secondary windings. This is in contrast to the experimental results, which suggest that CTs do not exhibit such an attenuation at high frequencies . Alternatively, capacitors can be added to the CT model to accurately represent the high-frequency behaviour of CTs over a wide range of operating conditions [7]. However, this modeling approach would require experimental results to obtain the capacitance values. CTs exhibit saturation for large input currents. However, even for three phase faults (worst case), fault currents would take from several milliseconds to a cycle to become large enough to cause CT saturation and by this time, TW transients of the line will be damped out. Therefore as a simple solution, CTs are modeled using gain blocks, which would sufficiently represent the CTs for TW studies.

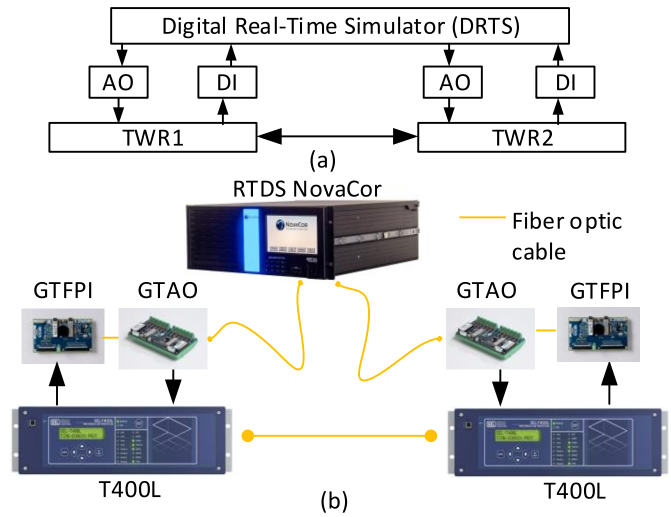

Fig. 2. Traveling-Wave Relay Testing (TWRT) of differential element (a) block diagram (b) experimental setup

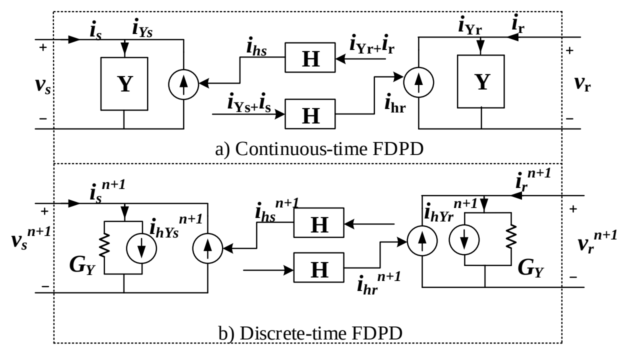

Fig. 3. FD phase-domain line model (a) Continuous-time. (b) Discrete-time.

D. Generator and Transformer

A synchronous generator can be represented using various models with different levels of details. Classical models are used to represent large power systems for voltage stability studies. Third order and sixth order models are typically used for transient stability studies. Since the transmission network is represented using distributed parameter line models in electromagnetic transient studies, it is recommended to model generators with stator transients (speed and transformer voltage terms in flux) to capture interactions between the stator quantities and network quantities. This study uses the eighth order synchronous machine model with saturation characteristics. In addition, standard governor models are used for frequency control and exciter models are used for terminal voltage control of generators. Step-up transformers at generating stations and transformers at transmission levels are modeled using generic transformer models. This model considers an equivalent circuit for transformers and also models saturation characteristics.

IV. Simulation Case Studies

In this paper, the TWRT is performed in a realistic application, where TWRs are used to improve the transient stability of power systems.

A. Transient Stability of Power System

Transient Stability (TS) of a power system is defined as the ability of a power system to maintain synchronism when subjected to a severe transient disturbance such as a fault on a transmission line, loss of load, or loss of generation. The TS margin of a power system can be quantified using Critical Clearing Time (CCT). For a Single Machine to Infinite Bus (SMIB) system, the CCT can be calculated using the well-known equal area criterion. The SMIB system shown in Fig. 4 is used to explain the concepts of TS and CCT. The generator 'G' is connected to an infinite bus via a unit transformer and a double circuit transmission line.

