Digital Twins of Distributed Energy Resources for Real-Time Monitoring: Data Reporting Rate Considerations

Jiaxuan Han, Qiteng Hong*, Zhiwang Feng, Graeme Burt, Campbell Booth
Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom
jiaxuan.han.2018@uni.strath.ac.uk, q.hong@strath.ac.uk

***Abstract*—This paper analyzes the requirements for the reporting rate of the live data source to support the operation of Digital Twins (DTs) of Distributed Energy Resources (DERs) for real-time power systems monitoring applications. The visibility of distribution networks is currently limited due to the lack of sufficient measurement and communication infrastructures. With the rapid increase of DERs, it becomes increasingly important to improve the visibility of the distribution networks to ensure the critical system operating constrains are continuously met. DTs are virtual replicas of physical systems, and with certain live measurement data, they can be used to accurately represent the real-time dynamics of the physical entities. The features of DTs could therefore be applied to increase the visibility of network and potentially support real-time decisions making. This paper presents the investigation of the impact of data reporting rate on DT accuracy, based on which, the paper presents a method that could be used to quantify the minimum requirements for data reporting rate to adequately support the DT operation, which provides valuable learning for specifying measurement devices and communication networks to enable DTs-based solutions.**

***Index Terms*—Digital twin, bandwidth, discretization, distributed energy resources, reporting rate.**

I. INTRODUCTION

The public concerns about climate change due to carbon emissions and the uncertainty of fuel supply in some countries have driven the rapid increase of converter-interfaced renewable energy in power systems worldwide. One of the major challenges of converter-dominated power system is the significant decrease in system inertia, which will lead to faster frequency deviation during power imbalance events. Many renewable resources are distributed across the system and integrated into the power network at distribution level, and these resources are referred to as Distributed Energy Resources(DERs), e.g., PV cell, micro wind turbines, energy storage, biomass, etc. [1], [2]. The DERs have characteristics of being intermittent and uncertain by nature, however, via appropriate coordination [3], they have significant potentials to contribute to the system operation, including frequency control in future low-inertia system [4].

Presently, there are different control concepts have been proposed for DERs, which can be categorized as three main control strategies: 1) real and reactive power (PQ) control; 2) voltage and frequency (V&f) control; and 3) droop control [5]. The responses of individual DERs in frequency events can vary significantly due to the differences in control concepts and characteristics of DERs. For example, the DERs with droop control might respond to frequency events without the knowledge of other DERs participating frequency control, which might have faster responses. As a result, it is difficult to achieve the optimal and most effective response to support the frequency control. In the worst case scenario, the uncoordinated response might compromised the frequency control due to them acting in a uncoordinated manner in different time scale, and this is particularly problematic when there is a large scale of DERs in the system contributing to frequency regulation.

In order to establish effective coordinated control of DERs with different characteristics, real time monitoring of DERs' status (e.g. active power output) is typically required. However, installing high resolution measurement units on DERs and constructing corresponding communication networks can be very costly, which makes it impractical to implement. Therefore, a new low-cost method that enables the visibility of real-time information of DERs is urgently required. Restricted by bandwidth and inevitable time delay, the existing communication network is not capable to exchange massive real-time data between DERs and controllers.

Digital twin (DT) is an emerging technology that has attracted significant interests in many industrial applications, including power systems domain [6]–[8]. The concept of DT was summarized by Michael Grieves as a virtual representation of a physical component/system [9] after its first practice in aerospace [10]. At the initial stage of development in the last century, the original prototype of DT is considered to contain three main parts, i.e. the physical entity in real world, the virtual replica in virtual space, and the connections between them [9]. With the development of artificial intelligence in the past several decades, the data generated by DT has been proved as the most valuable part. The generated data set could also be utilized for pre-training or machine learning. A typical layout of a DT-based system with five main elements was proposed in 2018 [11], i.e., the physical entity (the physical twin), the virtual entity, the data flow between the physical system and the DT, the communication links, and the services provided by the DT to enable various applications.

A key advantage and strength of DTs is that it can be used

This work was supported in part by the EPSRC RESCUE project (EP/T021829/1).

This is a peer-reviewed, accepted author manuscript of the following conference paper: Han, J., Hong, Q., Feng, Z., Burt, G., & Booth, C. (2023). Digital twins of distributed energy resources for real-time monitoring: data reporting rate considerations. In IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society https://doi.org/10.1109/IECON51785.2023.10312555

for enhancing the visibility of the physical system/entity via limited live measurement data, i.e. the comprehensive real-time system status can be estimated based on the selected live measurement data. This provides a promising solution for accessing the real-time status of DERs with reduced communication and measurement requirements. Instead of measuring and communicating all required data from physical system, the application of DT allow the acquisition of real-time data via virtual replica of DERs in virtual space with limited live measurement data. The benefit of such an approach is the virtual space could be hosted in any desired location to reduce the delay between information source and the end applications (e.g. monitoring or control functions), and the real-time dynamics of DERs could be sampled with much higher frequency without presenting a high requirement on the communication network.

