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Design and Implementation of a Real-Time Hardware-in-the-Loop Platform for Prototyping and Testing Digital Twins of Distributed Energy Resources

Jiaxuan Han, Qiteng Hong *, Zhiwang Feng, Mazheruddin H. Syed, Graeme M. Burt and Campbell D. Booth

Institute for Energy and Environment, University of Strathclyde, Glasgow G1 1RD, UK
* Correspondence: q.hong@strath.ac.uk

Abstract: Power systems worldwide are experiencing rapid evolvements with a massive increase of renewable generation in order to meet the ambitious decarbonization targets. A significant amount of renewable generation is from Distributed Energy Resources (DERs), upon which the system operators often have limited visibility. This can bring significant challenges as the increasing DERs' can lead to network constraints being violated, presenting critical risks for network security. Enhancing the visibility of DERs can be achieved via the provision of communication links, but this can be costly, particularly for real time applications. Digital Twin (DT) is an emerging technology that is considered as a promising solution for enhancing the visibility of a physical system, where only a limited set of data is required to be transmitted with the rest data of interest can be estimated via the DT. The development and demonstration of DTs requires realistic testing and validation enviorment in order to accelerate its adoption in the industry. This paper presents a real time simulation and hardware-in-the-loop (HiL) testing platform, specifically designed for prototyping, demonstrating and testing DTs of DERs. Within the proposed platform, a software-based communication emulator is developed, which allows the investigation of the impact of communication latency and jitter on the performance of DTs of the DERs. Case studies are presented to demonstrate the application of the developed DT prototyping process and testing platform to enable frequency control using the DTs, which provide valuable learnings and tools for enabling future DTs-based solutions.

Keywords: Digital Twin; Distributed Energy Resources; real-time simulation; hardware-in-the-loop testing

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1. Introduction

Power systems worldwide have been experiencing unprecedented changes with massive increase in renewable generation in order to achieve ambitious decarbonization targets. In the 26th UN Climate Change Conference of the Parties (COP26), participating countries reached an agreement to take further actions in order to achieve the objective of restraining the temperature increase within 1.5 degrees and achieving the global net-zero goal by the middle of the century [1]. This will lead to further accelerated transition in power systems worldwide from fossil fuel resources to renewable generation, among which a massive amount will be from Distributed Energy Resources (DERs) [2,3]. DERs are typically connected at distribution networks, where the system operators often have limited visibility [4]. A significant increase in DERs without sufficient visibility can lead to critical network constraints being violated, presenting risks to system security and reliability [3,5–7]. Furthermore, DERs are increasingly expected to play an active role in providing ancillary services, e.g., fast frequency response during power imbalance disturbances [3,6]. Without sufficient visibility of the DERs, it is challenging to achieve the coordination among the large number of DERs in order to deliver effective ancillary services to support the grid operation. The visibility of DERs can be enhanced via the provision of communication links so that critical data of interest can be transmitted to the system operators. However, a key issue with the application of communications is the cost, particularly for real-time applications considering the massive number of DERs and the amount of data needed to be transmitted. Distributed and automatic control approaches have been developed to address the visibility issue of power grid [8–10]. These algorithms enhanced the coordination of DERs in microgrids by reducing long-distance communications. However, the proposed coordinated control is mainly suitable for DERs within microgrids, and cannot resolve the issues of large number of DERs which could be located across wide areas. Therefore, cost-effective solutions are required to access the DERs visibility, while minimizing the need for communications.

Digital Twin (DT) is considered a promising solution for addressing a wide range of challenges associated with power system decarbonization via the provision of enhanced capability in planning, monitoring and operating future systems. While there are different definitions for DT, it is widely considered to be a virtual and digital equivalent to a physical system [11]. A typical DT-based system consists of a number of key elements, i.e., the digital model in the virtual space (i.e., the DT itself), the hardware system being represented by the DT, the communication links between the DT and the physical system, the data to be communicated, and the services provided by the DT to support specific applications. The key defining difference between a DT and a conventional system model is the access and link with live measurement data to have real-time view of the system status. While DTs are typically considered as virtual replicas of physical systems, the digital models for DTs could only reflect a selected set of attributes such as electrical properties, geometry, heat or motion, depending on the targeted applications and design considerations (e.g., the computation power required) [12].

Presently, the DT technology is being widely utilized in many industrial fields, e.g., telecommunications [13], manufacturing [14] and aerospace [15]. An example of very early application of the DT concept was by NASA [16] to address the challenge associated with real-time monitoring of spacecrafts, where communication bandwidth was limited to communicate all critical data required. Therefore, virtual models of the spacecrafts (i.e., the DTs) were constructed, which can be updated via limited communicated data while still enabling the rest of the critical system status information, and can be used to evaluate the consequences of instructions. Following the successful DT implementation in the aerospace area, smart manufacturing noticed the advance of DT in cyber-physical automotive system. In vehicle corporation, DT is not only applied to optimize the production scheduling by simulating and making decisions in virtual space [17], but also to monitor and prognosticate electrical vehicle motors to provide life-cycle management [18]. However, in the power system domain, the DT technology is still a relatively new but certainly an emerging field. For example, in [19], a DT-based fault type identification system was developed to locate the failed DERs in micro-grid with only overall response; and in [20], a power converter health condition monitoring approach was proposed by taking DT outputs as references. In [21], the DTs of DERs are applied for coordinating the active power response in order to provide effective frequency response. The capability of the DT technology provides an ideal solution to address the aforementioned challenges in DER integration due to their large number, lack of limited visibility and lack of coordination. For example, the visibility of DERs could be improved by monitoring the dynamic behaviors of interest directly from the virtual DT in local control centers rather than communicating all measurements via communication networks. Therefore, this paper focuses on establishing a testing and validation platform for developing and demonstrating DT in a power system, and the prototype DTs of three DERs are taken as examples to demonstrate the monitoring capability of the a DT-based solution.

The development and demonstration of DTs requires realistic testing and validation environments in order to accelerate their adoption in the industry. There has been extensive work conducted in the research community on real-time simulation and hardware-in-the-loop (HiL) testing environments [22–27]. However, DTs have unique features in the need for linking data between the physical system and virtual replica, and the performance can be significantly affected by the data transmitting rate and communication delay. These unique features present special needs for testing environment, where existing testing setup has not been designed for, and thus not adequate to suit the purpose. Therefore, this paper presents a real-time simulation and HiL testing platform, specifically designed for prototyping, demonstrating and testing DTs of DERs for different applications. The proposed platform considers all critical aspects for DT operation, and specifically a software-based communication emulator is developed, which allows the investigation communication latency and jitter on the performance of DTs of the DERs. The paper shares valuable leanings and considerations required on designing such a platform, offering valuable experience for the research and industry community.

In addition to the challenge associated with decreasing system visibility, another key challenge for the future power system operation is that the inertia of the power system will be significantly further reduced, which could lead to the conventional primary frequency response from Synchronous Generators (SGs) not being sufficiently fast in containing frequency deviation during contingency power imbalance events, thus presenting the need for new and more effective frequency control solutions [28]. Therefore, while this proposed testing platform can be used to demonstrate DTs for the purpose of enhancing monitoring, novel DT-based frequency control methods could also be developed and validated on this platform as the communication channel is dual-directional, which is capable of transmitting information and commands between hardware and virtual controllers.

The rest of the paper is organized as follows: Section 2 presents the design consideration for the HiL testing platform for DERs' DTs; Section 3 presents an overview of the implemented platform and the details of the critical elements within the DT testing platform; in Section 4, case studies are presented where DERs' DTs are validated and tested for supporting a frequency control application; and Section 5 provides the conclusions of paper.