Active power output of generator 'G' can be expressed as in

$$P_g = \frac{|V_g||V_i|sin(\delta)}{X_t}, \tag{1}$$

where X_t is the total reactance and δ is the voltage phase angle difference between bus 1 and bus 3. Since the infinite bus voltage is a constant, the power transfer depends on the generator bus voltage and the total reactance. At the steady state operating condition (pre-fault), both lines line 'L1' and 'L2' transfer power to the infinite bus. When there is permanent fault on line 'L2', the fault is isolated by tripping line 'L2' and the rest of the system operates with only line 'L1' (post-fault) transferring power to the infinite bus. The relationship given in equation (1) is used to generate power angle (PA) characteristics, shown in Fig. 5, where curves S1, S2, and S3 correspond to pre-fault, post-fault and fault conditions respectively.

In pre-fault condition, the system operates at Operating Point (OP) 'a'. When the fault occurs, the OP moves to point 'b' and the generator accelerates since it receives a mechanical power larger than the electrical power it can deliver to the grid. The isolation of fault at δ=δ_{clr} shifts the OP from point 'c' to point 'd', which is on the post-fault PA characteristics 'S2'. Since the electrical power output of the generator is larger than the mechanical power input when it is at point 'd', it decelerates while moving on path 'd-e-g'. Depending on the inertia of the machine, after a number of oscillations, it settles at the post-fault steady-state OP 'g' on curve 'S2'. If the fault is isolated too late that the generator crosses point 'x' (δ_{max}) on curve S2, it will loose synchronism. The corresponding fault clearing time to make the generator reach point 'x' is known as the CCT. On the other-hand, the TS of the system can be preserved if the fault is cleared before CCT. The difference between the operating angle and the critical clearing angle is known as the TS margin and hence, a larger TS margin is better for the TS of the power system.

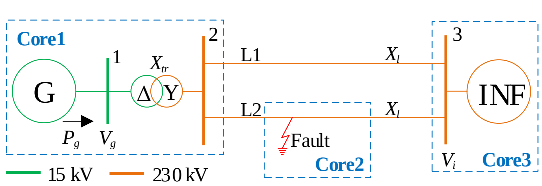

Fig. 4. SMIB system model

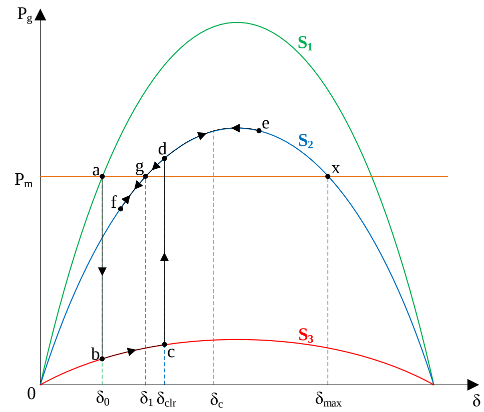

Fig. 5. Power angle characteristics

The time taken to isolate the fault consists of fault detection and breaker tripping times. Typically, mechanical breakers are installed at both ends of transmission lines in practical power systems. After receiving a trip signal, a mechanical breaker takes about 1 to 2 cycles to trip. Since the tripping time of breakers installed in a power system cannot be improved, having a fast fault detection scheme would improve the TS of rated loaded power system, and also would preserve the TS of highly loaded power system.

