

Enhanced Frequency Control in Future
Low-Inertia Power Systems Based on
Digital Twins of Distributed Energy Resources

PhD Thesis

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Abstract

The increasing penetration of converter-interfaced renewable energy sources has fundamentally transformed modern power systems, which results in a dramatic reduction in system inertia and creates urgent challenges for frequency control. Distributed energy resources (DERs), which constitute a major part of emerging power generation, are expected to play a crucial role in supporting frequency regulation in future low-inertia systems. However, their effectiveness remains constrained due to limited visibility, diverse response capabilities, and communication challenges. This thesis investigates the use of Digital Twins (DTs) as an enabling technology to address these issues through providing real-time monitoring and predictive capabilities for DERs, thereby enabling new frequency service dispatch and control schemes for future power systems.

Three DT modelling approaches, i.e. physics-based, system identification-based, and data-driven, are developed and validated, each providing distinct advantages for dynamic representation of DER behaviour. The proposed methodologies consider the model fidelity and efficiency for different applications, and the developed DTs represent the first of their kind to enable real-time representation of DER frequency and active power responses. A method for determining the minimum reporting rate of input signals is also introduced, which ensures accurate DT behaviour under practical operating conditions. In addition, a novel strategy for handling communication delays and jitter is presented, based on sample reordering and timestamp-based linear reconstruction, which significantly improves the robustness of DT-based applications. Case studies are conducted using a hardware-in-the-loop platform, which is specifically designed and established to meet the unique requirements of DT applications. The test results confirm

that DTs can accurately replicate DER dynamics.

A DT-based DER dispatch framework is developed based on these foundations. The CNN-based DTs within aggregators enables system operators to assess the aggregated response of DERs, and identify gap between expected and actual responses in real time. The iterative what-if scenario analysis is performed on the framework and initiate re-dispatch processes to correct shortfalls. Case studies demonstrate that the proposed dispatch framework reduces the risk of under-provision and enhances system resilience under frequency events.

A DT-based coordinated control scheme is proposed to further enhance the frequency control capability of DERs. Both centralised (cloud-hosted) and distributed (edge-hosted) architectures are investigated to address different system and communication requirements. The DTs enable conventional coordinated control of DERs by avoiding communication delay in DERs' dynamics transmission. A series of case studies validate the effectiveness of the approach, showing improvements over conventional control in terms of speed, overshoot, and accuracy of active power responses. The grid frequency is more effectively supported by coordinated DERs, result in an increased frequency nadir during potential events.

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List of Abbreviations

AC	Alternating Current
ADC	Analogue-to-Digital Converter
AGC	Automatic Generation Control
AI	Artificial Intelligence
BESS	Battery Energy Storage Systems
BMU-only	Balancing Mechanism Unit only
CCGT	Combined-Cycle Gas Turbines
CHP	Combined Heat and Power
CNN	Convolutional Neural Network
CVDT	Collaborative Visual Data Twin
DC	Dynamic Containment
DERs	Distributed Energy Resources
DFIG	Doubly-Fed Induction Generator
DM	Dynamic Moderation
DNOs	Distribution Network Operators
DR	Dynamic Regulation
DRRs	Demand Response Resources
DT	Digital Twin
DSA	Dynamic Security Assessment
DSO	Distribution System Operator
EFCC	Enhanced Frequency Control Capability
EFR	Enhanced Frequency Response

List of Abbreviations

ENSIGN	Energy System Digital Twin
EPS	Electric Power System
ESO	Energy System Operator
EU	European Union
ESS	Energy Storage System
FD	Fault Detection
FFR	Fast Frequency Response
FI	Fault Identification
Firm FR	Firm Frequency Response
FPGA	Field-Programmable Gate Array
FRR	Frequency Restoration Reserve
GAST	Gas Turbine
GB	Great Britain
GFC	Grid-Forming Converter
HiL	Hardware-in-the-Loop
IGBTs	Insulated Gate Bipolar Transistors
LFDD	Low-Frequency Demand Disconnection
LFC	Load Frequency Control
LoM	Loss of Main
MAE	Mean Absolute Error
MFR	Mandatory Frequency Response
NASA	National Aeronautics and Space Administration
NDTP	National Digital Twin Programme
NERC	North American Electric Reliability Corporation
NESO	National Energy System Operator
NIST	National Institute of Standards and Technology
OPAL	OPAL-RT Real-Time Simulator
PCB	Printed Circuit Board
PCC	Point of Common Coupling
PHIL	Power Hardware-in-the-Loop

List of Abbreviations

PLL	Phase-Locked Loop
PLM	Product Lifecycle Management
PMSM	Permanent Magnet Synchronous Motors
PMUs	Phasor Measurement Units
PSO	Particle Swarm Optimisation
PSC	Power-Synchronisation Control
PWM	Pulse Width Modulation
PV	Photovoltaic
RES	Renewable Energy Sources
RMSE	Root Mean Square Error
RoCoF	Rate of Change of Frequency
RTDS	Real-Time Digital Simulator
RTS	Real-Time Simulator
SCADA	Supervisory Control and Data Acquisition
SG	Synchronous Generator
SIF	Strategic Innovation Fund
SNR	Signal-to-Noise Ratio
SoC	State of Charge
SPEN	Scottish Power Energy Networks
SQSS	Security and Quality of Supply Standard
TRL	Technology Readiness Level
UDP	User Datagram Protocol
UK	United Kingdom
UKRI	United Kingdom Research and Innovation
US	United States
VSG	Virtual Synchronous Generator
VSM	Virtual Synchronous Machine
WAMS	Wide Area Monitoring Systems
ZOH	Zero-Order Hold

Chapter 1

Introduction

1.1 Research Context

The global energy landscape is under unprecedented transformations, driven primarily by decarbonisation targets aiming at reducing greenhouse gas emissions [1]. The UK government released the Clean Power 2030 Action Plan in December 2024, which outlines the transition to a clean power system by 2030 and serves as the backbone of its net-zero strategy [2]. The action plan focuses on reducing emissions from electricity generation as its primary objective, followed by the displacement of fossil fuels in other sectors, such as transport and heating. This shift is reshaping the energy mix, which has led to a dramatic increase in the penetration of renewable energy sources (RES), e.g. wind and solar, being integrated into the electrical power systems. The increasing share of converter-based renewables not only alters the energy mix but also affects the fundamental dynamics of the grid, with significant implications for the control and stabilisation of system frequency.

Conventional frequency control is centred on large synchronous generators (SGs), which are primarily thermal power plants. These generators are typically equipped with turbine governors that regulate mechanical power input in response to frequency deviations, following the droop characteristic [3]. The rotating machines also store significant kinetic energy in their rotors, which plays a crucial role in limiting the Rate of Change of Frequency (RoCoF) immediately after a disturbance. Compared with

conventional thermal power plants, RES are generally less controllable, and are often intermittent and fluctuating in nature due to their dependency on weather and seasons. Furthermore, most RES, e.g. solar and wind, are connected to the power grid via power electronics converters, which do not inherently provide rotational inertia. As a result, while the ongoing energy transition advances the decarbonisation agenda, it has introduced significant operational challenges due to the dramatic reduction in system inertia across the power grid.

Lower inertia can result in system frequency deviating more rapidly during power imbalance events (e.g. loss of generation or demand), which increases the risk of breaching the statutory frequency limits (e.g. 49.5–50.5 Hz in the GB power system) and raising operational costs [4]. Furthermore, many DERs, embedded in the distribution systems, are equipped with protection systems that monitor the RoCoF for detecting Loss of Main (LoM) events, and they will automatically disconnect from the grid when the measured RoCoF exceeds the predefined thresholds [5]. The decrease of system inertia will result in an increased RoCoF for the same power imbalance event, and it could trigger unexpected tripping of DERs, which leads to cascading failures that further deteriorate the system conditions [6]. According to [7], the minimum system inertia level in the GB system can decrease to 102 GVAs by 2025, from 140 GVAs in 2023. To securely operate the system, National Energy System Operator (NESO), the system operator of the GB transmission system, has to invest millions of pounds to procure effective ancillary services in order to contain the frequency deviation within the required range and limit the RoCoF (e.g. within 0.5Hz/s during a 1800 MW loss, the largest single loss of generation event [8]).

In parallel to the large-scale transformation in the transmission network, future power systems are also featured by the rapid increase of DERs. These include both small scale synchronous generators (e.g. hydro plants and gas turbine based combined heat and power - CHP units) and converter-interfaced sources, e.g. solar, battery energy storage systems (BESS), and wind generation. In GB, around 59% of total distribution-connected capacity is from renewable generation, primarily due to the rapid deployment of PV panels and wind turbines [9]. The capacity of DERs in UK has grown by over 10%

annually between 2013 and 2020 [10], and in the US, the DERs market is considered to nearly double in capacity between 2022 and 2027 [11]. Such a trend is expected to continue in the foreseeable future. Presently, DERs provide limited contribution to the frequency as they are often not visible to the system operator and many DERs' individual capability can not meet the system operator's requirements [10].

The massive changes in power systems as discussed above reveal the following key observations relating to the frequency control: 1) conventional frequency control mechanisms, relying on large thermal plants designed for centralised inertia-rich networks, might no longer be effective and adequate for future low-inertia systems; 2) DERs, due to their rapidly increased volume, have the potential to play an increasingly important role in supporting the overall system, including frequency control; 3) new framework and control solutions are required in order to enable DERs to more effectively participate in the frequency control of future grids.

However, there are several key challenges presented on the use of DERs in supporting the frequency control in current and future power systems:

- **Limited Visibility and Controllability**

DERs are typically dispersed across the distribution networks and are owned by different entities. Due to the cost constraints, most systems lack sufficient measurement devices and communication infrastructures to capture their real-time dynamic behaviour [12]. As a result, system operators often have limited real-time visibility of the DERs' status, location, and general capability in providing frequency control services. Unlike large SGs, the frequency control ancillary services from DERs are often provided via service aggregators. Therefore, it is difficult for the system operators to have direct understanding and control of the behaviours of these DERs. When rolled out at a large scale, the aggregated behaviour might be different from the expectation of the system operators, resulting in the response being ineffective. This lack of observability also compromise the system operators' ability in effectively dispatching the DERs in order to meet the associated technical requirements.

- **Diverse DERs' Dynamic Responses**

DERs can be of different types with very different capabilities in responding to frequency events. For example, hydro plants and gas turbine-based CHP are both synchronous machines, but they have very different responding speed and dynamic characteristics in increasing active power. Converter-interfaced resources can also have very different frequency response behaviour from SGs and among themselves, which is determined by their supplying sources and the internal control algorithms. These control algorithms vary widely between manufacturers and can differ even within the same device class. Some DERs may be configured to provide synthetic inertia [13], while others may follow predefined control strategies such as step changes (e.g. firm frequency response) [14] or ramp-based responses (e.g. dynamic containment (DC)) [15]. Furthermore, many DERs currently remain non-responsive to frequency changes due to limited control capabilities. Even for those that do provide support, leaving each to act independently can lead to fragmented and ineffective system-wide responses. Coordinating a large number of DERs to deliver a unified and reliable frequency response remains a major challenge due to the complexity and infrastructure requirements involved (as further discussed below).

- **Requirements for Measurement and Communications**

Coordinating DERs to provide a fast response for effective frequency regulation may require timely and accurate measurements of the DERs (e.g. real-time active power), along with low-latency communication between DERs and the control centre. This can be very challenging in practice, as many distribution-level assets are currently not equipped with high-resolution measurement devices or reliable communication links. The potential communication performance issues relating to latency and packet loss can also introduce challenges to the coordinated control scheme designed for DERs, which can compromise the effectiveness of the frequency support or even lead to stability issues [16].

- **Operational Integration Challenges**

In many regions, regulatory frameworks and market designs were originally developed for centralised generation and do not readily accommodate DERs. System operators currently lack appropriate tools to assess the frequency support capabilities of DERs and to accurately determine the amount of ancillary service from DERs should be procured. This limits their ability to integrate DERs into system operations in a structured and reliable manner. Addressing this gap requires improved visibility and dynamic monitoring of DERs, and dedicated ancillary service scheduling and dispatch framework.

These emerging challenges highlight the need for innovative solutions that can unlock the visibility of DERs and coordinate their diverse responses in real time, while minimising reliance on communication infrastructure. Such approaches are essential to enable effective frequency response in future low-inertia systems.

Digital twin (DT) is an emerging technology that can provide enhanced monitoring and control of physical systems [17]. They are virtual models of physical objects, systems, or processes, which are coupled with their real-world counterparts by a two-way flow of right-time data [18]. The application of DT can potentially provide real-time visibility of the actual system with limited measurement data. Such visibility can further enable “what-if” simulation and control actions in real time, which can improve the dynamic responses of the physical systems [19]. DT technology has gained significant interests in various industrial sectors, including aerospace, manufacturing, transportation, and healthcare [20–24]. In the energy sector, the combined momentum of decarbonisation and digitisation has accelerated interest in DT applications. While existing studies have explored the role of DTs in power systems, the majority have concentrated on fault diagnosis and grid monitoring, with many other applications still being preliminary stages [25–27].

The key strengths and features of DT technology make it a promising solution for addressing the aforementioned challenges of enabling DERs to deliver effective frequency control services in future power grids. By creating DTs of DERs, system operators can be equipped with tools to accurately capture the real-time dynamics of geographically dispersed resources using only minimal measurements, e.g. frequency, which is

readily available across the system. This approach may significantly reduce the need for extensive communications infrastructures [28]. With appropriate modelling techniques, DTs can enhance system visibility by reconstructing a broader set of dynamic variables for comprehensive monitoring while requiring only a limited set of input data. Moreover, DTs can generate outputs at higher sampling rates than the original source measurements, improving both the temporal resolution and the effectiveness of monitoring and control operations [29]. In addition to improving observability, different modelling strategies (e.g. physics-based and data-driven) are available, which allows the balance of accuracy and computational efficiency to meet the requirements of different targeted applications. DTs can be deployed in real-time, offering live what-if simulation capabilities to support predictive analysis under realistic grid conditions. These features position DTs as a promising solution for facilitating the integration of DERs into low-inertia power systems, and thus they are selected as the key enabling technology investigated in this thesis [30].

1.2 Research Motivations

While DT technology has demonstrated significant potential in enabling DERs to provide effective frequency control and has been successfully applied across various industrial sectors, its applications in power systems remain at a relatively early stage with only limited implementations [31, 32]. The literature reviews presented in Chapters 2 and 3 reveal several important research gaps that motivate this thesis.

As discussed in Chapter 2, frequency control services are becoming increasingly dependent on DERs, however, the existing monitoring and control approaches do not fully capture their dynamic behaviour at the sub-second time scales required for fast frequency response [33, 34]. Chapter 3 shows that the reported applications of DT in power engineering are largely limited to fault diagnosis and system-level monitoring. These implementations typically operate at much longer time scales and do not provide the resolution needed for real-time frequency services. the application of DT in the power sector mainly include fault diagnosis of power electronic equipment and infor-

mation integration across different layers of the energy system [35, 36]. Although these applications offer valuable examples of DT use cases in power systems, they are mainly limited to element-level monitoring or operate at much longer time scales (e.g., minutes) rather than the sub-second resolution required for real-time control.