2. Design Considerations for the DT Testing Platform

DT is a multi-disciplinary technology by nature, covering a range of techniques, e.g., physical system modeling, sensing, communications, etc. Therefore, the design of the testing platform for DTs needs to consider their unique features. Figure 1 illustrates a typical layout of a DT-based system, which contains five main elements as proposed in 2018 [29], i.e., the physical entity (i.e. the physical twin), the virtual entity (i.e. the DT), the data flow between the physical system and the DT, the communication links, and the services provided by the DT to enable various applications. The design of the DT testing platform in this paper is based on this five-dimension architecture, and the key design considerations are discussed below:

- **Representation of the physical system:** As mentioned previously, DT is a virtual replica of a physical system. In a real-world application, the physical system is the actual assets, e.g., DERs. However, in a testing environment, it is not always possible to have the physical DERs due to issues with hardware availability, system capacity, cost, etc. Therefore, when testing a DT-based system, the representation of the physical entity should be carefully considered. The following are a list of options:
  - Direct use of the original physical system: suitable when the original physical system is available and typically small in capacity, and can be installed in the lab environment.
  - Representing the physical system via real-time simulator (RTS): this option can model the physical system in an RTS to emulate the physical entity, which is relatively low cost and scalable, but the real-time model needs to be validated against the physical system's behaviors.
  - Power-Hardware-in-the-Loop (PHiL) simulation: this option is a balance of the first two options, where a small DER can be coupled with the RTS via an amplifier

to represent a scaled version of the physical system while largely maintaining the accurate realistic behavior of the physical system.

- **Hosting and execution of the DT:** for a DT testing platform, DTs have to be hosted and executed on a platform to emulate its real-world application environment. Depending on the targeted application of the DTs, the performance requirements of the platform for hosting and executing the DTs can be significantly different. The key consideration is to ensure the platform's computation capability is sufficient to execute the DT within each specified time-step.
- **Investigation of impact of data reporting rate:** DTs need to receive actual/emulated measurement data with certain rates in order to accurately represent the physical system status. The test platform should allow for investigation of a suitable data reporting rate for the DTs and test how varied data rates could affect the DTs' performance.
- **Evaluation of communication performance impact:** the link with real-time data via communication links is one of the key differences and advantages of DT compared with conventional models. The communication performance can have significant impact on the DTs' accuracy, so the testing platform should contain the elements that allow the evaluation of such impacts.
- **Validation of services provided by the DTs:** DTs can be used to enable a wide range of applications, e.g., monitoring and control, and the testing platform should contain elements for executing and demonstrating such applications using the DTs to ensure the DTs are fit for purpose.

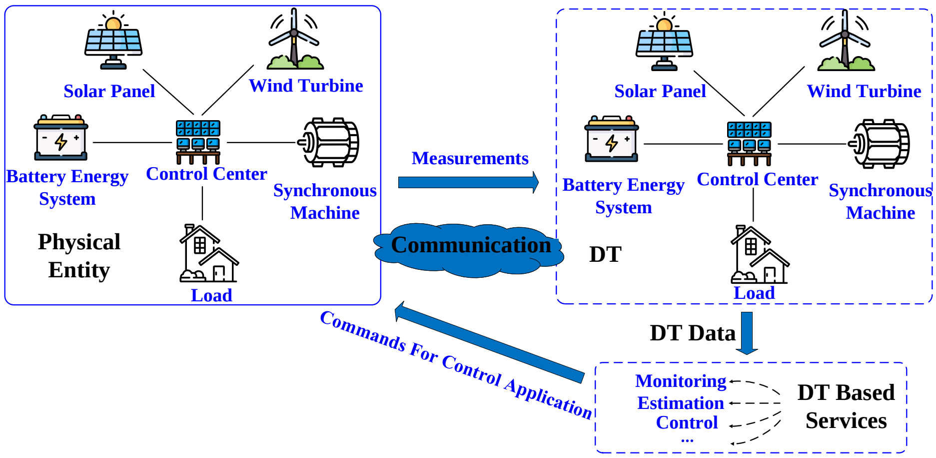

Figure 1. A typical five-dimension layout of a DT-based system.

As DT is a very broad subject and can be used for a wide range of applications, the above list are general considerations and can vary depending on the specific DTs' needs and requirements. Therefore, for demonstration purpose, this paper will focus on designing a testing platform specifically for DTs of DERs to enable frequency control ancillary services.

3. Design and Implementation of the Testing Platform for Digital Twins of Distributed Energy Resources (DERs)

3.1. Overview of the DT Testing Platform

With the consideration factors for DT-based applications listed in Section 2 fully taken into account, a real-time HiL testing platform specifically designed for prototyping and testing DTs for DERs has been designed and implemented. The testing platform, as illustrated in Figure 2, comprises the five key elements typically required for demonstrating and testing DT-based solutions. The key characteristics of these elements are summarized as follows:

- The physical DERs are represented with real-time DERs models simulated in an RTDS simulator.

- The DTs of the DERs are accurate models, along with communication interfaces and other associated functions. In this work, for demonstration purpose, the DTs are used for monitoring the DERs' active power output for frequency studies, so they are compiled as executable programs hosted on a dedicated high-performance PC to emulate a cloud server.
- The real-time measurement data (e.g., frequency, voltage, etc.) are transmitted via a Socket-based Giga-Transceiver Network (GTNET-SKT) card, which is a network interface in RTDS. The exact data to be transmitted depend on the targeted application of the DTs. The data reporting rate can be controlled in RTDS to evaluate its impact on DTs' accuracy.
- The communication channels between the emulated DERs in RTDS and their DTs are emulated by via the GTNET card and an Ethernet switch, along with a dedicated software-based communication delay emulator implemented in this platform, which will be discussed in detailed in Section 3.4.
- The services provided by the DTs, e.g., the estimated active power outputs and critical status information of the DERs, are used by the applications that are hosted also in the same PC with the DTs.

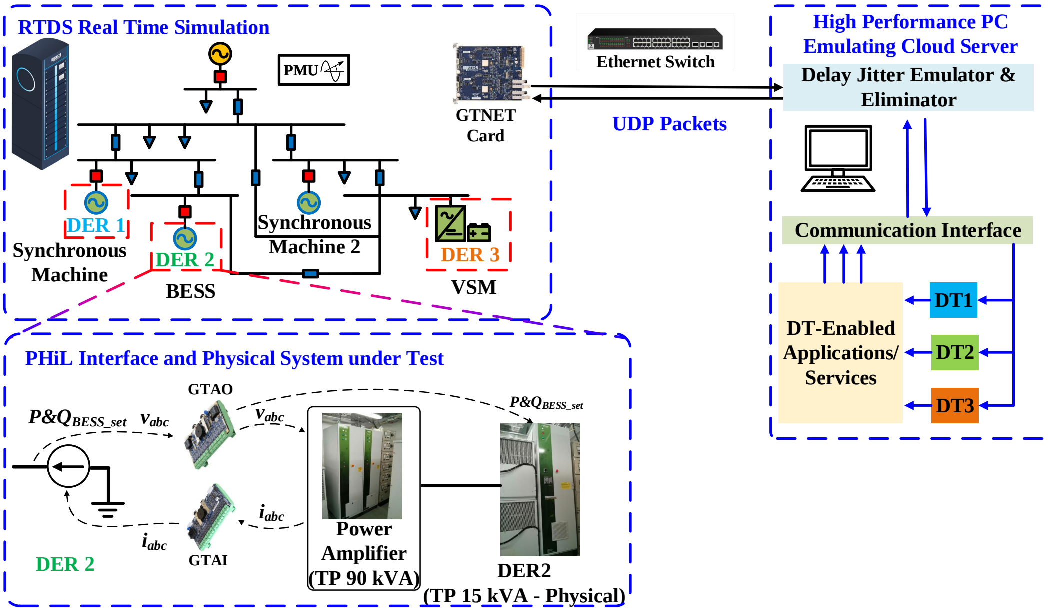

Figure 2. A representation of the DT-based real-time HiL platform.

