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Geographically distributed real-time digital simulations using linear prediction

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ABSTRACT

Real-time (RT) simulator is a powerful tool for analyzing operational and control algorithms in electric power systems engineering. For understanding the dynamic and transient behavior of a power systems, significant RT computation capabilities are essential. A single unit of RT simulator has limited simulation capabilities. The most common way of augmenting simulation capability is using a bank of locally connected RT simulators. However, creating a large-sized bank of RT simulators involves significant financial investments and hence may not be feasible at all research facilities. Power and energy systems research facilities that use RT simulators are at diverse physical locations. In addition to RT simulators, research facilities around the world house an array of facilities with unique power, energy, and control systems for innovative research. To leverage these unique research facilities, geographically distributed RT simulation based on Wide Area Network (WAN) is required. Typical RT simulators perform simulations with time-steps in the order of milliseconds to microseconds, whereas data latency for communication on WAN may be as high as a few hundred milliseconds. Such communication latency between RT simulators may lead to inaccuracies and instabilities in geographically distributed RT simulations. In this paper, the effect of communication latency on geographically distributed RT simulation is discussed and analyzed. In order to reduce the effect of the communication latency, a Real-Time Predictor (RTP), based on linear curve fitting is developed and integrated into the distributed RT simulation environment. Two geographically distributed digital RT simulators are used to perform dynamic simulations of an electric power system with a fixed communication latency and the predictor. Empirical results demonstrate the effects of communication latency on the simulation and the performance of the RTP to improve the accuracy of simulations.

1. Introduction

In order to enhance collaboration and leverage investments between different national research labs, academic research centers, and the industry, it is desired to integrate geographically dispersed assets for energy systems research. This includes large-scale Real-time (RT) digital co-simulation environments for analyzing the advanced grid and its component interactions. Simulation is a powerful tool for the analysis and design of complex engineering systems such as the electricity grid and its constituent control and operations. Simulations are performed in myriad ways using numerous environments, depending on the objective of the analysis. Simulations are classified based on the type of environment used. With respect to simulation clocks and application timeline, simulation environments may be classified as either RT, non-RT, or faster than RT. The software, hardware, and external interface mechanisms constituting a RT simulation environment varies significantly from the non-RT and faster than RT environments. For instance non-RT or offline simulation environments may not require dedicated computational hardware. However, RT or faster than RT simulation environments typically require specialized computational hardware with dedicated processors, and lower operating system overheads to provide the necessary computational capability. Parallel simulation technology, utilizing multiple processors, can also be used for RT simulation. Some examples of traditional offline simulation software used for

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electromagnetic transient analysis are PSCAD and EMTDC. Similarly for electromechanical transient analysis of varying degree, environments such as PSS/E® and PowerWorld® are commonly used. RT simulator generally provides simulation results closer to field data by allowing an interface between the software simulation and hardware in RT. Comparison of RT simulators with the traditional offline simulations are presented in [1,2]. For example, to perform controller design verification and validation prior to integration with an actual system, an RT simulator with Hardware-In-the-Loop (HIL) can be used to generate real life operating scenarios [3–9]. With significantly higher computational capability, RT simulators can analyze complex and detailed scenarios in power systems with customizable time-steps. Customizable time-steps provide the flexibility to analyze high frequency events such as transients with a high degree of accuracy. The simulation time-step of RT simulators is in the range of few microseconds to hundreds of microseconds to allow a wide spectrum of analysis. With the powerful computational capability and high-speed input/output (I/O) port, RT simulators possess the capability for HIL simulation.