Several technical challenges must be addressed in order for DTs to be used for enabling DERs in participating effective frequency regulation. These are summarised as follows:

Availability of DTs with appropriate accuracy and resolution to support DER monitoring and control. DTs requires accurate modelling for dynamic tracking and synchronisation between physical hardware and its digital counterpart. The visibility into the internal structure of the physical system plays a key role in selecting suitable modelling approaches. Even when the structure is fully known and all parameters are available, reproducing the detailed physical architecture in a digital environment can be computationally intensive. Such high-fidelity models often conflict with the lightweight implementation and real-time performance requirements of DT-based applications. Therefore, it is essential to create DTs of DERs specifically for supporting frequency control purposes.

The need for real-time data link between physical DERs and their DTs. In addition to modelling, the quality of input signals also has a significant impact on DT performance. Although DTs can reduce the dependence on communications, locally measured inputs are still required to drive computations. It is recognised that accuracy of DT dynamics is positively correlated with reporting rate of inputs [29]. However, achieving a high reporting rate depends on advanced measurement devices and sufficient communication bandwidth. In practical applications, trade-offs must be made between signals resolution and efficiency. Despite its importance, research into identifying the minimum viable sampling rate for reliable DT operation remains limited and insufficiently explored.

Lack of testing and demonstration platform specifically for DT-based applications. Before DTs can be deployed in real-world power systems, their performance must be validated through a staged development process. This typically involves pro-

gressing from offline simulations (e.g. in Simulink) to real-time simulation environments, and ultimately to hardware-in-the-loop (HiL) testing within physical platforms. In the context of power systems, much of the reported work focusses on modelling and applications of DT, and there is a lack of practical frameworks for validating DT performance under realistic hardware and system conditions. To support future deployment, there is a pressing need for practical HiL-based platforms that can evaluate DT behaviour in real time under realistic system conditions. Such platforms would help assess model performance, verify dynamic responses, and improve the technology readiness level of DTs in power system applications.

Lack of control schemes for coordinating DERs in real time using DTs.

Individual DERs may not be able to deliver the level of dynamic performance required by system operators. However, by coordinating multiple DERs, for example, allowing faster-responding units to support slower ones, the overall system response can become sufficiently effective. This coordination enables large numbers of DERs to collectively provide frequency control services. There are existing schemes [37,38], but are economically costly and also affected by communication delays. Despite its significant potential to unlock these capabilities, research into DT-based framework for dispatch DERs and real-time control an remains very limited.

Given the challenges outlined above, this thesis presents a comprehensive investigation into the the use of DTs as the enabling technology to address these issues. By creating DTs that are capable of providing real-time monitoring and predictive capabilities for DERs, this research aims to establish new frequency service dispatch and control schemes that enables DERs to provide effective frequency control services for future low-inertia systems.

1.3 Principal Contributions

The core contributions of this work to knowledge are the following:

- Creation and validation of three modelling approaches for DTs of DERs, i.e. physics-based, system identification-based and data-driven modelling, for real-

time monitoring and frequency control purposes. These approaches advance understanding of the trade-off between modelling precision and overall DT system performance in frequency control applications.

- Design of a DT-based DER dispatch platform that enables more accurate estimation of the DER capacity required for participation in frequency control ancillary services. The platform supports real-time execution of what-if scenarios, ensuring that the dynamic response capabilities of DERs are considered when determining ancillary service requirements. It also provides system operators with a valuable tool to assess and enhance the effectiveness of ancillary services during severe frequency events.
- Development of a coordinated control scheme for DERs by utilising the advanced capabilities of DT technology. By strategically hosting DTs across cloud and edge environments, the proposed control scheme coordinates DERs with diverse characteristics to provide effective frequency control, while mitigating the impacts of communication constraints.
- Establishment of a method to determine the minimum reporting rate of input signals required to preserve the dynamic fidelity of digital twins (DTs). This work provides new insights into how measurement resolution supports reliable DT-based systems. A complementary method is also developed to mitigate communication delays and jitter in DT environments. By applying sample reordering and timestamp-based linear reconstruction techniques, the approach enhances the adaptability and resilience of DT-enabled applications under unstable communication conditions.
- Design of a hardware-in-the-loop (HiL) platform specifically for validating the performance of DTs and DT-based applications, including monitoring, what-if analysis, and frequency control. This environment creates a new platform for accelerating DT integration into power systems by enabling robust pre-implementation testing.

1.4 Thesis Overviews

The structure of this thesis is shown in Figure 1.1 and organised as follows:

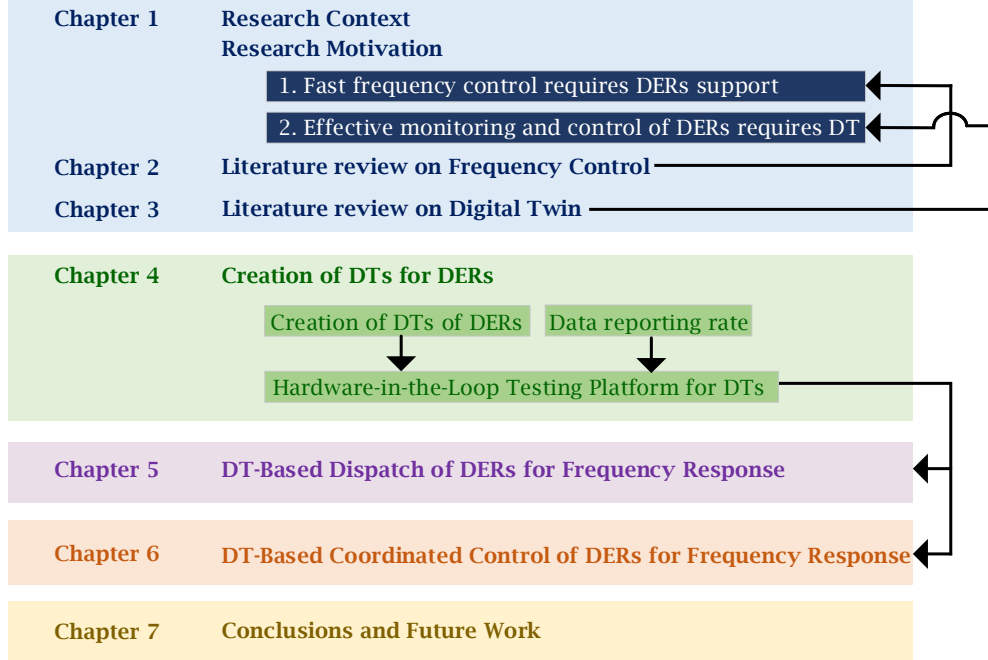


Figure 1.1: The structure of thesis

- Chapter 2 presents a literature review on frequency control, beginning with the fundamental requirements of frequency regulation and the operation of conventional control schemes, including primary, secondary, and tertiary frequency responses. The discussion then shifts to the challenges posed by low-inertia power systems, highlighting the increasing need for faster response mechanisms. In this context, fast frequency response and new dynamic services such as DC are examined in detail. The chapter also reviews recent research on enabling DERs to participate in frequency control, covering both DC and novel DER control strategies for rapid system support.
- Chapter 3 provides a literature review on DT technology, beginning with the evolution of the DT concept and a survey of applications across different industries. The discussion then narrows to power systems, where DTs have been applied to

areas, e.g. asset health monitoring, measurement and parameter estimation, fault diagnosis, grid management and operation, risk and resilience, and the testing of protection schemes. The chapter then examines research gaps in current DT studies, focusing on high-fidelity modelling of DERs, operational DER dispatch frameworks, DT-based coordinated control, and validation under practical constraints. Industrial implementations of DTs in the power sector are also discussed, including typical system architectures and examples.

- Chapter 4 addresses the creation, modelling, and prototyping of DTs of DERs, along with their validation through hardware-in-the-loop (HiL) testing. It begins by introducing the modelling of DTs, which outlines the selection of modelling techniques and presenting three complementary approaches: physics-based models, system identification methods, and data-driven models. The chapter then investigates the minimum data reporting rate required to preserve DT fidelity, including methods to mitigate distortions caused by limited measurement resolution. Following this, the design and implementation of the DT HiL testing platform are described, covering the representation of physical DERs, the execution and hosting of DTs, and the emulation of communication networks with delay, jitter, and protocol effects. The integration of measurement processes and DT-enabled services within the platform are also detailed. Finally, case studies based on HiL simulations validate the developed DTs by assessing their real-time tracking capability and evaluating the impact of communication delays and jitter on performance.
- Chapter 5 presents the use of DTs for real-time monitoring and dispatch of DERs in frequency response. It highlights the limitations of current offline approaches and introduces a DT-based framework that uses live what-if simulations to capture actual DER capabilities. The framework combines system-level frequency trajectory modelling with aggregator-hosted DTs, employing data-driven methods for accurate and efficient response estimation. Case studies demonstrate how DTs improve frequency stability assessment by revealing delivery shortfalls, updating

frequency trajectories, and enabling rapid re-dispatch.

- Chapter 6 introduces a DT-based coordinated control of DERs. It begins with a review of conventional coordinated control methods, including both centralised and distributed implementations, and highlights their strengths and limitations in improving local and global response. Based on this, the chapter introduces a proposed DT-based implementation of coordinated control, which include both centralised and distributed approaches. Case studies are conducted to assess the DT-based coordinated control approach to demonstrate its effectiveness in enhancing the DERs frequency control effectiveness.
- Chapter 7 summarises the contributions of this thesis and discusses potential directions for future research, focusing on the wider application of the DTs in supporting the operation of future power and energy systems.

1.5 Publications

The following publications have resulted from the work reported in this thesis:

List of Journal Papers

- **J. Han**, Q. Hong, M. H. Syed, M. A. U. Khan, G. Yang, G. Burt & C. Booth, "Cloud-Edge Hosted Digital Twins for Coordinated Control of Distributed Energy Resources," in *IEEE Transactions on Cloud Computing*, vol. 11, no. 2, pp. 1242-1256, 1 April-June 2023, doi: 10.1109/TCC.2022.3191837.
- **J. Han**, Q. Hong, Z. Feng, M. H. Syed, G. Burt & C. Booth, "Design and Implementation of a Real-Time Hardware-in-the-Loop Platform for Prototyping and Testing Digital Twins of Distributed Energy Resources." in *Energies*, vol. 15, no. 18, pp. 6629, 10 September 2022, doi: 10.3390/en15186629.

List of Conference Papers

- **J. Han**, Q. Hong, Z. Feng, G. Burt & C. Booth, "Digital Twins of Distributed Energy Resources for Real-Time Monitoring: Data Reporting Rate Considerations," *IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, Singapore, 2023, pp. 1-7, doi: 10.1109/IECON51785.2023.10312555.
- M. R. Jamieson, Q. Hong, **J. Han**, S. Paladhi and C. Booth, "Digital twin-based real-time assessment of resilience in microgrids," *11th International Conference on Renewable Power Generation - Meeting net zero carbon (RPG 2022)*, Hybrid Conference, London, UK, 2022, pp. 213-217, doi: 10.1049/icp.2022.1826.

Candidate's contribution: responsible for establishing the communication channel, and integrating the database.

- L. Shen, Q. Hong, **J. Han**, J. Wang and C. Booth, "Real-Time Estimation of Power Imbalance During Contingency Events: A Data Driven Approach," *IEEE Power & Energy Society (PES) Innovative Smart Grid Technologies (ISGT) Europe 2025*.

Candidate's contribution: responsible for building the hardware platform, establishing the communication channel, and integrating the database.

Chapter 2

Literature Review on Frequency Control

This chapter provides a comprehensive review of the fundamentals of frequency control in power systems, along with the state of the art research and development activities with a focus on low-inertia power systems with high penetration of RES. The chapter is organised as follows. Section 2.1 introduces the role of frequency control in power system operation and the typical requirements. Section 2.2 presents the conventional approach adopted in SG-dominated power systems for frequency control, including primary, secondary, and tertiary responses. Section 2.3 examines emerging frequency control techniques and strategies for low-inertia systems, which includes a discussion of the need for faster response services, followed by a review of fast frequency response (FFR) schemes. This covers the various FFR schemes that has been trialled and deployed in the GB transmission system. It also introduce the device-level control strategies developed for DERs to provide frequency control. The chapter concludes by identifying limitations of existing approaches and outlining research gaps relevant to this research presented in this thesis.

2.1 Need for Frequency Control and its Requirements

The electric power system converts primary energy sources, both renewable and fossil fuel, into electrical energy and transports it to the point of consumption. The generation and demand have to be balanced in real time in order to maintain the overall system stability. In an AC network, frequency is the indicator of active power balance, so it is critical to have effective control of frequency to ensure the secure operation of power systems.

Frequency stability refers to the power system's capability to maintain a steady frequency after a significant disturbance that causes a substantial active power imbalance between generation and demand [39]. Sudden large power imbalances (e.g. those caused by the loss of generation or demand) can result in severe deviations in system frequency. These deviations may trigger multiple adverse consequences. For instance, if the frequency drops below a critical threshold, a portion of the demand will be automatically disconnected through Low-Frequency Demand Disconnection (LFDD) to prevent further frequency decrease [40, 41]. Conventional synchronous machines and certain types of loads are designed to operate only within a specific frequency range, so if the frequency deviates beyond this range, these machines and devices may be damaged or automatically disconnected from the system for self-protection [42, 43]. Moreover, a large single loss event may produce a high RoCoF, potentially triggering protection in DERs via RoCoF-based LoM protection relays, which can further deteriorate the system condition due to the additional reduction in active power generation. Power systems are generally not designed to cope with such cascaded failures, so these events can lead to severe consequences including partial or even full system blackouts [44].

The Security and Quality of Supply Standard (SQSS) is the technical standard governing the planning and operation of the GB transmission system, which sets out the criteria to ensure reliable supply, including requirements for reserved capacity, system inertia, and operational margins [45]. In relation to frequency control, the SQSS specifies that the system must be capable of withstanding the single largest credible loss without breaching statutory frequency limits. For the GB power system, this is currently

defined as the sudden loss of 1800 MW of generation. According to recommendation, frequency deviations caused by single Balancing Mechanism Unit (BMU) events should be contained within the range of 49.2–50.5 Hz [8]. Additionally, the statutory operational frequency range is 49.5–50.5 Hz, with a normal operational target to maintain frequency within 49.8–50.2 Hz under standard operating conditions.

2.2 Conventional Frequency Control Schemes

To meet frequency control requirements, power systems worldwide, including the GB power system, traditionally adopted a three-stage frequency control framework. Large transmission-connected generators and power park modules above 50 MW are required to be capable of delivering Mandatory Frequency Response (MFR) upon request [46,47]. MFR ensures that sufficient capacity is available to deliver the initial stages of frequency control, as illustrated in Figure 2.1 and described below:

- **Primary response:** from a few seconds up to 30 seconds. This is the first line of defence, which is designed to act almost immediately after a disturbance (although there will be a delay in response due to inherent capability of responding generation units). Its purpose is to arrest the initial frequency deviation and stabilize the system in the very short term [48].
- **Secondary response:** from 30 seconds up to 30 minutes. Once the system frequency is stabilised, the secondary response will take over. Its main role is to restore frequency to its nominal value and release the primary response resources [49].
- **Tertiary response:** from 15 minutes up to several hours. This is the longer-term adjustment, which focuses on re-optimising generation scheduling and ensuring that adequate reserves are available to handle potential future events with consideration of economic factors [50].