3.2. Representation of Physical DERs

As discussed in Section 2, in order to test and demonstrate DT-based applications, a means of representing the physical system is required. The representation of the "physical" DER systems is achieved by two main methods in the proposed platform: i.e., (1) pure real-time DER models connected to a microgrid model simulated in RTDS, and (2) a physical DER converter that is coupled with the real-time models developed in RTDS simulator via Power-Hardware-in-the-Loop (PHIL) simulation. Both options allow the communication of live measurement data from the emulated physical DERs to their corresponding DTs for testing their DTs' accuracy and the associated DT-based applications.

The use of real-time DER models to represent physical DERs is considered to be relatively fast, flexible and cost-effective for setting up and conducting the associated tests and demonstrations. In this platform, a Synchronous Generator (SG) and a battery-based Virtual Synchronous Machine (VSM) are hosted on RTDS as illustrated in Figure 2.

The option of PHIL allows a more realistic representation of the physical DERs (e.g., via connecting the actual DERs to the testing environment), while still being scalable via the tuning of the PHIL feedback signal. In this platform, the actual physical hardware system incorporated into this PHIL is a back-to-back Triphase 15 kVA (TP15 kVA) power converter, which is utilized to represent one of the DERs.

3.3. Execution and Host of DTs

The development of the DTs for DERs can depend on many different factors, with two key factors being (1) the targeted application; (2) the knowledge on the physical DERs. The application will determine the level and type of details the DTs need to replicate the physical DERs. For example, asset-management-related applications might be interested in the thermal behavior of the DERs in different environments and operating conditions, while monitoring and control applications might be more interested in representing electrical properties of the DERs (e.g., active and reactive power).

The knowledge of the physical system available at hand also determines how the DTs should be constructed, where typical approaches can be broadly classified as: (1) physics-based [30], (2) data-driven [31] and (3) big data cybernetics [32]. In this work, for demonstration purposes, the DTs are developed used the physics-based approach, where the DT is constructed by the knowledge of the physical topology and control of the DERs.

Selecting a platform for running and hosting the DT is highly dependent on the application as well. In general, the hosting platform should be able to execute the DT, i.e., process the input measurement data and generate outputs, within the defined time-step. In this work, the example application for the DTs is on monitoring the active power-related properties, which is considered to be used for coordinating DERs for frequency support. Therefore, analytical models representing the active power dynamics of the DERs have been constructed in Simulink, which are then generated as executable codes and combined with a communication program as illustrated in Figure 3. This will be used as an example of a DT-based application to validate how the DTs' accuracy and how time-step and other factors affect their performance.

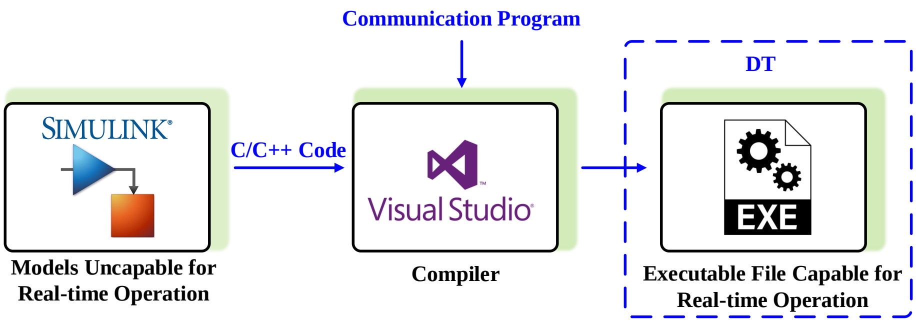

Figure 3. The detailed process of DT development

3.4. Emulation of Communications

DTs require the live system measurement data from the physical world in order to replicate the physical system's behavior. Therefore, communication channels are required to transmit the live system data. Typically, DTs are hosted in the cloud or in the control room environment, which could be located at a distance away from the physical system, so wide-area communication could be required. Communication of data across a wide area is subject to latency and jitter, so emulation of a such communication effect is critical for evaluating DTs performance. Furthermore, the protocol of communication channel used is also critical to the DT performance and is elaborated in Section 3.4.2.

In this platform, the dynamic behaviors of DERs are packaged by a GTNET-SKT card within the RTDS simulator. Ethernet switch encapsulates the streaming data with IP addresses and forwarding it to predefined destinations, i.e., the location of the DTs. To emulate different degraded communication performance, a software-based communication emulator is developed, which is discussed in detail as follows.

3.4.1. Delay Jitter Emulator

The accuracy of the DTs in reflecting the physical systems' behavior highly depends on the data that are transmitted through the communication network. It was found in this work that communication jitter, if not dealt with appropriately, could significantly compromise the DTs' accuracy. As reported in [26,33], the physical time delay can be compensated to some extent by adding additional phase shift to mitigate its impact on system performance. However, the delay jitter has randomness in nature which makes the compensation more difficult, and handling methods could be required in DT development. The effectiveness of potential solutions to communication instability also needs a testing platform for comprehensive evaluation.

The work assumes that the live measurements from the physical system are timestamped, so the signals sending from physical entities are attached with timestamps to identify the actual order of messages. However, jitter of communication delay could occasionally occur in transmission process, which means the previous package could arrive at the receiving end after its following packages. In this platform, a software-based communication emulator, as shown in Figure 4, has been developed to introduce an artificial random delay to the DT signals to emulate unstable communication channels. The working mechanism of the developed communication emulator does not introduce actual delay to the communicated packets, but it adds an a random number to the timestamps of the packet to emulate arrival time, and reorders the packages based on the added "arrival time", which is based on the values added to the timestamps. The actual arrival order of the packets is changed by reordering process based on modified timestamps, thus emulating the packet disorder.

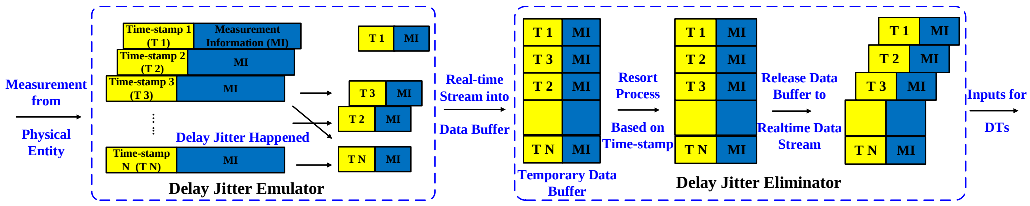

Figure 4. A representation of the design criteria of the delay jitter emulator and eliminator

As mentioned previously, DTs are required to be robust against certain level disturbances in communication channels and capable of handling a certain level of communication system degradation. For the purpose of demonstrating how the communication emulator can be used to test DTs' capability in handling communication jitter, a delay jitter eliminating method is embedded within the DTs in the testing platform, which creates a data buffer at the receiving end to store the upstream data temporarily and re-sort the order of packages according to the attached timestamps. The timestamp of latest received packet is designed to be compared with all the packets already existing in the temporary buffer. Even though the data flow is interrupted by this buffer, the streaming feature of the data is maintained as the first row of data buffer matrix that is released to DT periodically. Consequently, a real-time data channel is established to evaluate the effect of certain delay jitter to DT monitoring performance.