B. Test Cases

Two test systems, namely an SMIB system and the 12 bus power system were built on a DRTS to perform TWRT and to show the TS improvement achieved when using TWRs. Commercially available TWRs were connected in an CHIL setup with the DRTS to protect a selected transmission line in the simulated power system. Simulation results generated when the line protection scheme had phasor based relays and TWRs are compared in this paper to demonstrate the TS enhancement. Typically, mechanical breakers will take about 1 to 2 cycles to operate. Therefore, a breaker operating time of 1.5 cycle ($\approx$ 24 ms) is assumed in this study. In addition, a fault detection time of 1 cycle ($\approx$ 16 ms) is assumed for the phasor based relay that was modeled using control components in the DRTS.

1) Single-machine power system: The SMIB power system shown in Fig. 4 is used for the initial investigation. This network consists of a synchronous machine connected to an infinite bus via two transmission lines. The IEEE Type AC1 exciter is used for voltage regulation and the TGOV1 governor is used for frequency regulation of the generator. The system parameters are provided in the APPENDIX. The system model is divided into three subsystems such that each subsystem is connected to the others via transmission lines. This decouples the system admittance matrix, as explained in Section III-A. Each subsystem is allocated to a single core of the DRTS platform which helps reducing the simulation time-step to 3.1 μs for this case.

The following test was performed to show that the quick isolation of a faulted line can stabilize a heavily loaded power system. The generator was controlled to supply 805 MW to the infinite bus. At steady state, a permanent three phase to ground fault was applied on line 'L2' close to the generator.

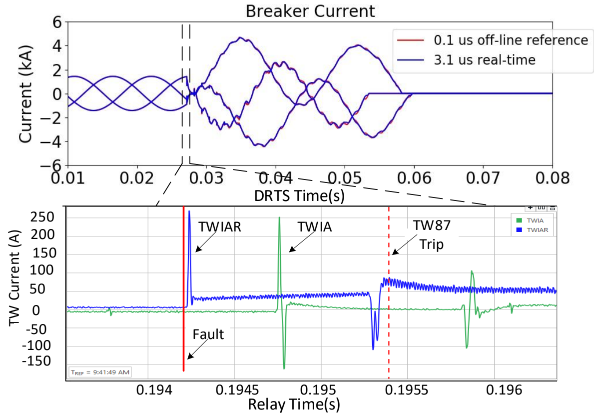

Fig. 6. (a) Three-phase currents on line ‘L2’ at bus 3 (b) Phase-A TW current variables derived by the TWR at bus 3 (TWIA) and bus 2 (TWIAR)

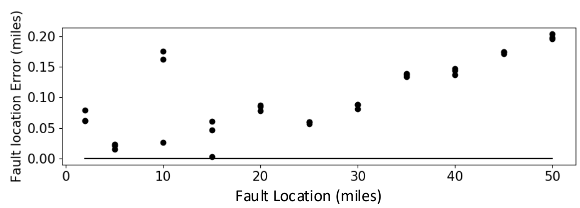

Fig. 7. Fault location error for three trials per location

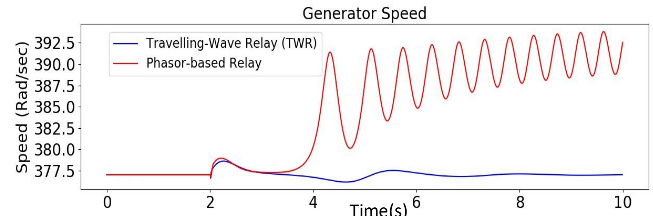

Fig. 8. Speed variation of generator by a three phase fault when line ‘L2’ is protected using Traveling-Wave Relays (blue) Phasor-based Relays (red)