These stages are discussed in detail in the following subsections, which outline their

operating principles, practical implementations using the GB power system as the example, and evolving technical requirements.

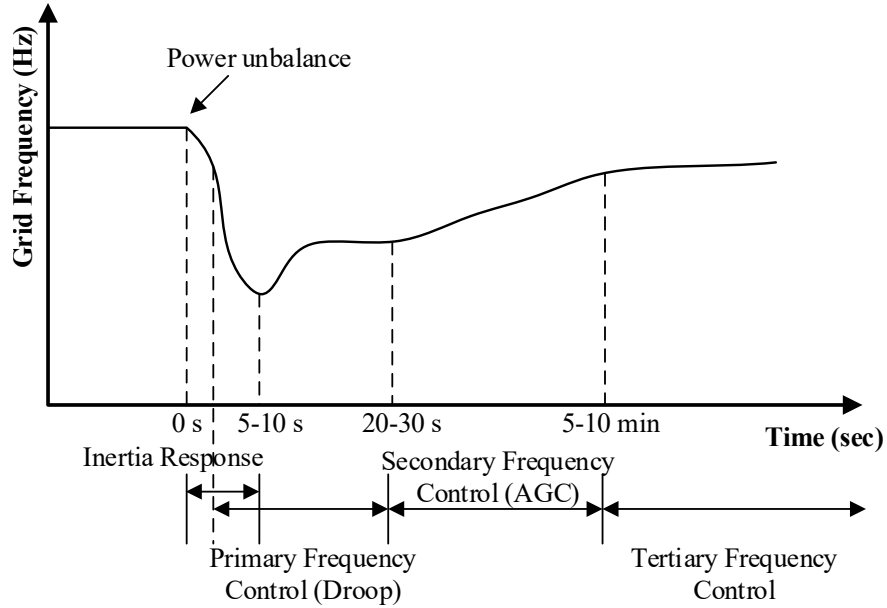


Figure 2.1: Conventional frequency control framework by timescale in response to a power imbalance event [51]

2.2.1 Primary Frequency Response

Primary frequency control is the first layer of response after a frequency disturbance. In the GB system, it is triggered automatically by the speed governors of SGs when the frequency deviates beyond a deadband, which is typically set as ± 0.015 Hz [52]. The response is required to reach full output within 10 s and sustain for up to 30 s [53]. In Europe, the response delivery time is typically 0–30 s with a ± 0.02 Hz deadband, while in North America it is often set as 0–16 s with ± 0.017 - 0.036 Hz deadbands [54–56]. As highlighted previously, the objective of primary response is to contain the initial frequency deviation and stabilise it at a quasi-steady-state value, preventing further decline or rise that could trigger load shedding or generator tripping.

Primary response is typically realised by a control scheme that adjust power output to be proportional to the frequency deviation using a droop characteristic as illustrated in Figure 2.2. During under-frequency events, i.e. the system demand is greater than

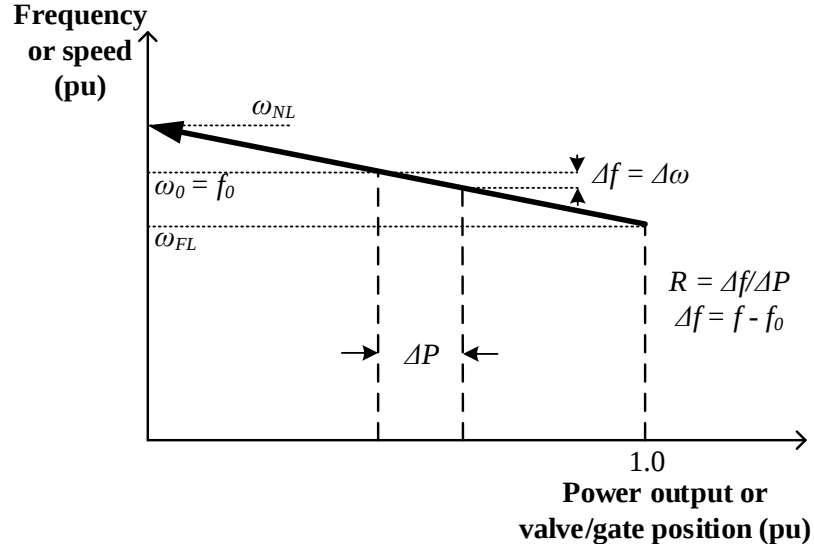


Figure 2.2: Droop characteristic of a governor [50]

generation, the power output of a generator P will increase as the system frequency f (thus its rotor speed ω) decreases. In contrast, the generator will decrease its active power during over-frequency events to rebalance the system generation and demand. In multi-generator systems, droop control enables proportional load sharing, i.e. generators with larger capacity will take a larger share of the load [57]. If sufficient reserve is in place, the total change in output from all participating generators will compensate the active power imbalance in the system. Typically, the droop is set to be in the range of 3-5% [58].

In the GB power system, only a sub-set of generators contracted to provide frequency control ancillary services are designated as frequency-sensitive. Other generation units, such as baseload nuclear or thermal generators, operate in non-frequency-sensitive mode [46]. The system operator (i.e. NESO) procures the primary response through ancillary services markets to satisfy SQSS requirements for the largest credible loss, which is currently 1800 MW [59].

The primary response was conventionally provided by SGs and it was effective when the system was dominated by SGs with a relatively high inertia level. Figure 2.3 illustrates a block diagram of a standard turbine governor model.

Such primary responses provided by SGs have been effective for many years due

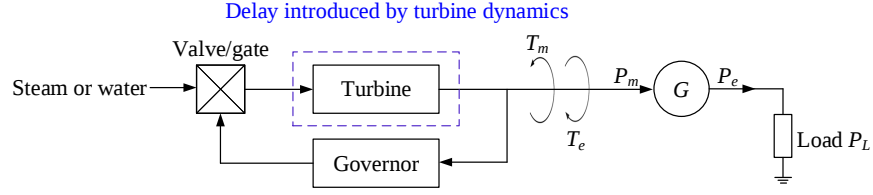


Figure 2.3: Block diagram of a standard turbine governor model [50]

to the relatively high system inertia, where the frequency deviation can be contained within the requirement despite the delay in turbine governors. However, it faces critical limitations in systems with dramatic decrease in system inertia, due to its slow responding speed not being adequate in containing the frequency deviation. Therefore, new frequency control (often referred to as fast frequency control) is being increasingly implemented in many countries, which will be discussed in detail in Section 2.3 in this chapter.

2.2.2 Secondary Frequency Response

Secondary frequency response represents the second layer of frequency control, operating after primary response has stabilised the system frequency at a new steady state. If there is only primary control in operation, a change in system load will result in a steady-state frequency deviation determined by the governor droop setting and the frequency sensitivity of the load. All generating units operating in frequency-sensitive mode contribute to the aggregate change in generation, regardless of where the load change occurs. The main objective of secondary frequency control is to restore the grid frequency to its nominal value and maintain scheduled power exchanges between controlled areas. It is typically triggered automatically through Automatic Generation Control (AGC), while manual dispatch is instructed if the frequency remains outside the normal operating range [60]. Secondary control removes the steady state frequency deviation by adjusting the load reference set-points of selected generating units, either automatically via AGC or manually by operators, so that generation precisely matches system load at the nominal frequency. AGC continuously monitors frequency and sends set-point adjustments to participating units as shown in Figure 2.4. This process is also

known as load frequency control (LFC).

In the GB system, secondary response must reach full delivery within 30 seconds and be sustained for up to 30 minutes [53]. The main difference between GB and Europe on secondary control is that AGC is not applied in GB. In GB, secondary response is delivered through contracted providers instructed by the system operator, relying on market-based procurement and scheduled control actions. In Europe, secondary response is provided as Frequency Restoration Reserve (FRR) through AGC, which is activated within a few minutes and maintains full output for around 15 minutes [54]. In the United States, NERC defines secondary control as balancing services on a timescale of minutes, although some resources, e.g. hydro generation and fast electrical storage, can respond faster [61].

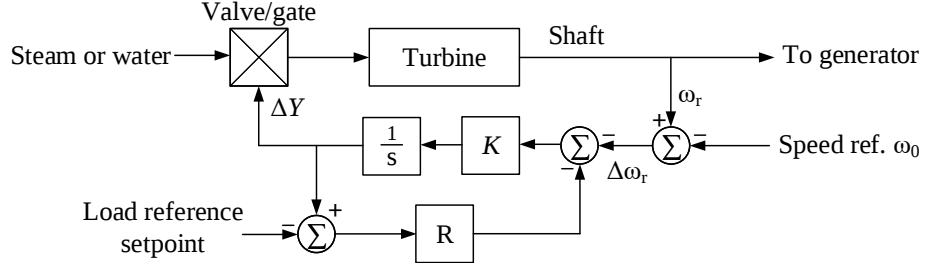


Figure 2.4: Control on generating units selected for AGC [50]

Another objective of secondary response is to reallocate the required change in generation across units in a manner that restores system frequency and scheduled power exchanges between areas. Unlike primary frequency response, secondary response is centrally coordinated by the system operator and relies on communication infrastructures. It is typically provided by medium- and flexible-ramping generation, e.g. pumped-storage hydro, and demand-side resources, that are unable to respond within the first few seconds but can sustain output over time [62]. The increasing share of RES raises variability and uncertainty in system balancing, resulting in more frequent AGC set-point adjustments in secondary control [63].

2.2.3 Tertiary Frequency Response

Tertiary frequency control generally refers to slower, manual adjustment of generation and demand to replace secondary reserves and restore system margins after a disturbance has been contained. While this category is widely in textbooks [50] and in some international operational frameworks [54], it is not included as a formal reserve category in the GB operational practice [64]. Instead, its functions are carried out through balancing actions in the balancing mechanism and through replacement reserve products procured closer to real time [65].

In the literature, the concept is sometimes described as grid-level balancing control, where power plant secondary controls are supervised by transmission-level balancing actions [48]. These range from automated feedback loops in AGC systems to manual operator interventions at dispatch centres.

Despite differences in terminology across Europe, many countries continue to include the tertiary reserve category in their operational frameworks. In Ireland, Tertiary Operating Reserve is divided into two bands with Band 1 being available and sustainable from 90 seconds to 5 minutes after an event; and Band 2 being from 5 minutes to 20 minutes [66]. In France and Italy, tertiary control can be activated during secondary control but can be sustained for no longer than 15 minutes [66]. In both cases, tertiary control is recognised as a separate stage of system operation, aimed at manual re-dispatch and reserve restoration within a time frame ranging from a few minutes up to several hours.

Although the GB system does not explicitly defines a tertiary control category, the function remains essential for restoring reserve capacity and re-optimising generation following a disturbance. With the evolving generation mix, these balancing actions are expected to rely on a wider range of resources, including DERs. Consequently, the potential contribution of DERs to future frequency control frameworks is emerging as a critical area of focus.

2.3 Frequency Control for Low-inertia Power Systems

2.3.1 Need for Faster Frequency Control in Low-Inertia Systems

In power systems, the system inertia refers to the rotational kinetic energy stored in synchronously connected machines, which acts to slow the RoCoF following a disturbance [67, 68]. If the entire power system is represented by an equivalent synchronous machine with an aggregated inertia, the inertia constant H in s is defined as the ratio of stored rotational kinetic energy E_{kin} in $GVA \cdot s$ at rated speed ω_0 in rad/s to the system rated apparent power S_{base} in GW :

$$H = \frac{E_{kin}}{S_{base}} = \frac{\frac{1}{2}J\omega_0^2}{S_{base}} \quad (2.1)$$

In the initial moments following a disturbance (neglecting damping and governor actions), the electrical-mechanical power imbalance ΔP is equal to the rate of change of kinetic energy:

$$\Delta P = \frac{dE_k}{dt} = J\omega \frac{d\omega}{dt} \quad (2.2)$$

In Equation (2.2), $\frac{d\omega}{dt}$ is the rate of change of angular speed. Using Equation (2.1) and (2.2), the relationship between $\frac{d\omega}{dt}$ and system inertia can be yielded:

$$\frac{d\omega}{dt} = \frac{\Delta P}{J\omega_0} = \frac{\Delta P \omega_0}{2HS_{base}} \quad (2.3)$$

By converting angular speed to frequency ($\omega = 2\pi f$), the RoCoF in Hz/s is:

$$\frac{df}{dt} = \frac{f_0}{2HS_{base}} \Delta P \quad (2.4)$$

$$RoCoF = \frac{f_0}{2H} \Delta P_{pu} \quad (2.5)$$

where f_0 is nominal grid frequency and ΔP_{pu} is the power imbalance in per unit based on the system base.

From Equation (2.5), it is obviously that for the same power imbalance, a lower

system inertia H will result in a higher initial RoCoF, which will lead to frequency deviating faster during disturbance. The combination of the reduced overall system inertia and the more fluctuating power outputs from RES both contribute to the reduced system frequency stability, which presents the need for faster and more effective frequency control schemes.

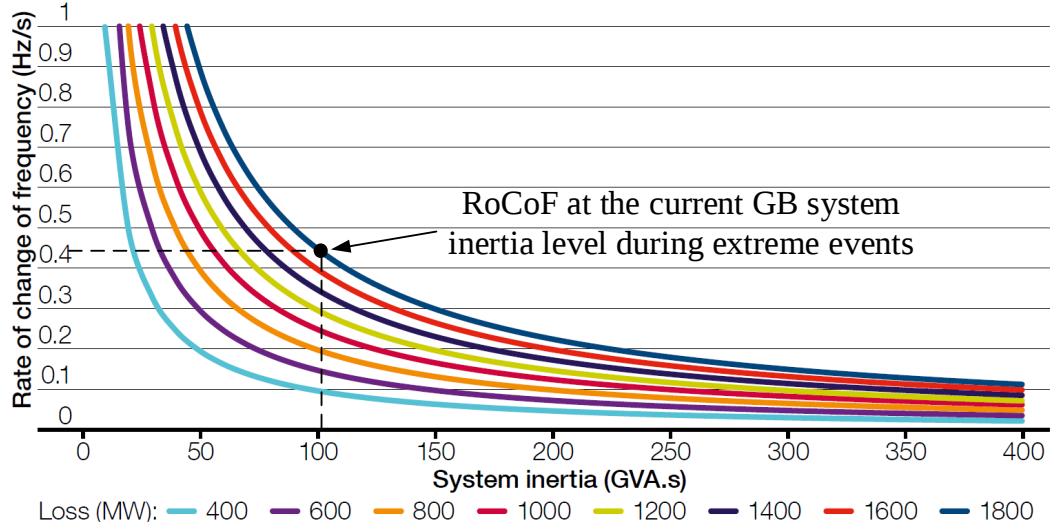


Figure 2.5: Instantaneous absolute RoCoF on different inertia level [68]

Figure 2.5 shows the instantaneous absolute RoCoF magnitude as a function of system inertia for various generation loss sizes. The curves follow the inverse relationship, as also illustrated in Equation (2.5), i.e. larger power imbalances or smaller inertia lead to higher RoCoF values. According to the figure, NESO's target of keeping RoCoF within 0.5 Hz/s for a single 1800 MW loss can be met under these conditions. However, the RoCoF is still dramatically higher than the conventional system, where RoCoF was typically controlled within 0.125 Hz/s [69].