3.4.2. Protocol

In this work, User Datagram Protocol (UDP) is adopted to set up communication channels as it is suitable for real-time and high reporting rate streaming communications [34]. For many industrial time-critical applications, it is a widely used strategy, i.e., to drop packets, rather than waiting for error-correction. Similarly, many DT-based applications are time-sensitive, which means any time delay arising from re-transmission can lead to streams disorder. To construct a duplex UDP channel, the structure contains the protocol type of the channel, the size of the message buffer and the IP addresses and ports that need to be defined, which is known as an Internet socket. The socket is created by programmed applications and would be closed at the end of process. During the lifetime of socket, the receiving end would utilize the reserved port to listen to incoming messages from the sending end.

3.5. Measurements for DTs

This DT platform aims at tracking the active power outputs of DERs with limited communicated data. The frequency of the grid is selected as the input signals for DTs, which is accessible in the current power system via devices, e.g. Phasor Measurement Units (PMUs). The reporting rate of PMU is also capable to support further frequency control applications. The upper limit of DT data resolution is determined by the inherent reporting rate of input measurements from the physical system. Frequency information with different time-steps could be provided by other sensors implemented in the power system with much higher/lower reporting rates. In this platform, the GTNET card is used to control the reporting rate of the measurement data that are sent to the DTs, which can be used to investigate the minimum sufficient reporting rate that is required for specific applications. An example application for estimating DERs' active power output based on frequency measurement using the platform is demonstrated in the case studies.

3.6. Services Provided by DTs

The services provided by the DTs are highly dependent on the targeted application. However, a fundamental capability of DTs is to provide visibility of interest to the users. Based on these basic functions, additional services such as performance optimization and behaviour prediction can potentially be further realiazed. This DT validation platform can be used to validate the accuracy of the DTs by comparing the differences between physical systems and DTs' outputs. In this work, as an example, the focus is placed on the provision of the visibility of DERs (i.e., its active power outputs) via the frequency measurement, and they can be compared with the actual outputs from the DERs to validate the DTs' accuracy.

4. Case Studies

This section presents case studies demonstrating the application of the proposed DT testing platform for validating and demonstrating the DTs for DERs. The tracking capability of DTs is validated by comparing its outputs against those of the RTDS-based DERs in Section 4.2. The effect of communication delay jitter and the effectiveness of jitter eliminator is assessed in Section 4.3. The impact of signal time-steps to the DTs' performance in replicating physical DERs is evaluated in Section 4.3.1 by applying digital measurements with different time-steps to DTs.

4.1. System Description

As illustrated in Figure 2, a microgrid network model, modified based on [35], consists of three generation sources, i.e., droop-controlled Battery Energy Storage System (BESS), SG and batter-based VSM. The functional units and the associated controllers of these power sources (e.g., Gas Turbine and its associated Speed Governor (GAST)) are implemented and executed in RTDS. Correspondingly, the DTs mimicking these power sources are implemented and executed on the target PC. In ideal situations, the controllers of these RTDS-based physical DERs and PC-based DTs receive the same inputs (e.g., PMU frequency measurement) simultaneously. The outputs of these controllers are the same provided that the DT systems are well established. The detailed structures including inputs and outputs of each DER are listed below. The detailed structures including inputs and outputs listed below are used to demonstrate the internal characteristics of of each DER, which are different from Simulink models used to produce DTs as part of the simplified functional subsystem.

- Figure 5 presents the block diagram of the BESS with droop controller that is implemented in RTDS. The input of the control loop is the grid frequency measured by PMU and the reference power set-point. The characteristic of a Triphase 15 kVA converter is represented by its equivalent transfer function. Therefore, with the knowledge of every pre-configured reference value (e.g., reference power and nominal frequency), a DT with the same I/O ports with BESS is developed.

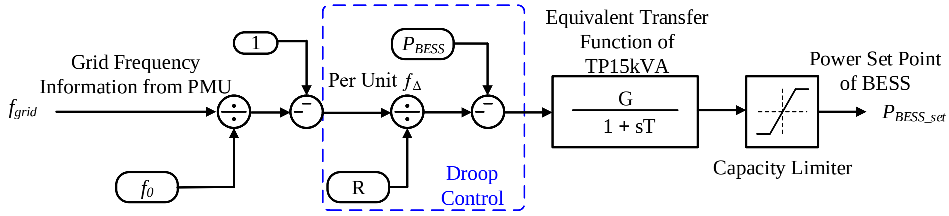

Figure 5. Block diagram of BESS [35].

- The input of GAST is the measured rotational speed of the SG. To apply droop control, the input is firstly converted into per unit frequency followed by the droop and damping multiplication. As shown in Figure 6, first-order transfer functions are used to represent the functional subsystems of SG including speed governor, combustion chamber and exhaust gas temperature limiter.

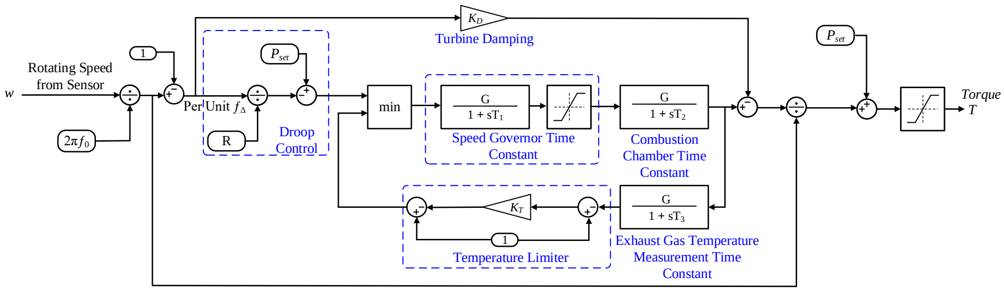

Figure 6. Block diagram of GAST [36].

- For the VSM model, a grid forming converter, as shown in Figure 7, is implemented in RTDS with conventional nested controller and inertia emulator. The output voltage of this converter is regulated by following the dedicated frequency f_{ref} and voltage magnitude $v_{dq_{ref}}$ references. Even though the final reference power determined by droop control algorithm is the most of interest, the inertia and damping power are also essential criteria to be investigated.

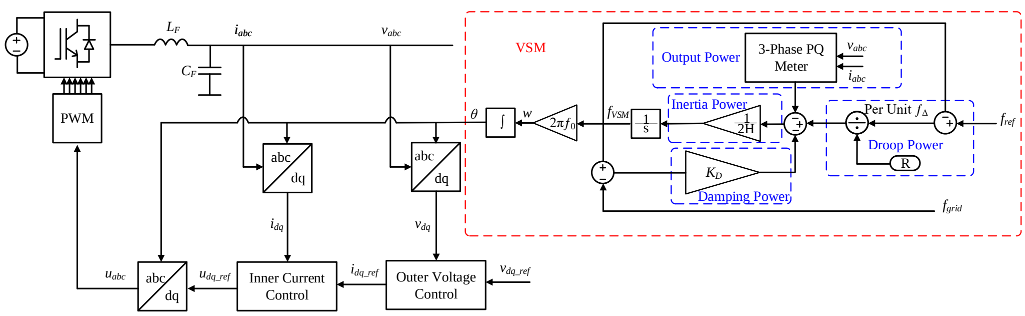

Figure 7. Block diagram of VSM [37].