There were several successful applications of DTs in power systems, which mainly focused on fault diagnosis and real-time online analysis of power grid. In [12], the fault patterns of PV system are pre-trained by DT estimator to support fault identification. The DT is also taken as a reference to evaluate the health condition of the physical system in [13] as they are unlikely to be affected by physical damage. In [14], a framework for online analysis of the power grid is presented, where a data-driven DT was developed and applied. Recently, a cloud-edge hosted DT for coordinated control of DERs has been proposed to support frequency regulation [15].

During the development of DTs of DERs [15], it has been found the input data reporting rate and thus the simulation time step of the DTs has significant impact on the accuracy of DTs in replicating real time systems' behaviour. The correlation between DT accuracy and data rate was evaluated using an experimental approach by testing DTs of DERs through a Power Hardware-in-the-Loop (PHiL) prototyping and testing platform [16]. However, there is very limited research focusing on a comprehensive analysis of the required data reporting rate in order to achieve satisfactory DT accuracy. Therefore, this paper aims to address the gap by presenting a method for determining the minimum reporting rate required for DTs, which provides valuable insights for the selection of measurement devices and communication networks that facilitate DT-based solutions.

This paper is organized as follows: Section II demonstrates the impact of data reporting rate on DT accuracy. Section III analyzes the mechanism of this phenomenon and proposes a method to improve the feasibility of an arbitrary DT application. Following by Section IV which provides two methods to identify the reporting rate requirement of DT for specific DER. Finally, Section V presents the conclusion of the paper.

II. Impact of Data Reporting Rate on DT Accuracy

To illustrate the impact of the data reporting rate on DT accuracy, a converter-based DER that is controlled as a Virtual Synchronous Machine (VSM) and connected to a microgrid is used as an example [17]. The VSM and microgrid are real time models in the Real-time Digital Simulator (RTDS),