The NESO's Future Energy Scenarios project a continued decline in GB system inertia under all transition pathways, as illustrated in Figure 2.6. Historic operational records and projections indicate that system inertia, which averaged above 180 GVA.s in 2021, is expected to fall toward 125 GVA.s by the early 2030s. Recent operational data further show that instantaneous system inertia has already dropped to approximately 102 GVA.s during minimum demand periods in 2024 [59].

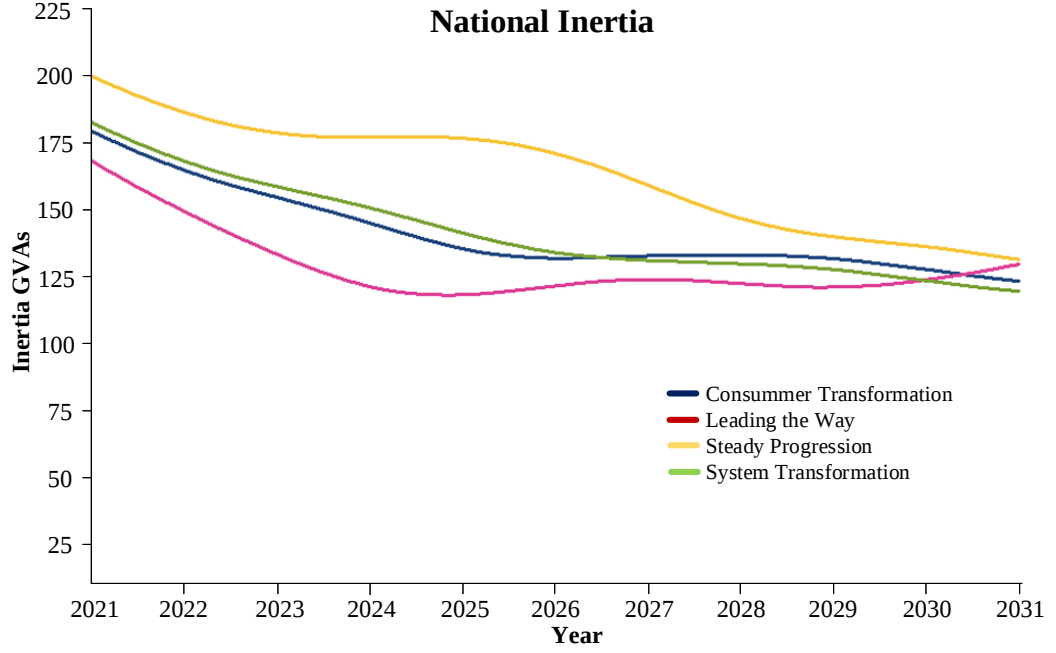


Figure 2.6: Decline of GB system inertia under the four future energy scenarios [68]

In the GB power system, frequency volatility has emerged an significant operational concern. Both the number of frequency excursions and the standard deviation increased sharply in 2017–2018, despite the system inertia remaining relatively stable during that period [70]. In 2018, the system experienced 5.45 events per day on average in which frequency deviated by more than ± 0.2 Hz from the nominal value [71]. This trend highlights the growing need for faster-acting ancillary services specifically designed to maintain frequency stability under low-inertia conditions.

2.3.2 Industry Practices in Frequency Control for Low-Inertia Systems

Fast Frequency Response

Fast Frequency Response (FFR) refers to the rapid injection or absorption of active power by controllable resources to arrest frequency deviation following a disturbance [72]. Although the term lacks a universally strict definition, it is generally used

to describe frequency response that is faster than the conventional primary response provided by SGs' turbine governors. FFR typically activates within 2 seconds of detecting a deviation, thereby complementing slower conventional primary controls [62, 73, 74]. In the GB power system, FFR has been procured from various sources, including battery energy storage systems (BESS), demand-side response, and other aggregated resources. Over time, the UK's FFR framework has evolved, transitioning from the original Firm Frequency Response (Firm FR) scheme to the current suite of Dynamic Response Services [75].

Firm Frequency Response (Firm FR) Firm FR was the commercial service procured by NESO to maintain system frequency within the statutory limits [76]. It required contracted providers to deliver active power adjustments in response to frequency deviations, with two delivery modes:

- **Static Firm FR**

- Only secondary response was procured.
- Must start within 30 seconds and sustain delivery for 30 minutes.
- Fixed output (static) triggered when frequency crosses predefined thresholds.

- **Dynamic Firm FR**

- Could be contracted to provide one or more response bands:
 - * **Primary** — Start within 2 seconds, full delivery by 10 seconds, sustained for 20 seconds.
 - * **Secondary** — Must start within 30 seconds, sustained for 30 minutes.
 - * **High** — Must start within 10 seconds, sustained indefinitely unless otherwise agreed.
- Droop-based continuous adjustment of power output.
- Deadband settings: wide band (± 50 mHz) or narrow band (± 15 mHz).

Firm FR was open to a range of technologies, including BESS, pumped hydro, fast-ramping thermal units, and demand-side response, with a minimum capacity threshold

of 1 MW (aggregation permitted). The delivery profile, including ramp rate and magnitude, was fixed within the contract, and the procurement was conducted through monthly tenders with pre-qualification.

As system inertia declined, the limitations of Firm FR became increasingly apparent. Its fixed trigger thresholds, inflexible delivery profiles, and relatively long procurement cycles limited its effectiveness in addressing high RoCoF events. These shortcomings led to the development of a new suite of dynamic frequency response services, which are designed to provide faster, more flexible, and continuously active control.

Enhanced Frequency Response (EFR) EFR was introduced by National Grid ESO (now NESO, thus used in the rest of the thesis to refer to the GB system operator) in 2016 as an ultra-fast ancillary service designed to complement the existing Firm FR [77]. As shown in Figure 2.7, Firm FR delivers full response within 10 s, whereas EFR achieves full activation in approximately 1 s. The specification requires the combined detection and instruction stages to be completed within 500 ms, followed by a rapid ramp to the contracted output. EFR was primarily targeted at converter-interfaced technologies, particularly BESS, due to their ability to deliver rapid and precise power modulation.

The service was procured through a one-off 200 MW tender, with four-year contracts awarded to successful providers. Unlike Firm FR, which had a minimum entry threshold of 1 MW with aggregation permitted, EFR was a pilot scheme to test large-scale ultra-fast response capability. This higher threshold was intended to validate both the technical performance and commercial viability of continuous sub-second frequency response before broader market integration.

EFR is provided through continuous droop-based control within an envelope that defines upper and lower output bounds, with a zero-output deadband between reference points C and D as shown in Figure 2.8 to facilitate state-of-charge management. Delivery must be maintained at 100% of contracted capacity for at least 15 minutes, which is a duration selected to bridge the time until slower-acting reserves can respond without imposing the additional cost of longer delivery times. Frequencies outside 50 ± 0.25 Hz are treated as frequency events and must follow the exact delivery profile, while those

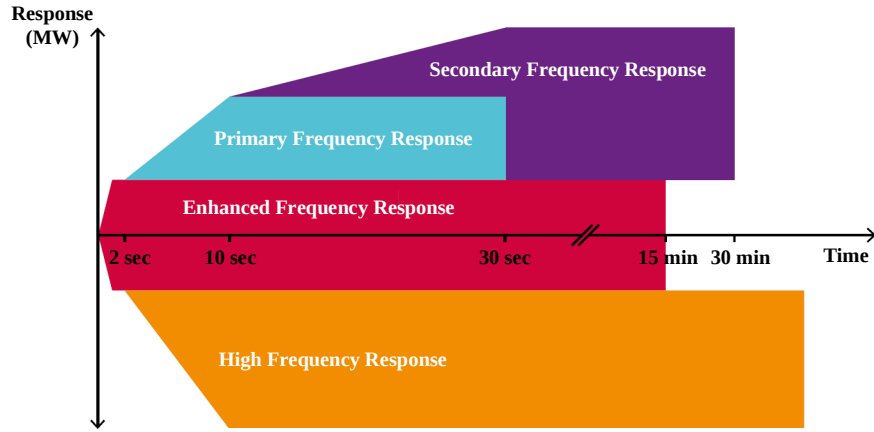


Figure 2.7: Conceptual timing of enhanced frequency control response [68]

within this range are subject to a more flexible envelope. Full EFR delivery is only required when the system frequency deviation is ≥ 0.5 Hz from nominal (i.e., outside 49.5–50.5 Hz), which is configured to balance the benefit of system with cost of provider. Output may vary within $\pm 9\%$ of capacity to allow operational flexibility without significantly affecting performance. Two insensitivity band options are available: a narrow band of 50 ± 0.015 Hz for high-inertia conditions to ensure precise control, and a wider band of 50 ± 0.05 Hz for low-inertia periods with potentially higher RoCoF. Service provision is restricted during the EFR delivery window if other activities could affect performance, although participation in other markets is allowed outside that period.

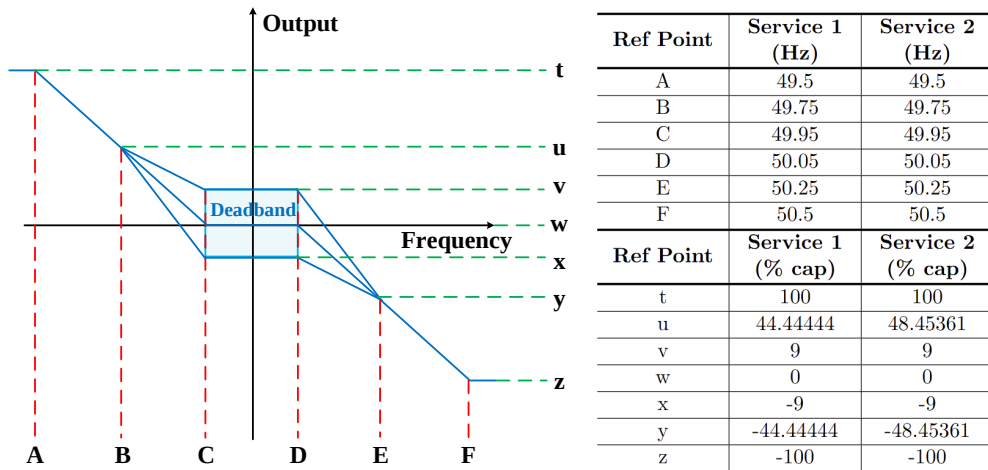


Figure 2.8: Enhance frequency response envelope [78]

Building on the technical principles demonstrated in EFR, the Enhanced Frequency Control Capability (EFCC) project was initiated by NESO in 2016, which is designed to further improve the speed and accuracy of frequency response in a low-inertia system [79]. Traditional Firm FR services is contracted centrally by NESO, but the response is automatic and decentralised, which triggered directly by deviations in locally measured system frequency. This delays the activation of contracted resources, making it harder to contain high RoCoF events. As discussed previously, EFR considered the system frequency as an uniform value during disturbances, and did not take into account the locational impact of power imbalance event when initiating frequency responses. In contrast, EFCC introduced a high-speed monitoring and control architecture based on Wide Area Monitoring Systems (WAMS) and Phasor Measurement Units (PMUs). These devices capture high-resolution phasor and frequency data across the network, enabling fast detection and location of frequency disturbances [80]. A distributed control approach was adopted, where PMU data were processed locally and regionally to identify events and trigger participating assets such as BESS, demand-side response units, and fast-ramping generation within hundreds of milliseconds. The response is proportional to the size of the event, which is estimated by the measured RoCoF and system inertia. The location of the power event is estimated based on comparing the phase angle change during the disturbance across the network, based on which the resources that are closest to the event will be prioritise for response. Test results demonstrated that EFCC could successfully deliver sub-second response, increasing frequency nadir following major events with the same amount of reserve. Although it remained a pilot rather than a commercial product, EFCC's key concepts of continuous measurement, rapid trigger logic, and decentralised activation influenced the design of the subsequent Dynamic Response Services.

New Dynamic Response Services

Since 2020, NESO has introduced new dynamic response services to replace Firm FR and EFR. These services deliver continuous, rapid, and proportionally controlled active power adjustments in response to system frequency deviations. The services, as illus-

trated in Figure 2.9, include Dynamic Containment (DC), Dynamic Regulation (DR), and Dynamic Moderation (DM), which address different phases of frequency stability management and operate under a unified procurement and performance framework [81]. The service designs incorporate lessons from previous fast-frequency response initiatives, including EFR and EFCC, while adopting more flexible procurement cycles, broader eligibility for distributed and aggregated assets, and tighter performance requirements aligned with low-inertia operational needs.

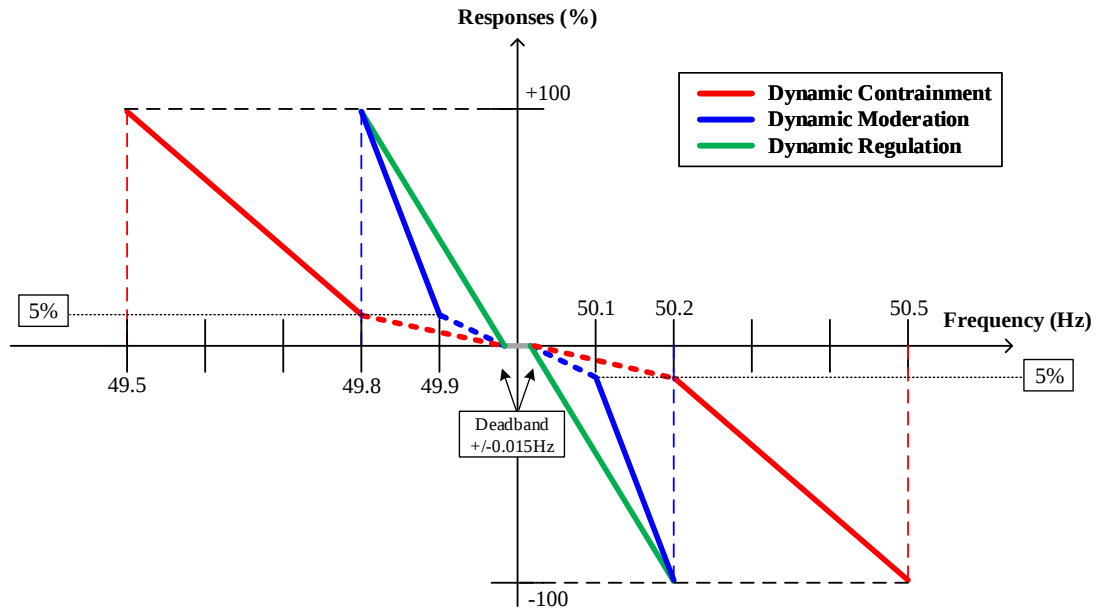


Figure 2.9: Control characteristics of GB dynamic response services: DC, DR, DM [81]

Dynamic Containment (DC) DC is the fastest service of the new dynamic response services, introduced in 2020 to provide immediate post-fault containment of system frequency [81]. It was designed to arrest high RoCoF events and reduce maximum frequency deviation following large generation or demand imbalances, particularly under low-inertia conditions.