As shown in Figure 2, the configuration of the PHiL setup is based on the voltage-type ideal transformer model (ITM) interface [23], which comprises a back-to-back Triphase 90 kVA (TP90 kVA) power amplifier that is coupled with a TP15 kVA converter. A Giga-transceiver analogue output (GTAO) card and a Giga-transceiver analogue input (GTAI) card are utilized for the signal transmission and conversion between RTDS and Triphase converters. The TP90 kVA power amplifier acts as a grid emulator by regulating its output voltage through following the reference signal v_{abc} measured at the point of common coupling (PCC) in the real-time emulated microgrid. TP15 kVA is utilized to represent the interfacing converter of DER2 in the emulated microgrid. The active and reactive power output signals of the BESS controller as duplicated in Figure 5 are transmitted to TP15 kVA as command signals to generate its current reference, according to which TP15 kVA regulates its output current. Correspondingly, TP15 kVA sources or sinks current to the TP90 kVA power amplifier and this current are further transmitted to the RTDS as the command signals for a controllable current source at the PCC in the real-time emulated microgrid. By doing so, the hardware power converter is interfaced into the PHiL closed-loop setup with its power dynamics replicated in the emulated microgrid. The parameters which determines internal characteristics of DERs are shown below in Table 1.

Table 1. Description of the parameters in Platform.

Parameters	Description	Value
R	BESS: Droop constant	0.05
P_{BESS}	BESS: Active power output	Variable
$P_{BESS_{set}}$	BESS: Active power output set-point	0.1 MW
R	GAST: Droop constant	0.05
P_{set}	GAST: Active power output set-point	0.8 MW
K_D	GAST: Turbine damping constant	0
K_T	GAST: Temperature limiter gain	2
L_F	VSM: Converter output filter inductance	1 mH
C_F	VSM: Converter output filter capacitance	2500 uF
K_D	VSM: Damping constant	50
H	VSM: Inertia constant	2
R	VSM: Droop constant	0.05
f_{grid}	Grid frequency measurement	Variable
f_0	Nominal grid frequency	50 Hz
Δf	Change of grid frequency	Variable

4.2. Validation of DTs' Real-Time Tracking Capability

This case study involves five scenarios that simulate the possible events in a grid that could result in frequency deviation. The microgrid is initially connected with the main grid and operates at the nominal 50 Hz frequency. The power between the microgrid and main grid is balanced. The control method of BESS and SG is droop control, which increases the power output of individual generation units against the frequency deviation to achieve basic coordinated control. The following scenarios are triggered with a period of 10 s for each, as shown in Figures 8 and 9.

1. **Frequency deviation event in grid-connected mode (50 Hz to 49 Hz).** At $t = 2$ s, upon the activation of the first scenario, the main grid frequency witnesses a significant drop from 50 Hz to 49 Hz with the Rate of Change of Frequency (RoCoF) at -0.5 Hz/s. This scenario is designed to emulate the effect of the loss of generation in the main grid.
2. **Frequency restoration in grid-connected mode (49 Hz to 50 Hz).** The frequency is recovered from 49 Hz to 50 Hz in the second scenario to emulate the frequency control process.
3. **System transition from grid-connected mode to islanded mode.** As the microgrid is connected with main grid, the power imbalance test of generation and load could only be performed under islanded mode. Otherwise, the active power from the main grid would be fed into the microgrid to maintain the balance condition. Therefore, the third scenario is used to monitor the tracking capability of DT when the microgrid status changes from grid-connected mode to islanded mode.

4. **Load power change (3.3 MW to 3.6 MW).** In the fourth scenario, the load power is increased from 3.3 MW to 3.6 MW to demonstrate the power imbalance occurring in the islanded microgrid.
5. **Load power change (3.6 MW to 2.9 MW).** In the fifth scenario, the load power is decreased from 3.6 MW to 2.9 MW to demonstrate the power imbalance occurring in the islanded microgrid.

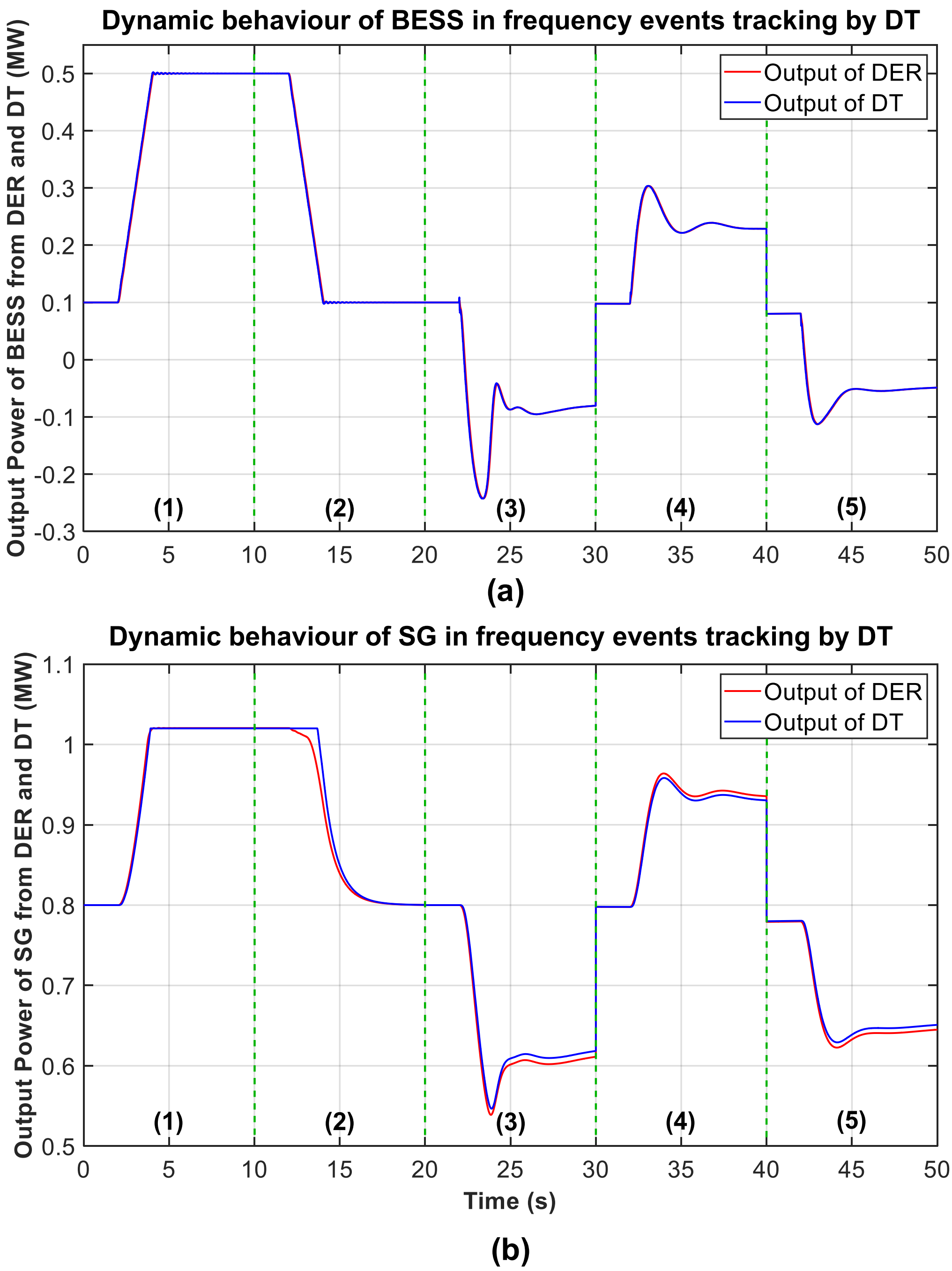

Figure 8. DTs of BESS and SG validation under five scenarios: (**a**) DT of BESS; (**b**) DT of VSM.