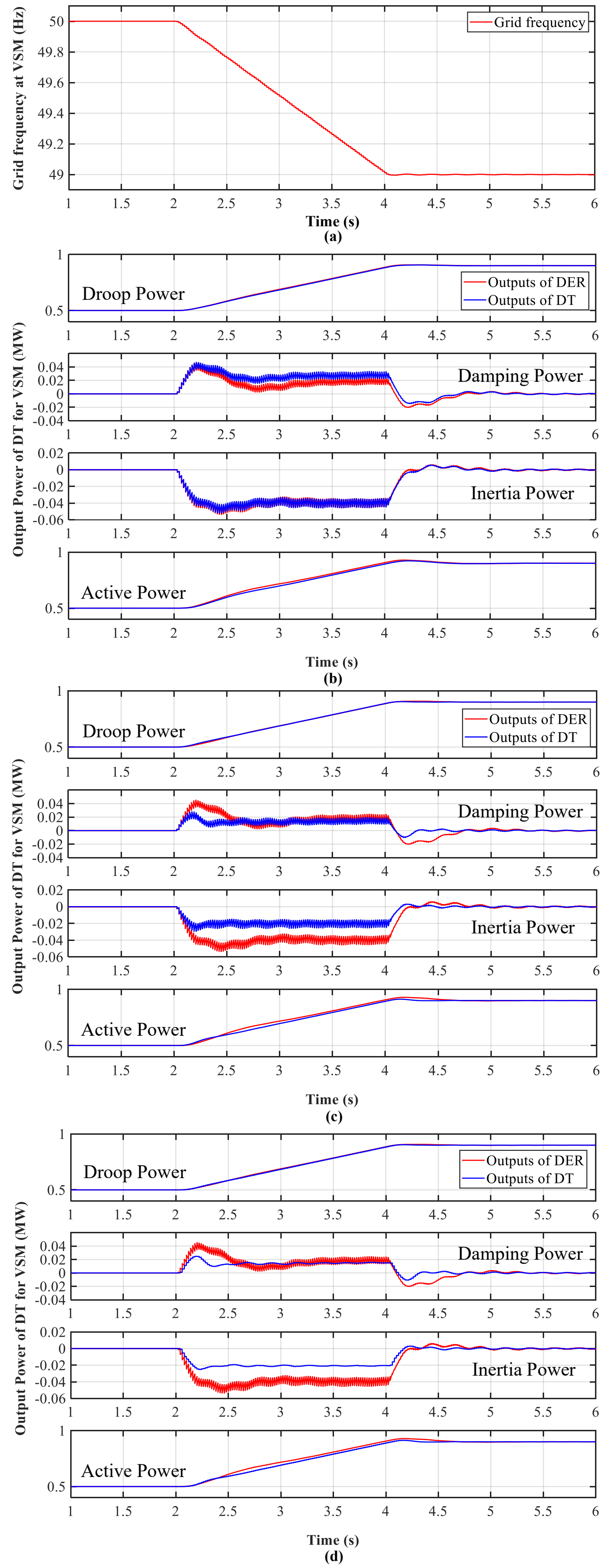

Fig. 1: The DT accuracy with information source at different reporting rate: (a) measured grid frequency as input signal (b) 5000 Hz (c) 500 Hz (d) 50 Hz

emulating physical systems. The control strategy of the VSM under study is available in [18], and it contains a droop control and a control block to emulate the inertia by monitoring the frequency deviation and producing power proportional to the change. In the VSM controller, the damping effect is achieved by a damping constant and comparing the VSM angular speed with the frequency estimated by a Phase Locked Loop (PLL). A DT of VSM was developed and implemented on a separate hardware platform [15], and it was designed to use the frequency information measured from the grid to calculate the real-time active power of physical entity. The information source for DT is a Phasor Measurement Unit (PMU) model available in the RTDS with a maximum reporting rate at 5000 Hz through an Ethernet connection. During frequency events, there are three main characteristics of the VSM that is critical, i.e. the droop power, inertial power and the damping power. These three key parameters are used as the examples in this paper to illustrate and evaluate the required data reporting rate for DTs.

A properly developed DT of the VSM is expected to track all the interested dynamic behaviours during frequency events. Therefore, the case study simulates the possible frequency deviation in power grid that can lead to apparent responses from the VSM. The microgrid containing the VSM was initially connected with the main grid and operated at the nominal frequency 50 Hz. Due to the droop characteristic, the active power output of VSM will proportionally against any frequency deviation, and inertial and damping controllers are also expected to respond to frequency changes. A frequency event was triggered with a period of 6 s, as shown in Fig. 1, where the DT accuracy with three different input data reporting rate was evaluated. At t =2 s, the main grid frequency witnesses a significant decrease from 50 Hz to 49 Hz with the Rate of Change of Frequency (RoCoF) at −0.5 Hz/s as shown in Fig. 1.(a). This case study is designed to emulate the effect of loss of generation in the main grid. The inputs are mainly PMU data with three different reporting rates, which were sent by the GTNET-SKTx2 card on RTDS to the DT hosted in a separate hardware platform. The results are shown in Fig. 1.(b) to (d).

From Fig. 1, it could be found that the amplitude offsets between VSM and DT occur when reporting rate drops below 500 Hz. The process of DT modelling is successful as the tracking capability is confirmed at 5000 Hz reporting rate. As a result, the problem is diagnosed as the reporting rate of measurement data, which is the inputs for the DT. For a typical PMU, the typical reporting rate is set as 50 Hz by default. The performance of the original DT of DER with typical PMU measurement will therefore lead to significant errors in the DT. In practice, the accuracy of the data generated by such DTs with the low reporting data rate will not be adequate for many real time applications and services.

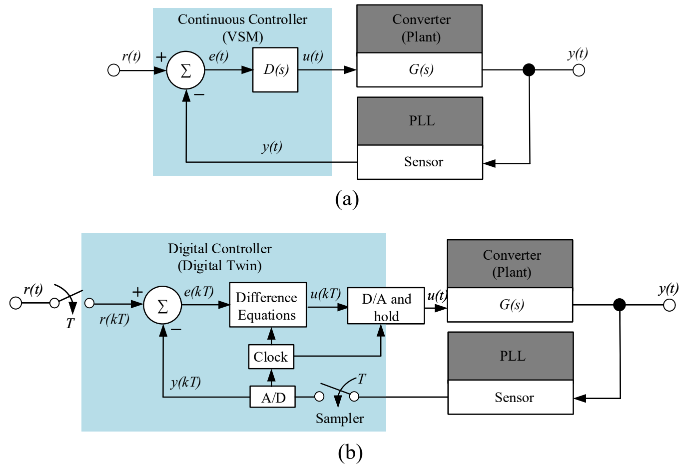

Fig. 2: Continuous controller to digital controller: (a) VSM (b) DT of VSM

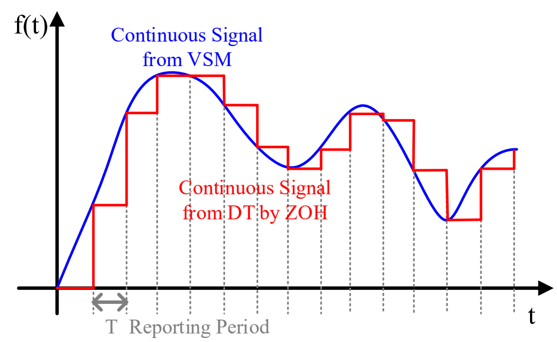

Fig. 3: Discritization of DT model by ZOH method.