DC is procured through daily auctions, with contracts awarded for delivery in 24-hour blocks [82]. The service is technology-neutral and open to aggregated resources, although BESS currently provide the majority of capacity due to their ability to meet the speed and precision requirements [75]. Providers must begin response within 0.5 s of

a triggering event and achieve full delivery in less than 1 s. Delivery is proportional to frequency deviation according to a specified droop setting and must be sustained for at least 15 minutes or until NESO issues a stop instruction. The permitted operating range is typically ± 0.5 Hz from nominal, and the delivery profile is defined in the service terms to ensure consistent performance. Compliance is monitored through metering data and subject to performance assessment, with penalties applied for deviations beyond the allowed tolerance. The detailed technical specification is provided in Table 2.1.

Table 2.1: Key technical parameters of Dynamic Containment (DC) [81, 82]

Parameter	Specification
Service type	Post-fault dynamic frequency containment
Initiation time	<0.5 s from trigger
Full delivery time	<1 s from trigger
Sustain duration	At least 15 minutes or until National Grid ESO stop instruction
Control mode	Continuous proportional control (droop-based with a slope of 0.6%)
Operating frequency range	within ± 0.5 Hz from nominal
Tolerance	Performance assessed with allowed deviation bounds
Procurement cycle	Daily auctions in 24-hour blocks
Eligibility	Technology-neutral; open to aggregated resources
Typical providers	Battery energy storage systems, pumped hydro, demand-side response

In the initial soft launch in September 2020, two battery storage projects with 90 MW were contracted for continuous operation, with capacity increasing to 165 MW in subsequent tenders. NESO set a medium-term target of 500 MW and signalled that total capacity could exceed 1 GW as more providers entered the market. By March 2023, operational protocols required providers to accept start and stop instructions in real time, transmit “heartbeat” readiness signals every five minutes, and submit forecasts of expected import or export behaviour. These measures supported more accurate system balancing and reduced the risk of non-delivery during critical events.

Dynamic Moderation: DM addresses frequency deviations that are significant

but not caused by identifiable faults. These include sudden but non-critical changes in generation or demand, often associated with variable renewable output. DM operates as a pre-fault service, activating when frequency begins to drift towards operational boundaries, i.e. 49.8 Hz and 50.2 Hz. It is characterised by a rapid response similar to DC (full response within one second) but is intended for more moderate deviations.

DM acts as a stabilising buffer during normal operation, providing additional support during periods of high variability or forecast uncertainty. Providers of DM are required to sustain their response for up to 30 minutes, which reflects its role in covering extended disturbances that do not necessitate full post-fault intervention. The service plays a critical role in preventing minor imbalances from escalating into significant frequency events.

Dynamic Regulation: DR is designed to provide continuous, fine-grained frequency control. Unlike DC and DM, which are activated by larger frequency deviations, DR operates within a narrow band around the nominal frequency (typically ± 0.1 Hz). It continuously adjusts power output to correct minor, routine imbalances between generation and demand. DR responses are slower than DC and DM, with an initiating time within two seconds and reaching full response within ten seconds, but can be sustained for up to 60 minutes.

This service provides the function traditionally associated with secondary control delivered by AGC and Firm FR for secondary control [83]. It ensures that frequency is maintained as close to 50 Hz as possible during normal operating conditions. DR is especially important in a system with high levels of renewable penetration, where small forecast errors or fluctuations can lead to persistent frequency drift if not corrected promptly [84].

All three dynamic services are procured through market-based mechanisms, typically via daily auctions. This allows NESO to procure exactly the volume needed based on real-time system conditions, such as forecasted inertia and weather-driven variability. The market design encourage participation from a diverse range of flexible assets, including BESS, demand-side response, and hybrid systems. The integration of DC, DM, and DR represents a significant evolution in frequency control strategy. Compared

Table 2.2: Key performance specifications of DC, DM and DR [81]

Specification	Description	DC	DM	DR
Initiation time	Maximum time between a change in frequency and change in delivery of response	0.5 s	0.5 s	2 s
Full delivery time	Maximum time between frequency deviation and delivery of the saturation quantity	1 s	1 s	10 s
Delivery duration	Time that an energy-limited provider must be capable of sustained delivery	15 min	30 min	60 min

with Firm FR, the new dynamic response services provide layered, targeted responses across different timescales and deviation magnitudes. This modular architecture enhances both the robustness and the economic efficiency of frequency management in the modern grid.

Despite these advances, existing dynamic services remain focus on specific assets, particularly BESS and a limited set of flexible industrial loads. Many other DERs with distinct dynamic characteristics, such as renewable generation interfaced via power converters and emerging hybrid combinations of storage, have not been fully explored for their potential contributions. Furthermore, the current frameworks require each participating unit to independently satisfy technical requirements. This limits opportunities for coordinated delivery from massive assets. Their different characteristics could complement each other to collectively meet performance criteria. These constraints illustrate the need for research into broader DER participation, coordination strategies, and control frameworks that can unlock additional flexibility for frequency regulation in low-inertia power systems.

2.3.3 Research Activities on Enabling Distributed Energy Resources for Frequency Control

DER Participation in Dynamic Containment

The research community has also been active in exploring the optimal solution for enabling DERs in supporting the future low-inertia grid's frequency regulation. [33] presents one of the first modelling studies, which compare DC with previous Dynamic Firm FR using a generalised BESS model. The simulations are based on real GB frequency measurements and with DC's technical specifications. The results indicated that DC imposes significantly lower average power and energy throughput than Dynamic Firm FR, which could reduce cycling stress and potential degradation of BESS. Sensitivity analysis on the energy-to-power ratio showed that DC can be reliably delivered by high charging-rate devices such as supercapacitors and flywheels in addition to conventional BESS rated for a one-hour charge/discharge cycle. When considering devices capable of a full charge/discharge within about half a minute, DC maintained 71% availability compared with 42% for dynamic firm response. The study also noted that state-of-charge management, for example via baseline charging, can support compliance but reduces contracted power and associated revenue. In further analysis [85], a detailed dynamic model of a BESS providing DC response was developed, incorporating primary and secondary frequency control loops and State of Charge (SoC) management with the 90-minute baseline adjustment delay specified by the service. The study showed that this delay, combined with high charging rates, can induce SoC oscillations, increase energy throughput, and risk control instability. A root locus stability analysis was used to determine optimal configurations for charging rate, SoC range, management ratio, and target SoC, which reduced equivalent full cycles and improved frequency quality compared to the previous EFR service.

In [34], the DC participation of slow-ramping industrial demand response resources (DRRs) such as steam power generation was investigated. These resources cannot meet DC's rapid ramp requirements independently. Therefore, a Virtual Energy Storage System (VESS) framework was proposed, coordinating DRRs with high-power, short-

duration ESS. This reduced ESS energy capacity requirements by nearly 89% compared to an ESS-only approach, lowering capital cost and sustaining service delivery during prolonged frequency deviations. These work demonstrate that while BESS can meet DC technical requirements, careful SOC control tuning is critical for stability and lifecycle cost management, and that hybrid ESS–DRR architectures offer a cost-effective pathway to expanding the resource base for fast frequency control in low-inertia systems.

Overall, existing studies indicate that DC specification favours high-power, fast-response technologies while placing comparatively low energy demands on providers. However, the studies still provide very limited insights on how a wide range of DERs could be controlled and coordinated in a manner to support frequency regulation effectively.

Novel Control of DERs for Fast Frequency Response

The ability of individual assets to deliver FFR depends directly on their local control strategies. Device-level controllers define how quickly and effectively DERs can respond to frequency disturbances, and they provide the foundation for any higher-level coordination.

A broad range of DER technologies can participate in FFR if equipped with suitable local control, including BESS, flywheels, supercapacitors, wind and PV generation, demand-side resources, and hybrid systems. Each type have distinct dynamic characteristics and technical constraints, which demand specific control designs.

Early control concepts for DERs can be grouped into three categories: real and reactive power (PQ) control, voltage and frequency (V&f) control, and droop control. These strategies were originally developed to facilitate microgrid operation or to satisfy basic grid code requirements, and serve as the foundation for converter control today. The transition to low-inertia power systems has created the need for sub-second frequency support. This has led to the development of new mechanisms for FFR, such as inertia-emulating methods where converters mimic synchronous machine dynamics, and enhanced droop or step-response schemes that provide rapid active power injection [86]. The choice of control strategy determines the speed and quality of the frequency re-

sponse of DERs.

PQ control PQ control, in as shown in Figure 2.10, is the simplest and most widely adopted operating mode for grid-connected converters. In this scheme, the active and reactive power outputs are regulated according to externally commanded set-points, often dispatched by aggregators. This arrangement has been widely used in early microgrid implementations and is embedded in grid interconnection standards, such as IEEE 1547 [87, 88]. The simplicity of PQ control allows straightforward integration of DERs into distribution networks, but devices operating under this mode do not autonomously respond to local disturbances. Their contribution to system services, including frequency regulation, depends entirely on higher-level coordination, which introduces communication delays and limits their usefulness for sub-second FFR [80].

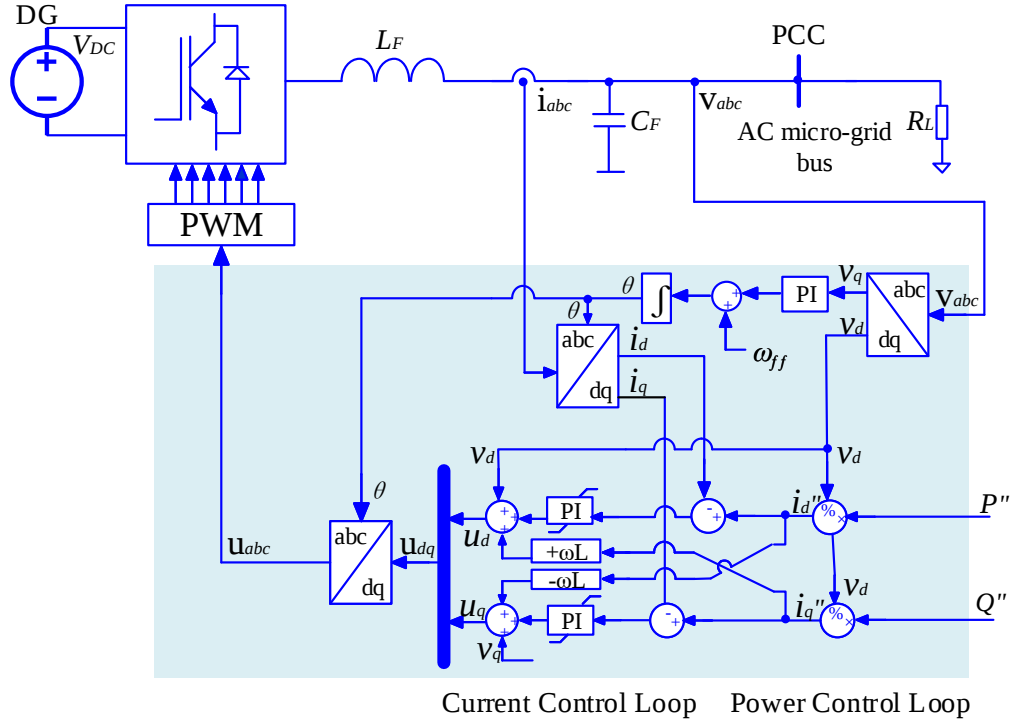


Figure 2.10: Basic structure of a PQ-controlled power converter [86]

Enhanced PQ control methods have been proposed to address these limitations. A significant direction in the literature improves the internal accuracy and speed of PQ regulation. For example, Pahlevani et al. [89] developed a hybrid non-linear adaptive

estimator that enables single-phase DERs with storage to achieve high-bandwidth PQ control without heavy filtering. This allows converters to deliver fast and robust active and reactive power regulation even under distorted conditions. Another enhancement focuses on communication frameworks. Colet-Subirachs et al. [90] implemented PQ control in a microgrid using IEC 61850 protocols, demonstrating both centralised coordination, where a supervisory controller manages total active and reactive power, and decentralised operation, where local controllers adjust their set-points autonomously. These developments illustrate how estimation methods and communication standards can extend PQ control from passive set-point tracking towards more dynamic participation in grid support.

Towards autonomous PQ-based FFR, researchers have investigated approaches further than external dispatch to enable fast, local response. [91] proposed a direct power control method for doubly-fed induction generator (DFIG) wind turbines, which directly regulates stator active and reactive power through rotor voltage selection. This achieved millisecond-level response and robustness to parameter variations, showing the potential of PQ-based schemes to deliver fast services. More recently, [92] introduced a model-free extremum-seeking controller that optimally coordinates active and reactive contributions of DERs without requiring a network model or phasor measurements. Their results demonstrated improved voltage regulation and efficient use of converter capacity in real time. These works suggest that PQ control, although originally conceived as a simple set-point-following strategy, is evolving towards autonomous, high-bandwidth methods capable of contributing directly to fast frequency response.

V&f control V&f control was first applied in islanded microgrids, where a converter operates in grid-forming mode by directly regulating voltage magnitude and frequency. This approach allows DERs to behave as reference sources, supporting islanded operation and maintaining power balance without relying on main grid. The method provides robustness to local disturbances but was not designed for integration into large interconnected systems, where most grid codes require PQ or droop-based operation.

Enhanced V&f control emerged as researchers aimed to extend grid-forming be-

haviour to weakly interconnected grids. Zhang et al. [93] proposed power-synchronisation control (PSC), which replaces the PLL with a synchronisation mechanism inspired by synchronous machines. By regulating active power through load angle and reactive power through voltage magnitude, PSC eliminates PLL-induced instabilities and provides strong voltage support under weak-grid conditions. Rocabert et al. [86] further classified converter roles into grid-feeding, grid-forming, and grid-supporting, highlighting how V&f-based control forms the basis of grid-forming converters in microgrids.

To provide FFR, V&f control has evolved into advanced grid-forming frameworks that target sub-second system support. [94] introduced a combined control scheme where both active and reactive loops contribute to frequency and voltage regulation, improving dynamic response in high resistance-to-reactance ratio distribution systems. More recently, reviews such as [95] have summarised developments in grid-forming control, including PSC, virtual synchronous machines, synchronverters, and virtual oscillator control, which enable DERs to provide inertia-like behaviour, fast active power support, and seamless transition between grid-connected and islanded modes. These outcomes indicate that V&f control could be a key method for DERs to deliver autonomous frequency and voltage regulation in low-inertia power systems.

Droop Control Droop control was introduced to enable autonomous power sharing among parallel inverters without requiring communication. The method directly mimics SGs with droop characteristic: active power is regulated by frequency droop (P - f), while reactive power is regulated by voltage droop (Q - V). This principle was formalised by [96], who demonstrated stable operation of parallel inverters in standalone AC systems using droop characteristics derived from local measurements. The approach was later extended to microgrids and standardised as a primary control method for distributed generators. The authors of [86] consider droop, along with PQ and V&f, as one of the three fundamental control strategies for DERs. Its modularity and communication-less operation made droop highly attractive for both islanded and grid-connected microgrids.

Enhanced droop control aims to address the main limitations of basic droop, including steady-state frequency and voltage deviations, and weak transient performance.