As illustrated in Figure 8, good DT tracking performance of DT for SG is achieved under these scenarios with acceptable offsets. As demonstrated by Figure 9, the overall tracking capability of DT for VSM is reliable, but there are some oscillations on inertia response and damping power, which are especially obvious in islanded mode. Part of the reason is the particular characteristic of these dynamic behaviors and the different time-steps between

RTDS-hosted DERs and PC-hosted DTs, which is analyzed in detail in Section 4.3.1. Another potential reason could be the change in per-unit value of impedance due to transition to islanded mode, which is outside of the scope of this paper and requires further investigation in the future.

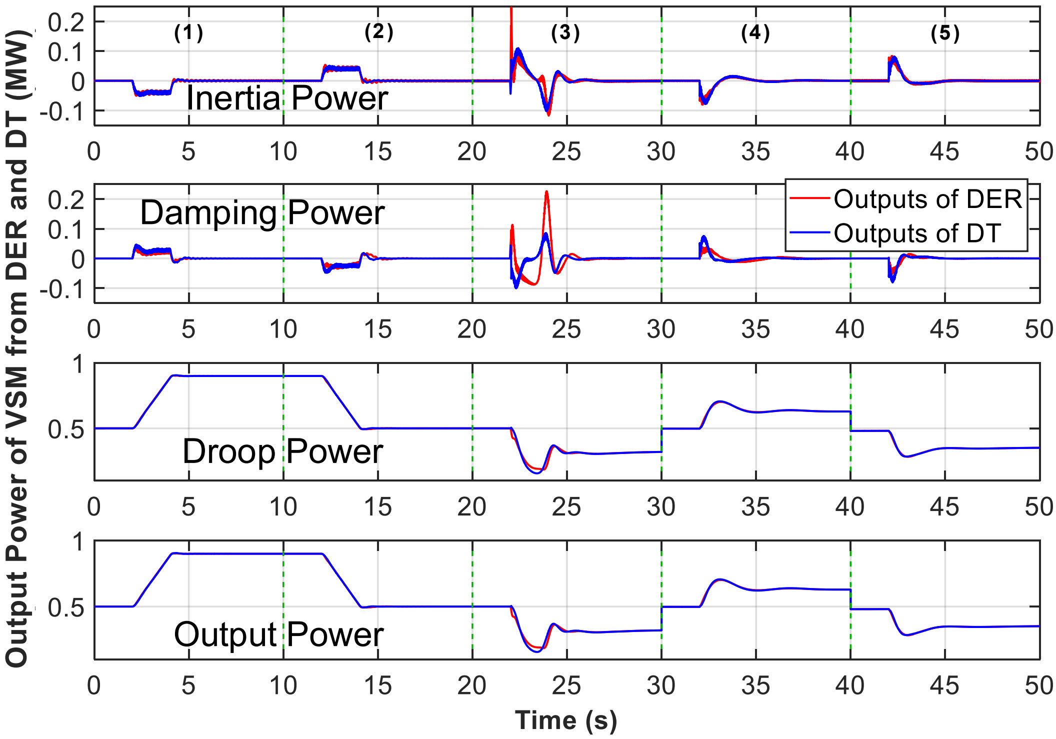

Figure 9. DT of VSM validation under five scenarios.

4.3. Impact of Communication Delay Jitter on DTs

The communication delay between physical and DTs is inevitable unless they are hosted by the same device, which has been applied in distributed control applications [21]. Therefore, it is critical to comprehensively investigate the effect of communication delay on the DT performance prior to its final-stage deployment.

The impact of delay jitter and the effectiveness of delay jitter elimination is validated by comparing the droop responses of BESS with and without delay jitter elimination. As illustrated in Figure 10a, the output of DT (without delay jitter eliminator) represented by the blue curve is distorted and presents significant deviation from the RTDS output represented by the red curve. This discrepancy arises from the artificially added delay jitter in the delay jitter emulator.

Figure 10b demonstrates the output signal of DT (with delay jitter eliminator) after jitter elimination is enabled. Compared with the DT output in Figure 10a, it could be found that the replicated output from the DT has been partly restored with most of the spikes eliminated. Furthermore, the effectiveness of the delay jitter eliminator is also validated by assessing the tracking performance of the power outputs of DTs for VSM. The power outputs of DTs for VSM and the RTDS-hosted VSM include damping power, inertia power and droop power as intermediate variables. As illustrated in Figure 11a, the damping power and inertia power output of DT (without delay jitter eliminator) presents remarkable deviations from that of the RTDS-hosted DERs along with significant oscillations. However, upon the activation of the delay jitter eliminator, the damping power and inertia power output of DT (with delay jitter eliminator) in Figure 11b presents less oscillations than that as presented in Figure 11a. A better tracking performance between the DT output and RTDS output has been achieved by enabling the delay jitter eliminator.