III. Mechanism of DT Response Distortion and Corresponding Solutions

The differences between the hardware operating in the real world and the DT in the virtual space are illustrated in Fig. 2 [19]. For a physical VSM represented by Fig. 2.(a), the actual system operates in a continuous manner, and thus the associated properties, e.g., grid frequency, power outputs. For the DT of the VSM, the model can be represented by differential equations as shown in Fig. 2.(b). The frequency measurement are supposed to be sampled by a Analog-to-Digital Converter (ADC) firstly to transfer it as digital signal, and distortion can be introduced in this step. The Signal to Noise Ratio (SNR) could be used to mathematically evaluate the severity of the distortion, which is related to the reporting rate. According to [19], the digital control systems are expected to give adequate performance if the sampling rate is at least 30 times faster than the bandwidth of a closed-loop system. This value is taken as a reference to be compared with experimental results presented in this paper.

In order to address the low accuracy issue as a result of the low data reporting rate, the discretization method could be performed on virtual model to mitigate the negative influence introduced by low sampling rate. Discretization involves converting continuous functions, models, variables, and equations into discrete equivalents, which makes them suitable to be

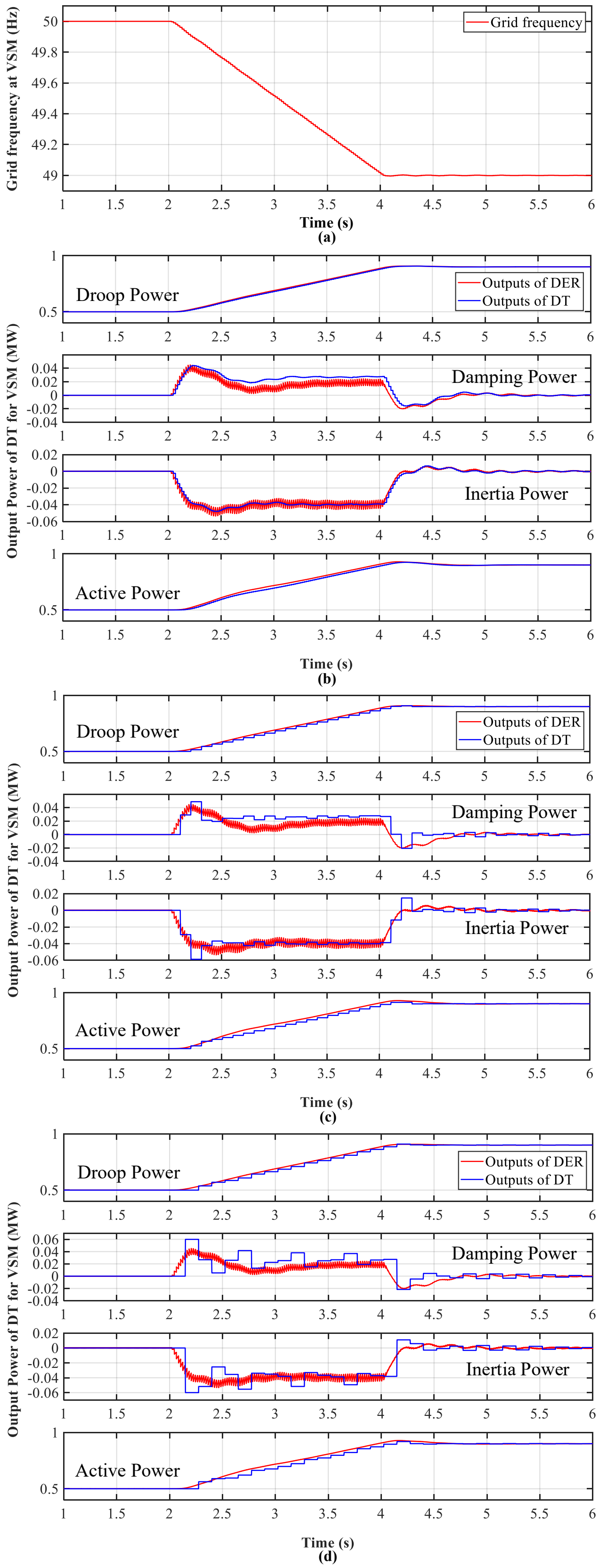

Fig. 4: DT performance after discretization at different reporting rates: (a) measured grid frequency as input signal (b) 50 Hz (c) 10 Hz (d) 8 Hz

implemented on digital computers. In the modelling process, the integrators of DERs are transferred to a discretized form by using the Zero-order hold (ZOH) method, which is a sample-and-hold operation that holds the input signal constant for the duration of the sampling interval and creates a piecewise-constant output signal that approximates the continuous input signal. This process could be illustrated by Fig. 3, which is similar to the function of step signals. All the continuous blocks in virtual model of DT need to be discretized by ZOH to monitor the intermediate variables such as damping power and inertia power.