A majority of the work introduced hierarchical droop control, where primary droop is complemented by secondary loops for restoring frequency and voltage and tertiary loops for optimising grid interaction, as reported in [97]. Another direction developed adaptive droop methods, where droop slopes are tuned online depending on system state. For example, the work presented in [98] integrated sliding mode control into adaptive droop for DC microgrids, eliminating current sharing errors and bus voltage deviations under dynamic loading. The authors of [99] further enhanced droop by embedding model reference adaptive control into dual active bridge converters, achieving robust, fast voltage regulation for storage integration. Consensus-based approaches, such as [100], extended droop into distributed frameworks, allowing multiple converters to coordinate via low-bandwidth communication while adjusting virtual impedances to achieve accurate reactive power sharing. These activities demonstrate how droop evolved from a simple load-sharing mechanism into flexible control methods, which are robust and accurate in diverse conditions.

To provide FFR, droop-based strategies have been extended into virtual synchronous generator (VSG) and virtual synchronous machine (VSM) concepts, which emulate the inertia and damping characteristics of synchronous generators. The synchronverter, introduced by Zhong & Weiss [94], implemented the full swing dynamics of a synchronous machine in inverter control, enabling inertia provision and native droop behaviour. [101] proposed a VSG with alternating moment of inertia, dynamically adjusting inertia during oscillation cycles to improve damping and stability. [102] presented enhanced VSG control that eliminates oscillations during transients and ensures accurate reactive power sharing without communication. These developments demonstrate how droop-inspired methods can deliver sub-second frequency support, bridging the gap between traditional load-sharing strategies and advanced grid-forming controls. As such, droop and its derivatives remain central to enabling DERs to contribute inertia, damping, and fast frequency regulation in low-inertia power systems.

2.4 Discussion

The review highlights that research on control strategies has progressed substantially, with many contributions improving the dynamic response of individual DERs. Nevertheless, gaps remain at both the device and system levels.

At the device level, existing studies have mainly focused on BESS and a small group of converter-based renewables, leaving other technologies such as responsive demand, hybrid systems, and novel flexible resources unexplored. Control schemes are often developed under the assumption that devices must act independently, limiting opportunities for coordination across different types of assets. The differences in ramp rates, energy capacity, and operating constraints are currently not considered and not able to be coordinated to improve overall response performance.

At the system level, the integration of advanced control strategies into real-world operation remains insufficiently understood. Most studies are still limited to simulations or laboratory demonstrations, which do not capture the complexities of grid conditions. Communication delays, and uncertainties in resource availability are rarely incorporated, even though they critically affect the scalability and reliability of DER-based FFR. Addressing this gap calls for approaches that can provide operators with access to dynamic behaviour in real time and reduce reliance on continuous communication, creating new opportunities for the development and deployment of control methods.

These gaps highlight the need for future research that not only advances device-level control but also integrates these developments into the broader context of DER coordination, with careful consideration of practical implementation factors such as dispatch frameworks and communication limitations. Such efforts will help ensure that DERs can provide fast frequency support in a coordinated and reliable manner.

2.5 Summary

This chapter has reviewed the evolution of frequency control, from the traditional multi-stage framework to emerging services designed for low-inertia systems. Using GB as an example, industry efforts to introduce faster and more flexible services, e.g. EFR

and DC, were highlighted, which reflects the growing need to stabilise systems with declining inertia and increasing DER penetration. The review also examined device-level control strategies, including PQ, V/f, and droop control, along with their enhanced variants, that enable DER participation in fast frequency support. However, the discussion revealed that significant gaps remain in extending DER participation across diverse technologies to collectively deliver effective frequency response within realistic operational frameworks.

As outlined in Chapter 1, these research gaps form a central motivation for this thesis. Frequency control services are becoming increasingly dependent on DERs, while current monitoring and control methods on network level do not capture their dynamics at the sub-second resolution required for fast response. To address this, Chapter 3 reviews the state of art of DTs to examine their capability for addressing the frequency control challenges identified here. Although DTs have demonstrated broad applications in other engineering sectors and are appearing in power engineering, their potential to support real-time frequency services remains under explored. This establishes the link between frequency control challenges and the potential of DTs, providing the foundation for the DT of DERs prototyping presented in the following chapters.

Chapter 3

Literature Review on Digital Twin

This chapter presents a review of the DT technology, its key strengths, existing applications and the potential for addressing the challenges in enabling DERs to provide fast frequency responses. The chapter first outlines the key definitions of DT adopted in different contexts and the evolution of the its concept. It then reviews representative DT frameworks and enabling technologies, with emphasis on those relevant to DERs. Finally, it examines existing applications in power systems, highlighting their capabilities, limitations, and research gaps.

3.1 Definition of DT and the Evolvement of its Concept

The term *Digital Twin* was formally introduced in 2002, and since then, diverse definitions of DT have been adopted by academia, industry, and governmental bodies [103]. These definitions often vary depending on the specific application fields of DT. This section reviews these definitions and establish a precise definition of DT for the targeted application in this work.

3.1.1 DT Definitions by Research Community and Industry

The early form of DT (although the name was not used at the time) was firstly introduced during the Apollo 13 mission in 1970, after a critical malfunction occurred while the spacecraft was 210,000 miles from the Earth [104]. The pre-trained and

pre-configured standard procedures failed under the unexpected and extreme conditions. Any incorrect operations could have further led the mission to failure, potentially stranding the astronauts in space indefinitely. NASA utilised 15 simulators at their mission control centre in Houston to train astronauts and refine control procedures. To assess the guidance provided to astronauts, these simulators were adapted to track the spacecraft's condition by analysing error messages from sensors and reports from the crew. This process highlights one of the core functions of DTs leading to their increased application in modern world, i.e. supporting the real-time what-if scenarios of physical systems. Although the data communication between the control centre and the spacecraft was simple by today's standards, this scenario illustrates another critical aspect of DTs, i.e. the necessity for live data connection between the physical asset and its corresponding virtual entity. This real-time data, which could be in different time resolutions depending on the specific application, is essential for updating the asset's status and making decisions. Although in this application, the concept of DT was not specifically defined, this process showcases the the basic functionalities that modern DTs can offer.

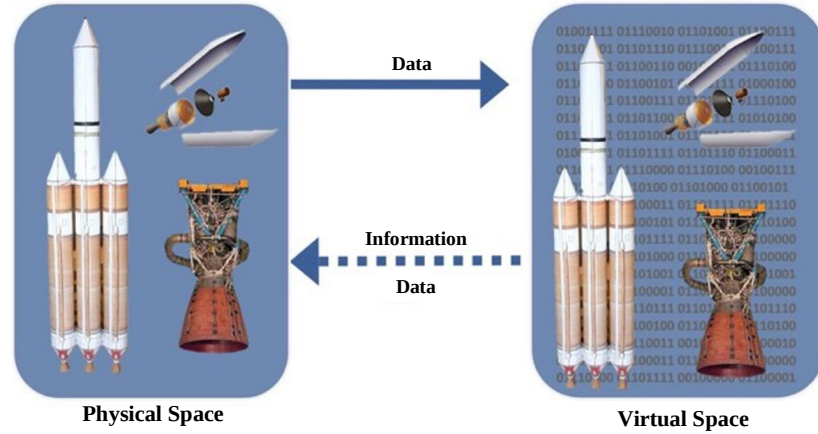


Figure 3.1: Three-dimension model for the DT [103]

As mentioned previously, the first formal definition of DT was introduced in 2002 by Grieves, in the context of product lifecycle management [103]. Grieves defined his initial DT system as a mirrored space consisting of three main components, i.e. the physical entity in the real world, the virtual model in the digital space, and the data

channels connecting the physical entity and virtual model, which are illustrated in Figure 3.1. This work served as the basis of the fundamental concept of DT. It also laid the groundwork for further DT research in Product Lifecycle Management (PLM). In the PLM area, DT was applied to bridge the gap between virtual models and physical products across the entire lifecycle. Its applications included virtual prototyping during design, synchronisation of production with design specifications, and feeding operational data back into maintenance and redesign processes [105–107]. However, due to technological constraints at the time, the data generated by DT systems received limited attention.

Research related to DT was very limited in the decade following the birth of the concept. In 2012, US air force research laboratory utilised DT technology on their F16 fleet maintenance and real-time evaluation of aircraft health. The laboratory reiterated the concept as: “A digital twin is a virtual representation of an instance of a physical object that shares data with its physical twin throughout the system lifecycle reference” [108]. This concept reinforced the importance of a continuous data link between the physical and virtual entities, extending Grieves’ earlier three-component model into a practical framework for PLM. Unlike the Apollo 13 application, which was limited by communication technologies of the time, the F16 programme demonstrated how DTs could be systematically integrated into complex engineering assets.

The concept gained more attraction after 2016, when researchers began to explore the theory of DTs and proposed frameworks for their development and implementation. Fang et al. introduced a DT-driven product design, manufacturing, and service model, expanding the concept beyond traditional applications in PLM [110]. The definition DT framework was updated by Tao in 2017 to a five-dimension structure as shown in Figure 3.2, which further include data and service as the main additional components [109]. In this reported work, the DT system is defined as a system consisted of five components: physical entities, virtual representations, integrated service platform, database, and communication links. During this period, the enabling technologies such as the Internet of Things (IoT), big data analytics, and cloud computing, significantly promote the development of DTs.

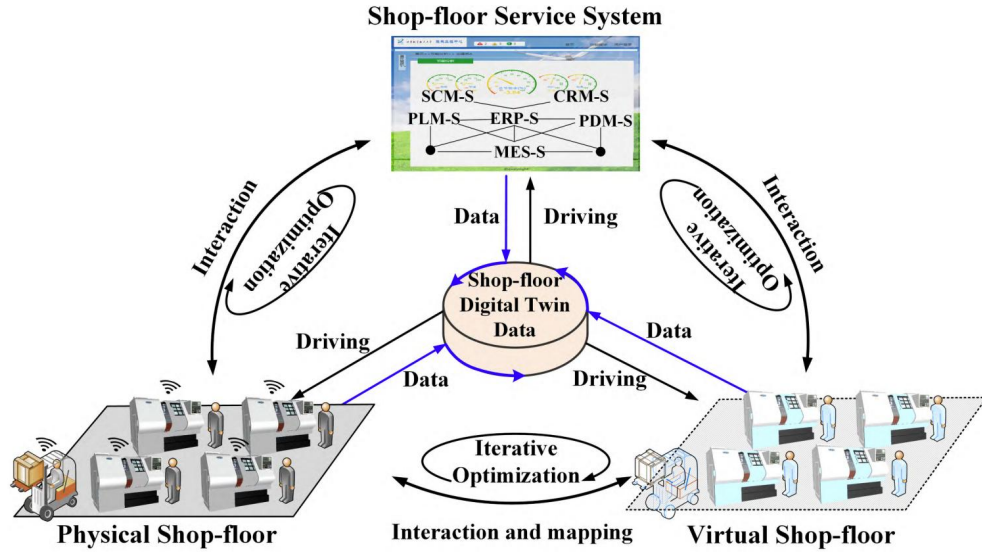


Figure 3.2: Five-dimension model for the DT [109]

The period from 2016 to 2020 saw a significant expansion in the application of DTs. In aerospace, DTs were used to predict aircraft maintenance needs and optimise flight operations [111,112]. In manufacturing, they were employed to create virtual factories, thus enabling real-time monitoring and simulation of production processes [113,114]. The healthcare sector also adopted DTs for personalised medicine in order to simulate patient-specific responses to treatments [24]. This era highlights the transformative potential of DTs in providing different functionalities across a wide range of industry sectors.

Recent research has focused on improving the accuracy and efficiency of DTs using advanced algorithms and machine learning techniques [115–117]. Their integration with artificial intelligence (AI) has further expanded the opportunities for predictive analytics and autonomous decision-making.

3.1.2 DT Definitions by Government Bodies

In addition to the definitions proposed by researchers in academic, government bodies and agencies in the United Kingdom (UK), European Union (EU), and United States (US) have also offered their perspectives on DTs, highlighting their significance and significant potential for wide applications:

- UK: The National Digital Twin Programme (NDTP) led by the Department for Business and Trade, defines a DT as “a virtual model of an object, a system, or a process. It is connected to its real-world counterpart by a 2-way flow of right-time data, meaning it mimics it in all aspects” [118].
- EU: Within the framework of EU’s digital strategy, the definition is “DTs create a virtual replica of a physical product, process or system”. The replica can for example predict when a machine will fail, based on data analysis, which allows to increase productivity through predictive maintenance” [119].
- US: National Institute of Standards and Technology (NIST) describes a DT as “the electronic representation, the digital representation, of a real-world entity, concept, or notion, either physical or perceived” [120].

Despite the wide range of different definitions of DTs, they largely share similar features and essential components. In this thesis, the definition from the NDTP (listed above) has been adopted, which will ensure the consistency in understanding and communications. However, it should be noted that, while the NDTP’s definition highlights DTs’ function in mimicking physical systems in “all aspects”, a practical DT system might still focus on certain properties of the physical entities, e.g. an electrical network DT might mainly focus on the electrical property of the physical system rather than the mechanical or dimensional properties.

An example DT-based system for power system applications is shown in Figure 3.3, which 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 (also referred to as the physical twin in some cases), 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, e.g. monitoring, control, etc. [121].

3.1.3 Key Differences between DTs and Conventional Models

Although both DTs and conventional models aim to represent the behaviour of physical systems, their capabilities differ depending on the developing platforms and application

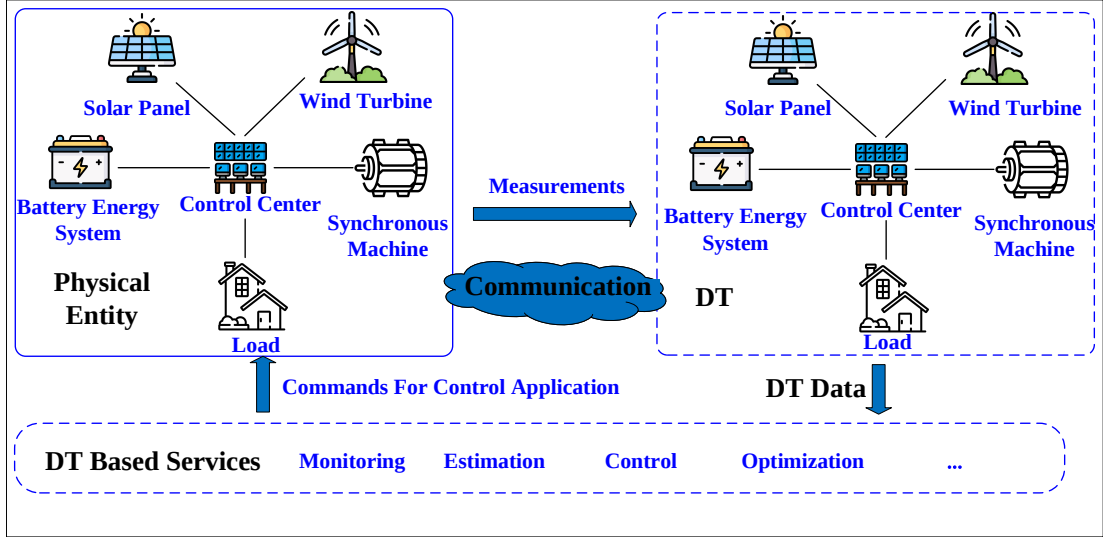


Figure 3.3: A typical five-dimension layout of a DT-based system in power industry [121]

scenarios. Conventional analytical models, such as those developed in Simulink, are valuable for offline studies and controller design, but they operate on a non-real-time platform and cannot remain aligned with assets once deployed. Updating such models requires re-running simulations or reconfiguring parameters, which limits their use in continuous operation.