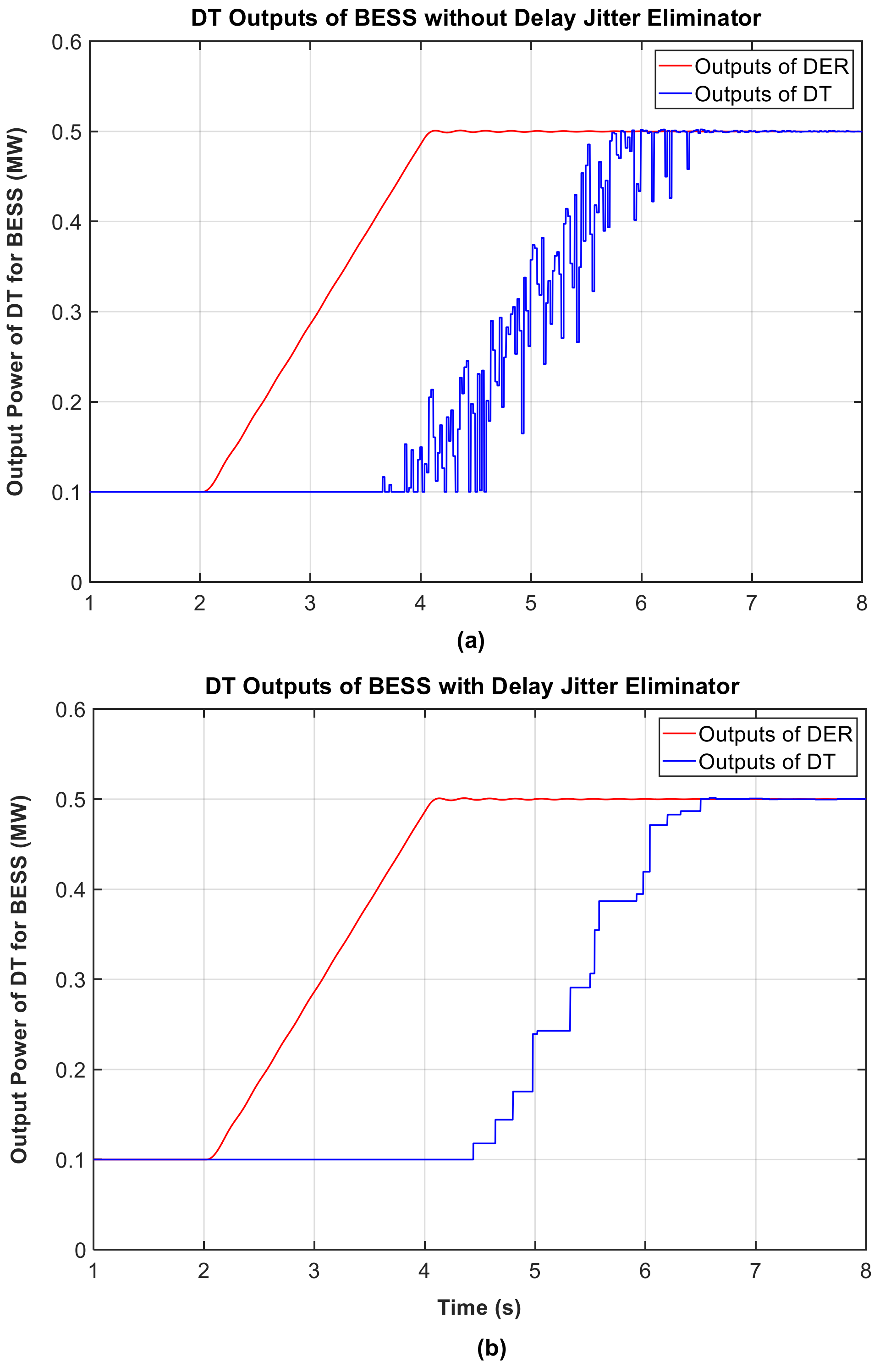

Figure 10. Effectiveness validation of jitter elimination on DT of BESS: (**a**) Comparison of original signal and signal with communication jitter (**b**) Comparison of original signal and signal after jitter elimination.

With the proposed DT-based platform, the impact of delay jitter on monitoring functionality is evaluated and the performance of embedded delay jitter eliminator is validated. The requirement of communication channel performance to monitor DERs with DTs could be investigated based on this platform by tuning the configuration of delay jitter emulator. The delay jitter eliminator not only improves the accuracy of system monitoring, but also benefits the potential coordinated control through equipping the DT with high tracking capability.

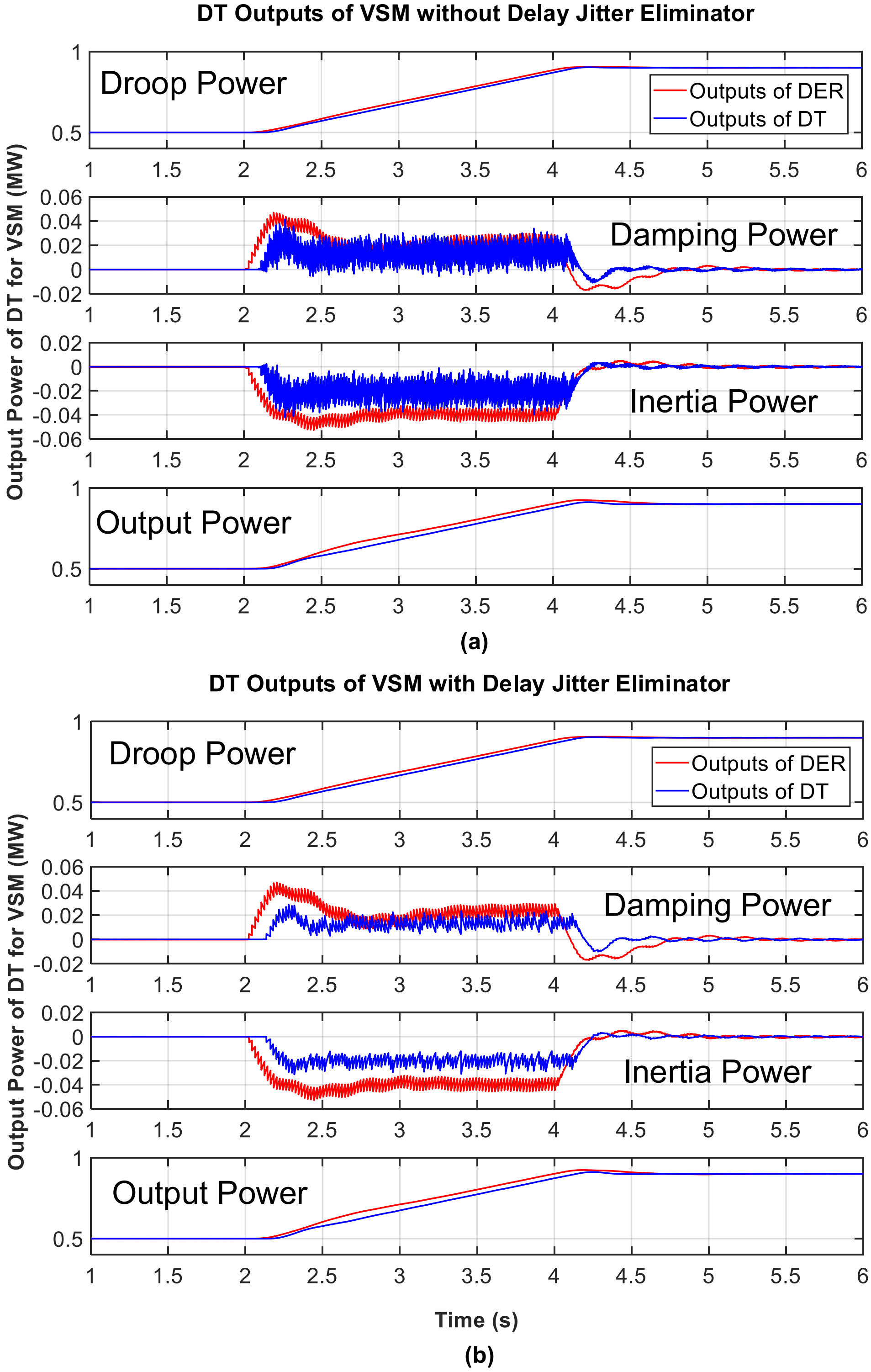

Figure 11. Effectiveness validation of jitter elimination on DT of VSM: (**a**) Comparison of original signal and signal with communication jitter (**b**) Comparison of original signal and signal after jitter elimination.

4.3.1. Impact of DTs' Time-Step

The state of physical systems changes continuously, but the digital measurements of dynamic behaviors are discrete. At the receiving end, the DT would sample the input digital measurement with its operation time-step as sampling frequency. The consistency of operation time-step and sampling frequency ensures the real-time characteristics of DT. As mentioned in Section 3.5, the resolution of DT data is determined by the reporting rate of information sources, where in the case of this work, which uses data from PMU as DTs input, the reporting rate is typically 50 Hz for PMU and can be as high as 200 Hz. However, higher reporting rates are commercially available, and the system reported in [38] could reach up to 14.4 kHz reporting rate. The GTNET-SKT card in RTDS is capable of reporting digital signals within a range of 0 to 5000 Hz to emulate frequency measurements from different sensors. DTs with different operational time-steps are tested in this section to demonstrate the corresponding effect.

Three operational time-steps with different orders of magnitude have been chosen to be applied on the DT of VSM, which are 0.02 s to represent PMU, 0.0002 s as the maximum reporting rate of RTDS and 0.002 s as reference. The dynamic behavior of VSM in frequency events has been monitored through four parameters: droop power, damping power, inertia power and the measured power output. By comparing the estimated value given by DT-based measurement of hardware with different time-steps, it could be found that the DT-based estimation of droop power is valid for all the scenarios with different time-steps, as shown in Figure 12. However, the estimation of damping power and inertia power fails when the time-step drops to 0.02 s.