Additional three scenarios have been studied to evaluate the performance of DT after discretization under different data reporting rates. The input signal of the VSM in RTDS is updated every 50 us which is considered as continuous but the reporting rate of DT input digital signal is 50 Hz (20 ms time-step). Even though there is an obvious difference between the scales of reporting rates, the dynamics tracked by DT has significantly improved even with low reporting rate of 50Hz as presented by Fig. 4. The tracking capability is weakening as the reporting rate decrease from 50 Hz (Fig. 4.(b)) to 8 Hz (Fig. 4.(d)). Further study has been conducted, and it was found that undamped oscillation will occur if the reporting rate decreases to 7 Hz which means 8 Hz is the minimum requirement for stable operation of the DT with acceptable accuracy. This case study show that via the discretization of DT model using the ZOH method, the accuracy of the DT can be significantly improved even with low data rate. In other words, the minimum required data reporting rate for DT can be mitigated via the the ZOH method. According to Fig. 4.(b), apparent errors are observed when the reporting rate drops to 10 Hz. In this paper, two methods to estimate the minimum reporting rate for DT of DERs in real-time monitoring applications are proposed and will be introduced in the following section.

IV. Methods of Determining Minimum Required Data Reporting Rate

As mentioned in Section III, the bandwidth of a closed-loop system determines the requirements of input signals reporting rate. Therefore, frequency domain analysis is the key part for understanding the required data reporting rate to support DT operation. In practice, most DTs of DERs are created with the knowledge of the detailed internal structure. The modelling method for this kind of DT is commonly referred to as the physical based approach. The frequency domain analysis of these DTs could be achieved by directly utilizing the associated tools, e.g. Model Linearizer Toolbox provided by Matlab. However, the structure information of some DERs could be inaccessible due to security concerns or data loss. In such condition, it is possible to apply the following two methods to determine minimum data reporting rate required. At the end, a DT real-Time HiL testing platform shown in Fig. 5 is used to verify the effectiveness of proposed methods.

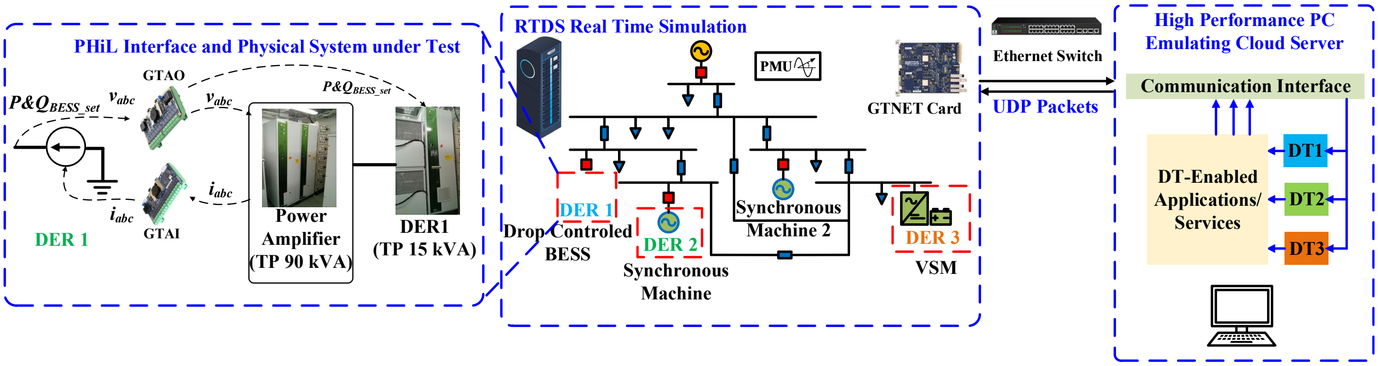

Fig. 5: Experimental platform to validate the effectiveness of the proposed reporting rate selection methods.

A. Physical Based Estimation

The procedure of a typical physical-based frequency response is setting the open-loop input and open-loop output on the analytical model e.g. Simulink model constructed by common blocks. Then the Model Linearizer application in Simulink could be used to generate the bode plot and identify -3 dB bandwidth (close-loop bandwidth). Based on the studies conducted in [19], multiplying the measured value by 30 would get the minimum sampling rate of digital input, which is the minimum requirement to have no obvious distortion on DT outputs.