Real-time simulators such as RTDS and OPAL-RT extend the capability by executing detailed power system models in synchrony with GPS time, allowing direct hardware-in-the-loop testing [122]. These platforms are suitable for system- and network-level DTs because topology changes at this scale are relatively infrequent and can be represented through events such as line tripping or generator integration. In addition, DTs at this level are often hosted in central control rooms, where greater computational resources are available to support real-time execution. However, their high computational burden and limited flexibility for detailed structural updates make them less suited to component-level DT development, where lightweight execution and rapid re-configuration are essential.

In contrast, DTs at the component level are designed for sub-second resolution with lightweight execution and built-in communication interfaces. They remain synchronised with real-time inputs and can continuously update their parameters and structures when

the configuration of the physical counterpart changes. A further distinction is that DTs reduce communication requirements and associated delays by providing dynamics of remote end directly at the point of deployment, avoiding the need to transfer large volumes of raw data to each edge device or a central controller.

3.2 Overview of DT Applications in Different Industrial Sectors

As mentioned previously, DT has been adopted for different applications in various industrial sectors, and they are with different mature levels. A summary of DT applications across various industry fields is listed below along with their technology readiness levels (TRLs), which is a systematic framework for assessing technology maturity during its development and application. TRL ranges from 1 (basic principles observed) to 9 (actual system proven in operational environments) and widely used across industries [123]. This structured analysis reveals the evolution of DT technology from conceptual stages to full operational deployment.

1. Aerospace and Defence (TRL 7-9)

DTs have been utilised for the lifecycle management of aircraft and military systems, from design and testing to operation and maintenance [108]. This includes predictive maintenance, performance optimisation and real-time monitoring of aircraft health [111,112]. The maturity of these DTs is at the higher end of the TRL spectrum with relatively long-term practice, along with strict safety requirements.

2. Manufacturing (TRL 6-8)

DTs in manufacturing have been used for optimising production processes, predictive maintenance of machinery, and product lifecycle management [124]. They enable manufacturers to create virtual replicas of their production lines and products to simulate, analyse, and optimise performance before implementing physical changes [114].

3. Automotive Industry (TRL 5-7)

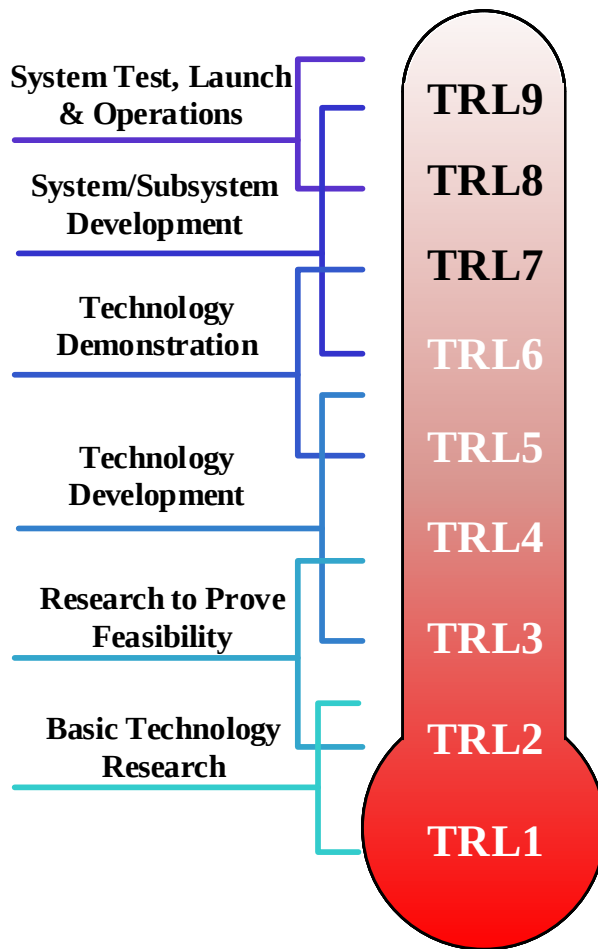


Figure 3.4: Description of TRL levels [123]

The automotive industry uses DTs for vehicle design, testing, and assembly line optimisation [125]. DTs are also applied to facilitate intelligent driving, where they simulate real-world conditions for safer and more efficient testing of algorithms and vehicle responses [126].

4. Energy and Utilities (TRL 4-6)

DTs are being explored for managing renewable energy generation, enhancing grid operation, and enabling predictive maintenance of critical infrastructures [25, 28, 127]. They help in simulating energy systems, forecasting demand, and enhancing the reliability and efficiency of energy production and distribution.

5. Healthcare (TRL 3-5)

DTs in healthcare are being developed for personalised medicine, patient monitoring, and simulation of drug interactions [128]. Although they are still in earlier stages of development compared to other industries, these applications show promise for improving patient outcomes and personalized treatment plans.

3.2.1 Reflection

The survey of DT applications across different sectors shows that the power system domain is still at a relatively early stage compared with industries where DT technologies have already reached higher TRLs. These sectors demonstrate the value of DTs for lifecycle management, predictive maintenance, and real-time optimisation. These functions are supported by universal data standards, integrated communication infrastructures, and reliable communication between physical assets and their digital counterparts. Power systems can learn from these experiences by adopting standardised data interfaces, designing modular DT frameworks that allow incremental scaling, and building validation platform that combine simulation with real operational data.

Furthermore, the aerospace, manufacturing, and automotive industries demonstrate that DTs can be advanced into practical tools for lifecycle management, predictive maintenance, and real-time optimisation. In the power sector, similar practices could be realised by using DT-based monitoring to maintain and manage grid assets throughout their lifecycle, and by testing extreme scenarios in a safe virtual environment to support real-time optimisation of system operation. Such approaches would allow operators to improve asset reliability and validate corrective actions before deployment, thereby enhancing overall system resilience.

3.3 DT Applications in Power Systems

In the power and energy sector, DT are still at a relatively early stage compared with their adoption in industries, e.g. aerospace and manufacturing. Nevertheless, they have demonstrated significant potential across several key applications. Most reported

academic research and demonstration projects can be grouped into following categories: asset health monitoring, measurement and parameter estimation, fault diagnosis and location, grid management and operation, risk assessment and resilience enhancement, and protection testing. Collectively, these applications highlight how DTs can deliver real-time visibility, enable predictive control, and provide safe simulation environments that go beyond the capabilities of traditional modelling tools.

3.3.1 Asset Condition Monitoring

DT technology has emerged as a powerful tool in power system asset health monitoring, offering solutions for precise real-time diagnostics and predictive maintenance. In power electronics, DTs are applied to monitor components, e.g. DC-link capacitors, pulse width modulation (PWM) rectifiers, and boost converters [129–131]. By replicating the behaviour of physical assets, DTs can enhance monitoring accuracy and fault detection. For instance, DT models for DC-link capacitor banks are integrated with sensors, e.g. PCB Rogowski coils, to dynamically update parameters using recursive algorithm [132]. It tracks frequency and temperature variations to ensure accurate condition assessments. Similarly, DTs have also been implemented for single-phase PWM rectifiers using particle swarm optimisation (PSO) and meta-heuristic algorithms to monitor the health of critical components including IGBTs and capacitors, which is reported to achieve high accuracy without the need for additional hardware modifications [129]. Furthermore, DT-based modelling of thermal dynamics in boost converters improves health monitoring by compensating for temperature-induced component variations [130].

3.3.2 Measurement & Parameter Estimation

DTs have also been applied to measurement and parameter estimation in critical power equipment, e.g. DC-DC converters, permanent magnet synchronous motors (PMSM), and power electronics modules. For DC-DC converters, DTs integrate particle swarm optimisation with dual extended Kalman filter to provide real-time, high-precision thermal modelling, which can enhance device reliability by adapting to changing conditions,

e.g. degradation [133]. In PMSM systems, DT models employing Chaos PSO enable non-invasive estimation of key parameters, e.g. stator resistance and flux linkage, which improves motor control efficiency without requiring additional sensors or signal injections that could disrupt operations [134]. Furthermore, in the domain of power electronics, thermal DTs have been developed for online thermal parameter identification, which combines real-time simulations with PSO and dual extended Kalman filter to optimise thermal models, thereby improving the monitoring and management of thermal impedance [135]. These advancements demonstrate the significant potential of DTs to enhance the accuracy, efficiency, and reliability of power systems through improved real-time monitoring and predictive maintenance capabilities.

3.3.3 Fault Diagnosis and Location

Fault diagnosis generally consists of two stages, i.e. fault detection (FD) and fault identification (FI) [136]. FD is a binary decision-making process for identifying the occurrence of a fault, while FI is the process of classifying the specific type of fault. [25] proposed a DT-based method for diagnosing faults in photovoltaic (PV) systems, which are composed of PV panels, power converters, and electrical sensors and are prone to various types of faults. In this method, the FI and FD functions are realised by measuring the error residual vector between the DT-estimated output and the measured PV output, and then mapping this vector to with a fault signature library. As illustrated in Figure 3.5, a typical DT-based FI process involves calculating correlations between the error residual vector and 16 predefined fault signatures. In the example, the vector shows the highest correlation with the 15th signature, and a fault is considered identified once the correlation surpasses a predefined threshold. By embedding such DT-enabled diagnostic modules directly within distributed PV systems, the need for high-bandwidth communication networks can be reduced. Similar research is also reported in [137], which explores the use of probabilistic DT for real-time diagnostics of power electronic subsystems.

The fault diagnosis application discussed above primarily focus on the component level. At the system level, a graph-based DT has been proposed to localise fault in the

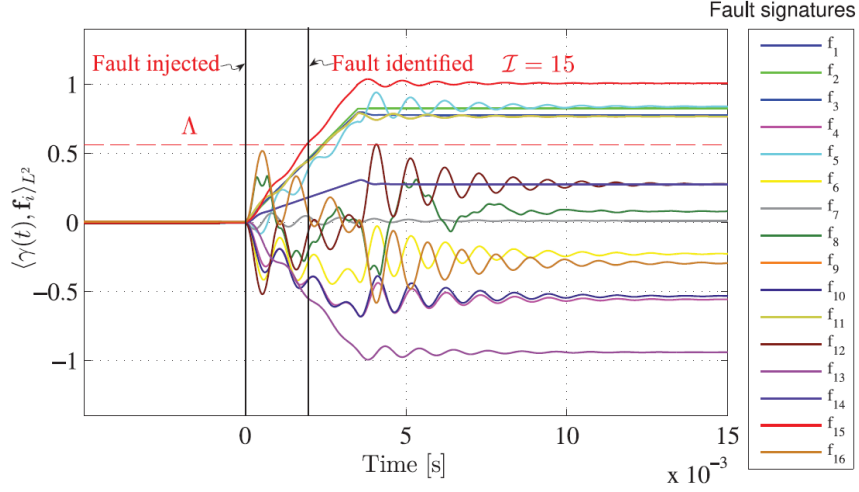


Figure 3.5: The DT-based fault diagnosis on distributed PV system [25]

system, where the New England test system that comprises 39 buses and 10 generators is used as the case study [138]. As shown in Figure 3.6, the physical entities of the Internet of Energy are represented as nodes in the graph, while the logical relationships between these entities are represented through edges and weights. PMUs are employed to gather status data from each component to enable real-time updates and support further analysis. Any change in the physical system triggers corresponding updates in the graph-based DT. By analysing the structured data in this graph-based representation, state changes of physical system can be predicted, and faulty components can be identified in time to support subsequent mitigation actions.

Another emerging example of application of DT is in the domain of cybersecurity. As the operations of power systems are heavily dependent on the integrity and reliability of measuring devices, e.g. PMUs, these devices can become potential targets of cyberattacks. In [139], a DT-based approach is proposed that leverages both the digital model and the physical attributes of a radial distribution network to compute a new metric, termed the residual rate of change. The metric enables the localisation of cyberattacks on load measurements and protective devices.

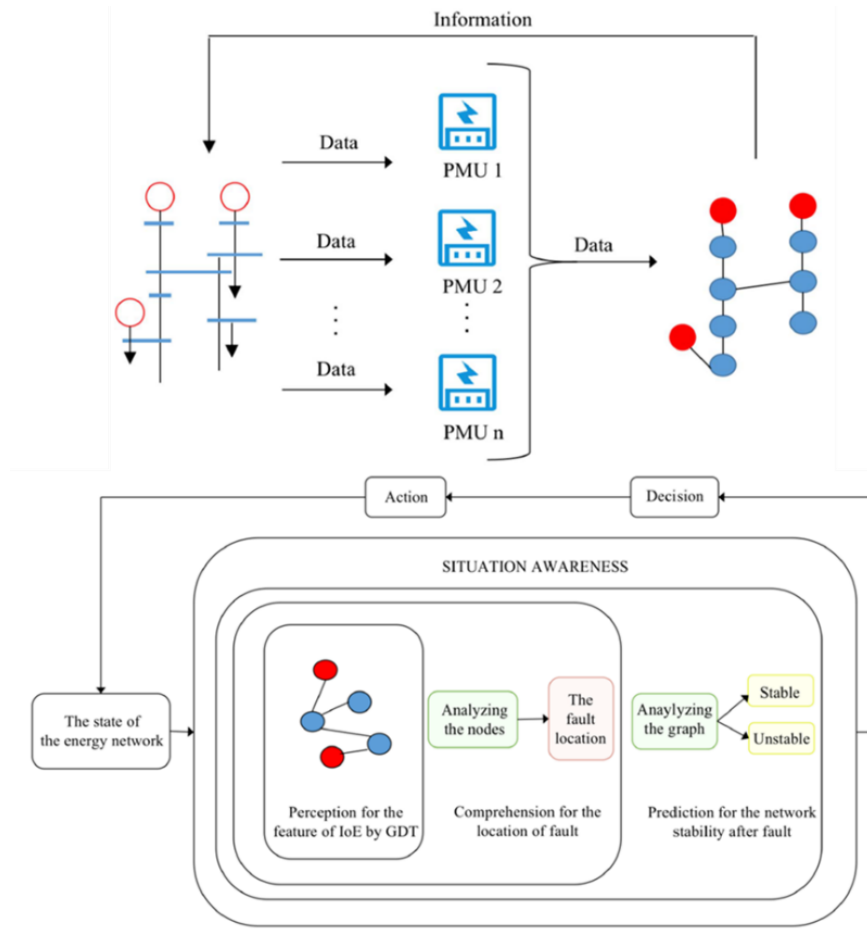


Figure 3.6: Graphical DT for the Internet of energy [138]

3.3.4 Grid Management & Operation

To support low-carbon and energy-efficient management of electrical equipment in smart industrial parks, [140] introduces a DT system called C3-FLOW, which is a framework that enables coordination across cloud, edge, and device layers. Practical DT implementations face various challenges, e.g. high communication costs due to frequent data exchange, and uncoordinated resource allocation among cloud, edge, and device layers. The reported C3-FLOW system address these issues by providing a collaborative, reliable and communication-efficient DT platform for managing renewable energy sources, controllable loads, and storage units. This is achieved by jointly optimising channel allocation and computational resources, thereby minimising long-term global

loss functions while reducing communication overhead.