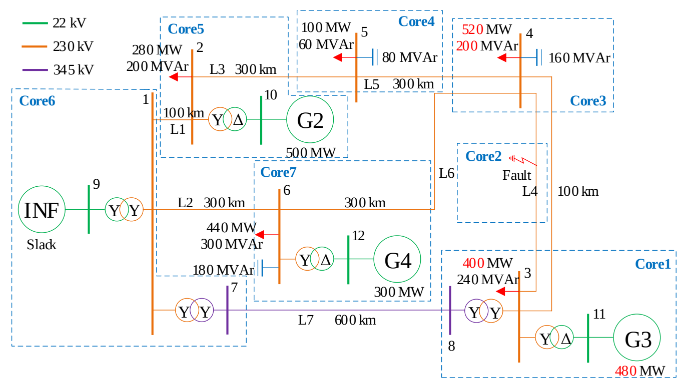

Fig. 9. One line diagram of 12 bus benchmark power system

Figure 6 shows the line current simulation results and TWR recording of the fault. In Fig. 6(a), the real-time results are compared against off-line results with a time-step of 0.1 μs to demonstrate the accuracy of the real-time simulation. TWRs exchange information and the differential element (i.e.: TW87) issues a trip signal. Figure 6(b) shows the phase-A TW current variables for the local (TWIA) and remote (TWIAR) terminals [8] derived and recorded by the TWR at bus 3. The dotted red line marks the fault detection moment. The fault detection time of the TWRs in this test is around 1.1 ms which is significantly less than that of phasor-based relays. It should be pointed that the latencies of the input/output cards in the DRTS are close to 1 μs and consistent to both TWRs, therefore, have negligible impact on the test.

Figure 7 shows the error of the fault location detected by the TWRs for different fault points. It shows that the error is less than 0.2 miles. In some protection schemes, the TWR uses this TW fault location information to distinguish TWs caused by real faults from those caused by physical transposition points of the line [8].

The fault was removed by isolating line ‘L2’ from the rest of the system and hence, the generator is expected to deliver power to the infinite bus via the healthy line ‘L1’. Simulation results of generator speed for the two cases are shown in Fig. 8; (i) when the line was protected using the TWRs and (ii) when the line was protected using phasor-based relays.

It can be observed that when there is a fault close to the generator terminal, the generator speeds up as it cannot deliver power due to the nearly zero voltage at its terminal. Since the phasor-based relay takes more time than the TWR to detect the fault, it is unable to issue a trip command to the breaker to isolate the fault before the critical clearing point of the system. Therefore, after line ‘L2’ is tripped, the generator looses synchronism. However, when TWRs are used to protect line ‘L2’, the generator is able to maintain synchronism in post fault conditions as the fault was isolated before the critical clearing point. This case demonstrates that use of TWRs in line protection schemes could preserve the TS of a highly loaded power system.

2) Multi-machine power system: The multi-machine power system considered in this study is the 12 bus benchmark power system, which was inspired by a physical high-voltage network in North America covering areas of Manitoba, North Dakota, and Minnesota [14]. This test system was proposed as a suitable platform to study the applications of flexible AC transmission system (FACTS) devices [6]. Figure 9 shows the one line diagram of the test system. The real-time simulation time-step in this case is 3.2 μs. The dynamic data available in [6] is not sufficient to model the generators for detailed EMT simulation studies. Therefore, the missing sub-transient data was taken from [14]. To provide voltage regulation the IEEE Type SCRX excitation system is adopted for generators ‘G2’ and ‘G4’, and the IEEE Type ESAC4A excitation system for ‘G3’. The TGOV1 type thermal governor is adopted for all three generators to control the frequency.

In order to create a case to demonstrate the TS enhancement achieved with the use of TWRs, the loading of the network is slightly adjusted as explained below. The load at bus 3 is increased from 320 MW to 400 MW and the load at bus 4 is increased 320 MW to 520 MW. To accommodate the increase in loads, the real power output of generator ‘G3’ is increased from 200 MW to 480 MW. The system consists a double circuit transmission line ‘L4’ between bus 3 and 4. The line ‘L4-1’ is protected by a line protection scheme. Simulation studies are carried out for two cases; (i) phasor-based relays are used and (ii) commercially available TWRs are employed,