B. Data-Driven Based Estimation

For a DER without structure information, the frequency responses could be analyzed based on the measured data in daily operations. Once there is a frequency deviation happened in the connected grid, the frequency deviation and the corresponding responses of the VSM can be recorded for further analysis. The process is shown in Fig. 6. Firstly, trigger a series of frequency events and record the responses of DERs. It is suggested to increase the diversity of events to make sure the training data set has signals on wider frequency bands. Secondly, the time series data is inserted into the System Identification Toolbox of Matlab. The data pre-processing can be performed in this application, e.g. including removing means and splitting the time-series data into two equal parts. The first part is used to train the model and the second part is used to validate the accuracy of the trained model. The optimal zeros and poles could be derived by using the Polynomial Model function. Take the optimal configurations as parameters to generate transfer function for further validation. The poor accuracy represents the training data set does not have enough frequency components and lack of representation. And longer and more diverse time-series measurements are required in recording process. Once the accuracy is acceptable, the frequency response could be easily performed in Matlab based on the transfer function obtained in Fig. 6.

Similar to the previous section, the minimum requirement to reporting rate of measurement units is obtained according to the frequency response of the estimated transfer function.

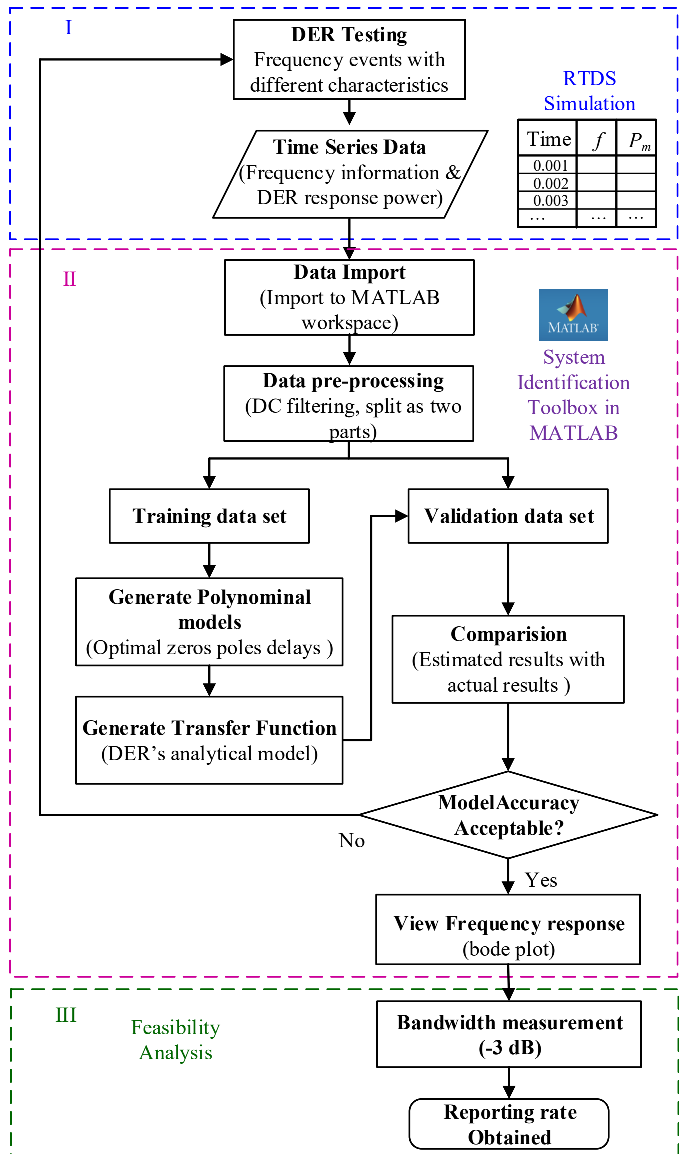

Fig. 6: Data-driven based frequency response analysis

C. Reporting Rate Estimation Examples

The effectiveness of proposed methods in previous sections is verified by using the real-Time HiL testing platform for DT