RT simulators are used for a range of electric power systems studies. Electric power and energy assets and systems, for performing HIL-type research and analysis, are dispersed through out the academic and research centers around the world, similar to that of RT simulators that needs to be leveraged. The goal of this research is to perform distributed RT HIL simulations. The proposed work in this paper is intended to form the basis of such geographically distributed RT simulation. In [10], a RT simulator is used to test the performance of a wind turbine generator coupled with a battery-supercapacitor hybrid Energy Storage System (ESS). The simulation results show the hybrid ESS has lower cost, longer lifetime, and higher efficiency comparing with the traditional ESS. In [11], the authors demonstrate an RT simulator application for performing innovative wind energy research. The simulation results present that the wind energy HIL test bed has the potential for the development of a unified multi-purpose platform with myriad functionalities for performance assessment. A high-power electrical traction system is also simulated in the RT simulator [12]. Comparisons between the HIL simulation and real experiment demonstrates performance and reliability of the HIL simulation. In [13], rapid controller prototyping of power electronic systems is simulated by an RT simulator. The results show that RT simulation is a fast, precise, and robust way to provide accurate results. In [14], an RT simulator for developing and studying the control algorithm of High Voltage Direct Current (HVDC) technology is presented. Based on the simulation results, it is observed that RT simulators can be used for numerous HVDC studies, such as the conceptual design of a control system and the testing of physical control devices. RT simulators are also utilized for the development, testing, and parameter optimization of power electronic controllers for numerous applications [12,13,15]. The results show RT HIL simulations can significantly improve the design process, provide high flexibility for device testing, and also assist in identifying software bugs. In [16], an RT simulator is used for the simulation of multilevel voltage source converters (VSC) using pulse width modulation (PWM) controls. The simulation results are compared with the field measurements which demonstrates the ability of the RT simulator for accurately testing VSC firing pulse controls using PWM control. In [17], an RT simulator is used as an education platform for power systems control design. Compared with off-line simulations, this method extends power system controller design to the next step and shows the important factors of algorithm implementation and RT testing. An overview of RT simulation applications specific to electric microgrids (islanded, controllable section of an electric distribution network equipped with supplying its own load) is presented in [18]. HIL is one of the most preferred ways of verification and validation of models, however, it is also acknowledged that this type of simulation is expensive, needs power conditioning equipment, and high fidelity measurement and controls.

RT simulators are available in multiple software and hardware platforms from a variety of vendors [19–33]. RT simulators designed by different manufacturers based on distinct architectures have different capabilities and can provide unique environments for power and energy systems analysis. The size of power systems simulated in an RT simulator is limited by computational capability and cost. In order to simulate larger power systems and share the resources, geographically distributed RT simulation seems to be a feasible way as most RT simulators have a communication component. These communication components support a wide array of communication protocols, of which Internet Protocol is one. Additionally, power systems can be divided into subsystems and processed using parallel computing algorithms. There are numerous advantages of pursuing geographically distributed RT simulations, as summarized below:

(i) Enhance collaboration and leverage investments between different research centers working in the electric power and energy systems domain.
(ii) Utilize distributed RT simulation to simulate more complex and larger-scale electric power system.
(iii) Connect RT simulators at different national laboratories, utilities, and universities to synergistically utilize resources, such as electric vehicle charging infrastructure, wind turbines, PV installations, and energy storage systems.
(iv) Enable the remote testing and control of different electric power devices and systems.

There are a few research papers that document RT simulation using geographically distributed computing resources. In [34], the authors integrated two RTDS® setups via an external test bed based on a customized advanced data acquisition system, located at Mississippi State University and Texas A&M University. They demonstrated a distributed simulation of transmission systems with different data transfer rates i.e., 118 bps and 36 bps with steady state and fault conditions. Although they introduced a way to mitigate effects of data loss by extrapolation method, the impact of data latency was regarded as insignificant. In [35], the authors present a thermo-electric co-simulation between RTDS® at Florida State University and OPAL-RT® at the University of Alberta. In this co-simulation, the time-step of RTDS® simulating electrical components is 50 μs and the time-step of OPAL-RT® simulating thermal component is one millisecond. The lower time step of the latter simulator assists in maintaining the synchronism between the distributed simulators. In [36], the author analyzes the round-trip latency of both the analog interface and the digital interface between RTDS® and OPAL-RT® and inferred that analog interfaces are numerically stable for studying thermo-electric transient simulations. Distributed simulation applied to shipboard power system is introduced in [37], where Virtual Test Bed® (VTB) is used to model and simulate a separate shipboard subsystem.

Even though geographically distributed RT simulation has multiple advantages, there are some major challenges such as: (1) partitioning of the power system; (2) synchronizing different RT simulators; and, (3) maintaining reliability of communication between the partitioned systems, such as data loss and communication latency.

The above discussion summarizes the state of the art related to impacts and interpretations of communication latency between RT simulators. However, research is focused primarily on the effect of the data loss during the communication and how to mitigate it