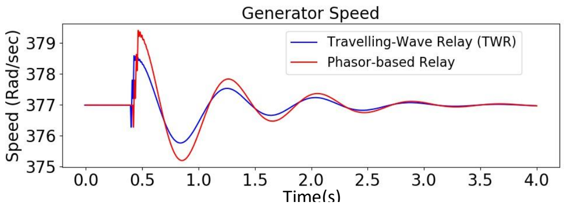

Fig. 10. Speed variation of generator ‘G3’ followed by a three phase fault when line L4 is protected using Traveling-Wave Relay (blue) and Phasor-based Relays (red)

to protect circuit ‘L4-1’. At the steady state, a permanent three-phase to ground short circuit fault is applied on circuit ‘L4-1’ close to bus 3 (3 % distance from bus 3), where the generator ‘G3’ is connected. Then, the fault is isolated by tripping circuit ‘L4-1’ and the post-fault system is expected to operate with circuit ‘L4-2’ to transfer power from bus 4 to bus 3. Simulation results for cases (i) and (ii) are shown in Fig 10. It can be observed that generator ‘G3’ accelerates since it receives a mechanical power larger than the electrical power it can deliver to the grid. When the fault is isolated by tripping circuit ‘L4-1’, the generator comes back to the rated frequency after a few oscillations by releasing its excess kinetic energy to the system. In case (ii), when line protection scheme uses TWRs, the peak of first swing in speed is reduced, and hence the TS of the generator is enhanced.

V. Conclusions

This paper introduces a closed-loop Control Hardware-In-the-Loop (CHIL) Traveling-Wave Relay Testing (TWRT) method for HVAC systems including synchronous generators. The configuration of the hardware platform, based on the characteristics of the Traveling-Wave (TW) phenomenon and the limitation of the current amplifiers, for AC system tests is explained. Different choices of power system component models are discussed and suitable models for TWRT are selected based on (i) fidelity of the models to simulate TW phenomenon and (ii) availability of the component model parameters. The platform is employed to perform CHIL TWRT of commercially available differential Traveling-Wave Relays (TWRs) and examining their impact on the Transient Stability (TS) of the AC power system. Test results show that the commercial TWR maintains the TS of a Single-Machine Infinite Bus (SMIB) system in extreme cases when phasor-based Relays cannot prevent system instability. The testing platform is also used to investigate the performance of the TWRs in a multi-machine benchmark power system and it is verified that the TWRs enhance the TS by reducing the fault detection time.

VI. Appendix

This Appendix reports the parameters of the SMIB system. Figure 11 shows the tower configuration of the lines. Table I reports the Generator (G) and Transformer (TR) parameters.

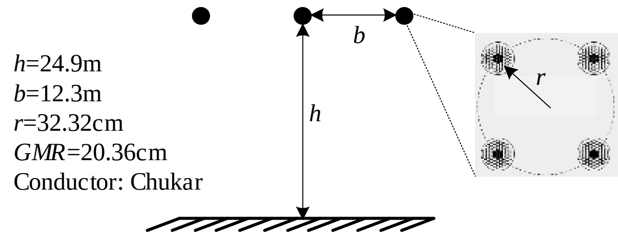

Fig. 11. Tower configuration

TABLE I
SMIB Parameters (TR-Transformer and G-Generator)

Parameter	value	Parameter	value
TR Vp	230 kV	G L_d	1.7134 pu
TR Vs	15 kV	G L'_d	0.4345 pu
TR S	900 MVA	G L_d"	0.3253 pu
TR Z_+	0+j0.00328 pu	G τ'_{do}	6.174 sec
TR Z_0	0+j0.00328 pu	G τ_{do}"	0.032 sec
TR G_{Shunt}	0.01 pu	G L_q	1.6224 pu
G S	900 MVA	G L'_q	0.6168 pu
G F	60 Hz	G L_q"	0.3253 pu
G V	15 kV	G τ'_{qo}	0.388 sec
G L_S	0.2327 pu	G τ_{qo}"	0.047 sec
G R_S	0.002 pu	G H	4.7 MWs/MVA

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