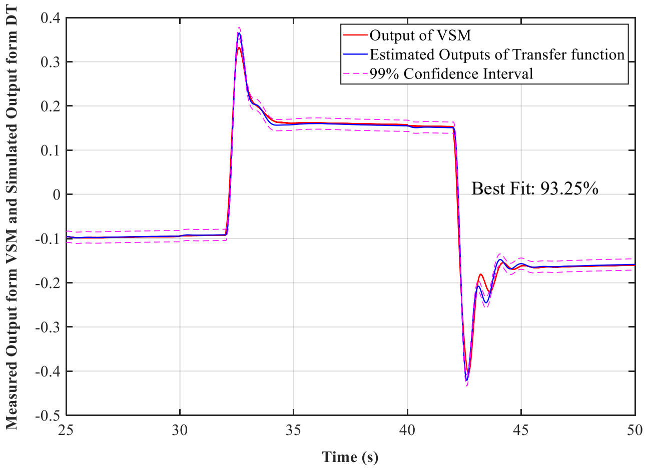

Fig. 7: Comparison between VSM and the corresponding transfer function

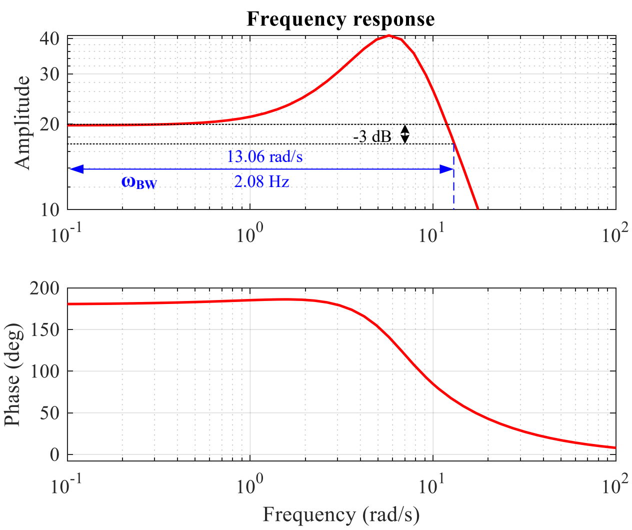

Fig. 8: Comparison between VSM and the corresponding transfer function

in [16]. As shown in Fig. 5, a modified microgrid network model based on [17] consists of three generation sources, i.e., droop-controlled BESS, SG and battery-based VSM. The BESS is replaced by Triphase 15 kVA converter to implement HiL test. 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.

The structure of VSM is assumed as an unknown black box. Five frequency events were applied on the islanded grid to obtain the frequency responses by creating power imbalance. The loads under islanded mode are changed in the order of 3.3MW, 3.1MW, 3.5MW, 2.9MW and 3.7MW. Each scenario lasts for 10 seconds and events are triggered at t =2 s. The input and output power from VSM is collected in real-time by scripts to ensure the continuity of data. The data of first 25 seconds is used to estimate the transfer function model and last 25 seconds are used to validate the accuracy of model

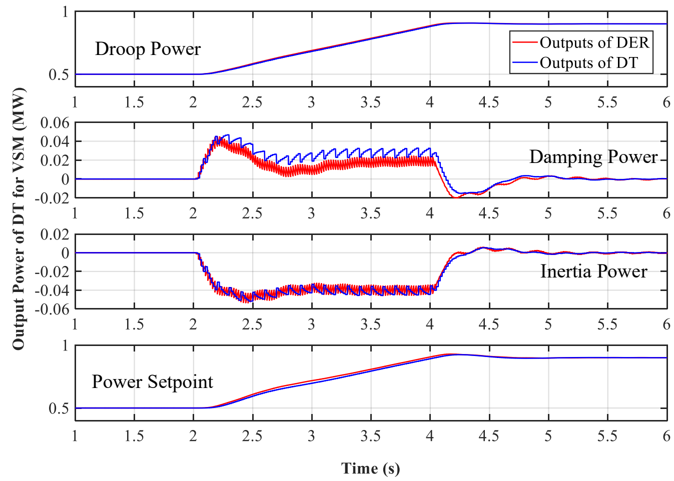

Fig. 9: The performance of DT in real-time monitoring with estimated minimum reporting rate (17 Hz)

by comparing the historic output from VSM with the output from transfer function. As shown in Fig. 7, the accuracy of transfer function model is 93.25% and the tracking capability is acceptable. Therefore, the bode plot of this transfer function is demonstrated in Fig. 8 and could be directly used to identify the closed loop bandwidth of VSM as a black box. The minimum reporting rate for the information source of DT in this case is 30 times of 2.08 Hz at 62.4 Hz. The DT of VSM is validated with this estimated reporting rate as shown in Fig. 9. Fluctuation of real-time tracking is noticed which proves the approaching of limits.

V. Conclusion

This paper has illustrated the impact of the data reporting rate on DT accuracy. The mechanism for the potential error associated with low data reporting rate has been analyzed. Subsequently, an optimized method to enhance the applicability of DT is introduced and validated by HiL test. Furthermore, data-driven method and physical-based method have been proposed to estimate the minimum requirement of reporting rate for DT-based real-time monitoring applications. The data-driven method for DERs without detailed knowledge of the internal structure has been demonstrated to validate the proposed method in the case study. The outcomes presented in the paper on data reporting rate required for DTs provides valuable learning to support the adoption of DTs and promotes the application of DT for enhancing the visibility of future power systems.