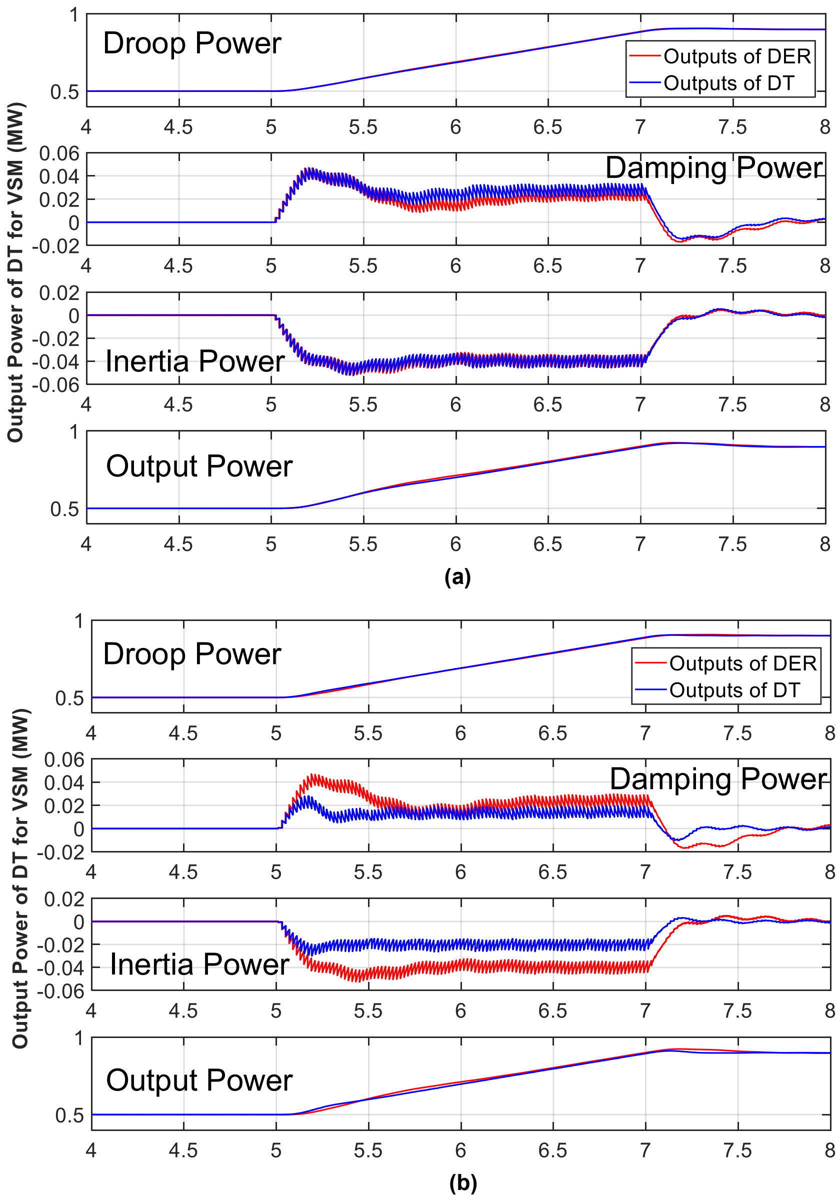

Figure 12. *Cont.*

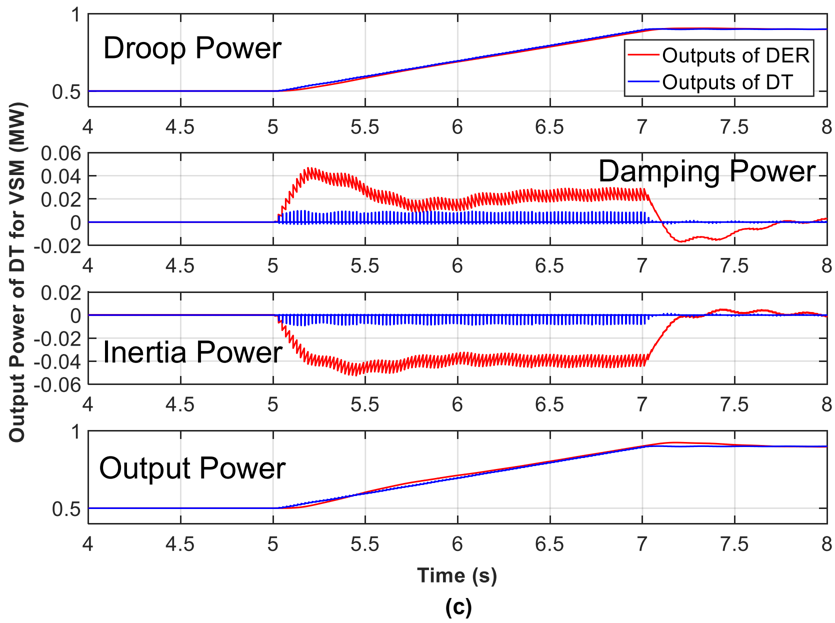

Figure 12. Time-step effect evaluation: (**a**) Time-step = 0.02 s; (**b**) Time-step = 0.002 s. (**c**) Time-step = 0.0002 s

Based on the test result, it could be concluded that the reporting rate of information sources for rapidly changing signals and non-linear systems must be relatively high to avoid the possible distortion. Based on this proposed platform, the selection of sensors with desired reporting rate which takes both cost and effectiveness into consideration could be determined according to the specific use cases.

5. Conclusions

This paper presents a real-time simulation and HiL testing platform, specifically designed for prototyping, demonstrating and testing DTs of DERs, which are considered a promising solution for addressing a range of challenges associated with DERs integration. The design considerations of the testing platform for DTs have been discussed, based on which a testing platform has been implemented and demonstrated. The platform considers the different options for representing the physical systems in a DT-based application, the host and execution of DTs, the emulation of a communication channel, and the specification of the reporting rate of the measurement data as input to the DTs. Case studies have been presented to illustrate how the proposed platform can be used to test the accuracy of DTs and the impact of various factors, e.g., communication jitter. It was found that both communication delay jitter and time-step (i.e., measurement reporting rate) selection can significantly affect the overall DT accuracy, and the proposed platform can be used for comprehensive assessment of such impact. The proposed platform provides an ideal solution for facilitating the future development of DTs of DERs and accelerating their adoption in the industry.

Future work will be focused on the development of control applications supported by this real-time DT-based platform, such as overshoot suppression by taking DER-hosted DTs of all the DERs in the same grid as decision-making units to achieve optimum operations. Furthermore, research efforts will be devoted to further investigating the effect of communication on DT tracking capabilities and the associated mitigating techniques.

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Abbreviations

The following abbreviations are used in this manuscript:

ADC	Analog-to-Digital Converter
BESS	Battery Energy Storage System
COP26	The 26th UN Climate Change Conference of the Parties
DERs	Distributed Energy Resources
DT	Digital Twin
GAST	Gas Turbine and its associated Speed Governor
GPS	Global Positioning System
GTAI	Giga-Transceiver Analogue Input
GTAO	Giga-Transceiver Analogue Output
GTNET-SKT	Socket-based Giga-Transceiver Network
HiL	Hardware-in-the-Loop
PCC	Point of Common Coupling
PHiL	Power Hardware-in-the-Loop
PMU	Phasor Measurement Unit
RoCoF	Rate of Change of Frequency
RTDS	Real-Time Digital Simulator
RTS	Real-Time Simulator
SG	Synchronous Generator
UDP	User Datagram Protocol
VSM	Virtual Synchronous Machine
WAN	Wide-Area Network.

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