References

[1] T. Wang, D. O'Neill and H. Kamath, "Dynamic Control and Optimization of Distributed Energy Resources in a Microgrid," in IEEE Trans. Smart Grid, vol. 6, no. 6, pp. 2884-2894, Nov. 2015.

[2] S. Patel, K. Murari and S. Kamalasadan, "Distributed Control of Distributed Energy Resources in Active Power Distribution System for Local Power Balance With Optimal Spectral Clustering," in IEEE Trans. Ind. Appl., vol. 58, no. 4, pp. 5395-5408, July-Aug. 2022.

[3] Wei Dai, et al., "Flexibility-enhanced strategies of generations to improve the integration of renewable energy considering uncertainties," Energy Reports, Volume 9, Supplement 7, 2023, Pages 1717-1725.

[4] R. C. Dugan and T. E. McDermott, "Distributed generation," in IEEE Industry Applications Magazine, vol. 8, no. 2, pp. 19-25, March-April 2002.

[5] M. A. Uddin Khan, Q. Hong, A. Dyśko, C. Booth, B. Wang and X. Dong, "Evaluation of Fault Characteristic in Microgrids Dominated by Inverter-Based Distributed Generators with Different Control Strategies," 2019 IEEE 8th International Conference on Advanced Power System Automation and Protection (APAP), Xi'an, China, 2019, pp. 846-849.

[6] N. Bazmohammadi et al., "Microgrid Digital Twins: Concepts, Applications, and Future Trends," in IEEE Access, vol. 10, pp. 2284-2302, 2022.

[7] P. Moutis, O. Alizadeh-Mousavi, "Digital Twin of Distribution Power Transformer for Real-Time Monitoring of Medium Voltage From Low Voltage Measurements," in IEEE Transactions on Power Delivery, vol. 36, no. 4, pp. 1952-1963, Aug. 2021.

[8] M. Zhou, J. Yan and X. Zhou, "Real-time online analysis of power grid," in CSEE Journal of Power and Energy Systems, vol. 6, no. 1, pp. 236-238, March 2020.

[9] Grieves, Michael. (2015). Digital Twin: Manufacturing Excellence through Virtual Factory Replication.

[10] Mohsen Attaran, Bilge Gokhan Celik, "Digital Twin: Benefits, use cases, challenges, and opportunities," Decision Analytics Journal, Volume 6, 2023, 100165.

[11] Fei Tao, Meng Zhang, Yushan Liu, A.Y.C. Nee, "Digital twin driven prognostics and health management for complex equipment, CIRP Annals," Volume 67, Issue 1, 2018, Pages 169-172.

[12] P. Jain, J. Poon, J. P. Singh, C. Spanos, S. R. Sanders and S. K. Panda, "A Digital Twin Approach for Fault Diagnosis in Distributed Photovoltaic Systems," in IEEE Trans. Power Electron, vol. 35, no. 1, pp. 940-956, Jan. 2020.

[13] M. Milton, C. D. L. O, H. L. Ginn and A. Benigni, "Controller-Embeddable Probabilistic Real-Time Digital Twins for Power Electronic Converter Diagnostics," in IEEE Trans. Power Electron, vol. 35, no. 9, pp. 9850-9864, Sept. 2020.

[14] M. Zhou, J. Yan and D. Feng, "Digital twin framework and its application to power grid online analysis," in CSEE Journal of Power and Energy Systems, vol. 5, no. 3, pp. 391-398, Sept. 2019.

[15] J. Han et al., "Cloud-Edge Hosted Digital Twins for Coordinated Control of Distributed Energy Resources," in IEEE Trans. Cloud Computing, pp. 1-15, 2022.

[16] Han, J.; Hong, Q.; Feng, Z.; Syed, M.H.; Burt, G.M.; Booth, C.D. "Design and Implementation of a Real-Time Hardware-in-the-Loop Platform for Prototyping and Testing Digital Twins of Distributed Energy Resources." Energies 2022, 15, 6629.

[17] Q. Hong et al., "A New Load Shedding Scheme With Consideration of Distributed Energy Resources' Active Power Ramping Capability," in IEEE Trans. Power Systems, vol. 37, no. 1, pp. 81-93, Jan. 2022.

[18] B. Barać, M. Krpan, T. Capuder and I. Kuzle, "Modeling and Initialization of a Virtual Synchronous Machine for Power System Fundamental Frequency Simulations," in IEEE Access, vol. 9, pp. 160116-160134, 2021.

[19] F. Gene, J.D. Powell, M.L. Workman, (2022). Digital Control of Dynamic Systems-Third Edition.