3.3.5 Risk Assessment and Resilience Enhancement

DT has also been explored for application in assessing and enhance grid resilience. In [127], a DT-based framework is proposed to improve the reliability, resilience, and operational efficiency of networked microgrids. The approach employs a neural network (NN) model as the virtual representation of the microgrid, which interacts in real time with the physical system to optimise energy management under both grid-connected and islanded modes. The NN-based DT is used to assess risk and predict the optimal schedule of power generation and storage units. Similarly, [141] presents a DT-based methodology for assessing the resilience of microgrids. Unlike traditional approaches that primarily address predictable outages, this method focuses on capturing dynamic responses and resilience under extreme and uncertain events. The DTs are used to evaluate the dynamic consequence of disturbance, thus more accurately evaluating their impact and inform the actual resilience level of the system.

3.3.6 Testing of Protection

The direct application of DTs in power system protection remains at an early stage, with some existing studies focusing on using DT-based network models to evaluate the effectiveness of protection methods [142]. In parallel, the industry is exploring the development of DTs for protective relays, which can serve as valuable tools for protection testing [143]. However, full reliance on DTs for real-time protection operations is currently regarded as infeasible due to the stringent performance and reliability requirements of protection systems.

3.4 DTs Industrial Implementations and Initiatives in Power Systems

3.4.1 Typical architecture of DT-based Systems in Power and Energy Sector

Depending on the targeted applications, the implementation of the DT-based systems can vary significantly. Figure 3.7 presents a typical and generic architecture for integrating DT technologies within the control and management framework of Electrical Power Systems (EPS) [144]. This architecture illustrates the implementation of various DT instances designed to support and realise a range of different services. These services include, but are not limited to, parameter optimisation, predictive simulation for future scenarios, and real-time monitoring of the EPS's operational state.

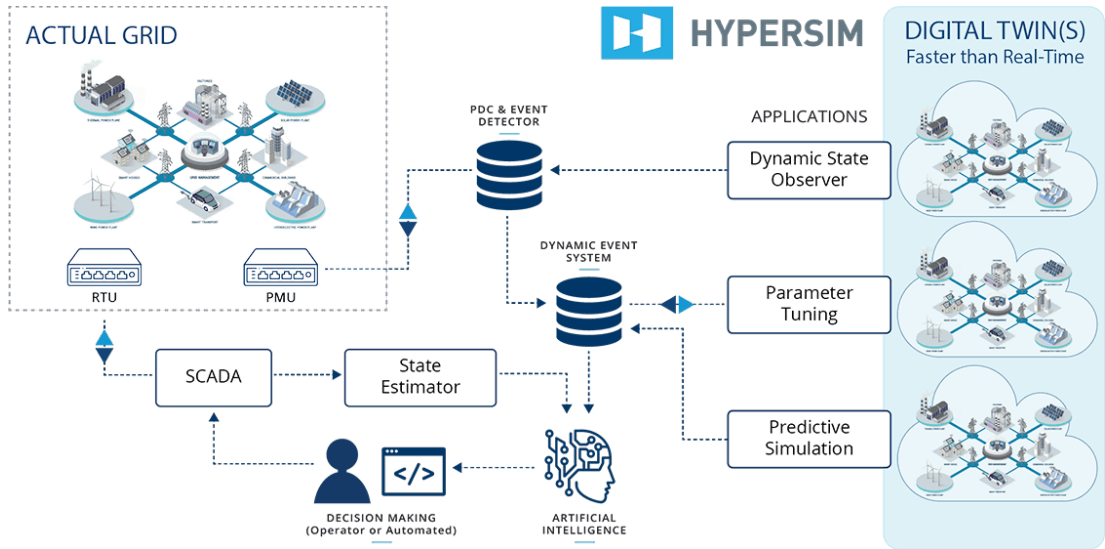


Figure 3.7: Power system DT architecture proposed by [144]

Furthermore, the figure also illustrates the interaction between the DTs and existing technological infrastructures, control methodologies, and operational protocols, e.g. Supervisory Control and Data Acquisition (SCADA) systems, PMUs, and the decision maker (i.e. engineers) in the control rooms. These interactions involve the integration of additional data inputs that reflect current transmission network conditions with various functionalities, e.g. predictive analytics for future network power flows and potential

constraints. Such integrations can potentially be facilitated through the utilisation of existing communication networks and field devices.

Conventional simulations (even with real time simulators) usually rely on pre-configured system conditions and scenarios, which are decoupled from the actual system. 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.

As also noted previously, while DTs are typically considered as live virtual replicas of physical systems, DTs could only reflect a selected set of attributes, e.g. electrical properties, geometry, heat or motion. The selection of attributes is dependent on the targeted applications and design considerations (e.g., the computation power required). In addition to these limitations, another key factor that requires consideration during the development and implementation of DTs is the availability of measurements with appreciate resolution and quality, which are used as essential inputs to drive the DTs. Consequently, the accessibility of measurement data and the methodology employed in modelling are critical factors that determine whether it is adequate for the DT to provide the services targeted.

3.4.2 UK Power Industry Activities on DT

The GB system operator NESO launched the Virtual Energy System (VirtualES) initiative in 2021, aiming to create a platform for integrating DTs across the energy sector to enable effective data sharing and coordination [145]. NESO manages information collected from different sectors under diverse protocols and standards as shown in Figure 3.8. With the energy system becoming more complex and interconnected, existing data processes are increasingly outdated and impractical.

The VirtualES provides an open framework with agreed protocols and standards for DT integration. It is designed to operate in parallel with the physical system as a shared industry asset, supporting simulation, forecasting, and whole-system decision-making for a zero-carbon electricity system. Within the framework, each DT contributes to and accesses real-time data, improving system understanding and enabling a virtual environment for innovation. The associated data management platform defines how

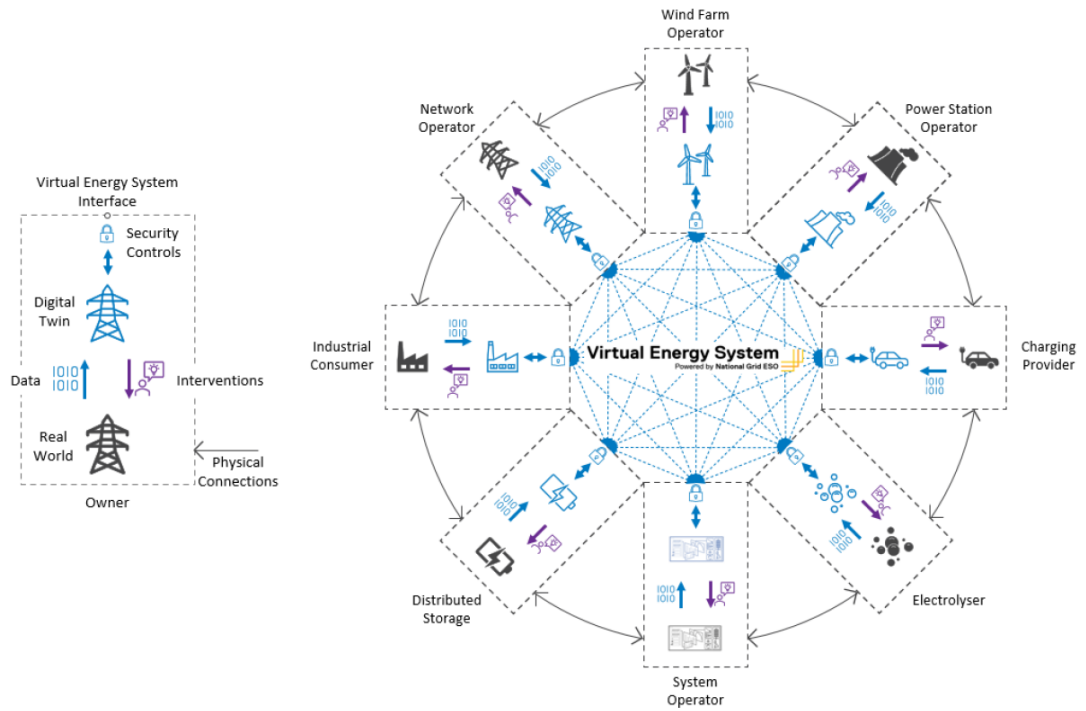


Figure 3.8: A simplified representation of potential components in the Virtual Energy System [145]

users interact with VirtualES, including preparing, publishing, searching, requesting, and consuming data.

SP Energy Networks (SPEN) has been active in recent years in exploring how DTs can support network management and operation. In 2022, it conducted the EN-Twin-E project, which was a preliminary study funded under the Strategic Innovation Fund (SIF) scheme, focusing on the assessment of the feasibility of using DTs to enhance distribution network visibility and unlock the potential of DERs [146]. The project examined how DTs could support the transition from distribution network operator (DNO) to distribution system operator (DSO), facilitate local balancing, and improve coordination between distribution and transmission. Its outcomes suggested that DTs can be used to construct system operational envelopes, simulate what-if scenarios, and disaggregate generation and load to support system operation.

Following in the initial study conducted in the EN-Twin-E, SPEN initiated a large-scale project called ENSIGN (ENergy System dIGital twiN), which is funded under

UKRI's Prosperity Partnership scheme [147]. ENSIGN, which is still ongoing and expected to complete in 2027, aims to develop the first integrated energy system DT that extends beyond electricity to include heat and hydrogen. The project aims to enable safe and secure operation of decarbonised local systems with multiple energy vectors, which AI-based modelling will be employed with real-time data integration to optimise network capacity, manage the additional demand from electrification and hydrogen, and support SPEN in deploying solutions for a reliable and resilient future network.

Other UK organisations have also been active in research and development activities relating to DT. The Energy Systems Catapult has developed both visual and technical demonstrators to assess how policy and investment decisions could influence energy system outcomes [148]. These demonstrators provide system awareness from individual households to regional energy systems, and showcase the role of DTs in connecting technical modelling with policy-making. The National Gas Transmission has focused on DTs for network operation and safety, where the Collaborative Visual Data Twin (CVDT) project was initiated to integrate real-time and historical data with 3D models to enhance asset management, particularly in the context of hydrogen transition [149].

3.5 Research Gaps in Applying DTs for DER-based Frequency Control

Despite the growing number of research and development activities in the academic and industrial community on DTs in the power and energy sector, which provide valuable experience and learnings for their applications in enabling DERs to provide effective frequency control in future low-inertia systems, there are several research critical gaps remain unaddressed. These gaps highlight limitations in current academic work and provide motivation for the investigations carried out in this thesis.

3.5.1 DTs of DERs Suitable for Supporting Real-Time Frequency Control

While DTs are, in principle, digital replicas of the physical system, in practice they can take diverse forms and be constructed in fundamentally different ways depending on the application and the properties they are designed to represent. Most existing research on power system DTs has focused on asset health monitoring, component-level diagnostics, or steady-state estimation. However, such DTs with low time resolution is not suitable and adequate for real time frequency control applications, which requires sub-second fast dynamic behaviour of DERs. There is fundamental knowledge gap on how such DTs should be created in order to effectively support the representation of dynamic behaviour of DERs, thus enabling coordinated frequency control schemes.

Furthermore, DT models in existing studies are often built under fixed assumptions about the physical asset, which typically rely on either physics-based or purely data-driven approaches. In reality, the information of DERs exhibit widely varying levels of accessibility, i.e. some can be treated as open-box systems with accessible internal structures and parameters, while others are black-box devices with limited information. This diversity means that no single modelling method is universally applicable. Fundamental research should be conducted to assess the feasibility of these modelling approaches, develop the appropriate methodologies, and identify their suitable applications.

3.5.2 Methods for Unlocking the DTs' Capability in Frequency Control

As noted earlier, most applications of DTs in the power sector are either at the component level or operate primarily on timescales of minutes. Such approaches are insufficient for supporting frequency control, which demands coordination of fast sub-second dynamics across the network. This highlights the need for new knowledge, as well as novel solutions, to determine what roles DTs can play and how they can enable DERs to participate effectively in frequency control.

One of the key strengths of DTs is their ability to perform what-if simulations in real

time using live system states. However, few studies in the power sector demonstrate platforms that integrate this capability with actual grid operations. Existing practice for scheduling frequency response resources remain confined to offline analyses, which can over or under estimation the effectiveness of the responses. As a result, a research gap persists in understanding how DTs can be designed to support system operators in evaluating security margins, testing contingencies, and ensuring that appropriate amounts of resources are scheduled in plants to contain frequency deviation during power imbalance events.

Furthermore, while DTs have been widely proposed for monitoring and predictive analysis, their utilisation in real time control remains underdeveloped. Existing work largely considers DTs at the single-device or component level, without addressing how they might coordinate large fleets of DERs during fast-changing system events. Moreover, practical constraints such as communication delays and bandwidth limitations are rarely considered when designing control scheme, despite their critical impact on the performance of coordinated control. This creates a gap for research into DT-enabled control strategies that explicitly account for distributed architectures, such as cloud–edge hosting options, to achieve scalable and resilient coordination of DERs.

3.5.3 Communication of Existing DT applications

Academic research has demonstrated contrasting communication approaches for DTs. At the component level, reduced-order DTs of power converters have been implemented directly on FPGA platforms, where physical and virtual models exchange signals locally through embedded interfaces [150]. This design avoids dependence on external networks and reduces latency, making it suitable for real-time control studies. At the system level, web-based DTs have been developed to support training and education platforms [151]. These typically rely on middle-layers to translate web protocols (HTTP/HTTPS) into device-level communication (e.g. UDP), enabling bidirectional interaction between DTs and laboratory instruments. Such implementations illustrate different communication approaches, but the impact of latency, reliability, and protocol design on DT effectiveness for real-time frequency control has not been systematically studied.

Industrial initiatives show a similar diversity. In GB, the Virtual Energy System (VirtualES) provides a data-sharing framework that defines protocols and access rules to allow multiple DTs across the energy sector to exchange information securely and in real time. Commercial tools such as OPAL-RT's HYPERSIM integrate DTs into power system communication standards, including IEC 61850 and IEEE C37.118, so that real-time simulators can interface directly with SCADA and PMU infrastructures. These examples demonstrate how industrial DTs emphasise interoperability, scalability, and integration into existing operational environments. However, despite these advances, a research gap remains in understanding how communication performance affects DT effectiveness in fast frequency response. Addressing this gap is essential for enabling DTs to coordinate large fleets of DERs under realistic communication conditions.

3.5.4 Quality of Data Supporting the DTs and Validation Platforms

Another critical area requiring dedicated investigation is understanding and quantifying the impact of the quality of measurement data that underpins DTs. This challenge is particularly relevant for frequency control applications, where the sub-second dynamics of DERs can strongly affect control effectiveness and overall system stability. However, many existing studies assume ideal signal availability and overlook the influence of reporting rates, noise, and missing data on model fidelity. Such over simplifications limit the applicability of DTs in real-world conditions, where data imperfections are unavoidable. Consequently, there is a pressing need for method for determining the suitable data reporting rates and methods to address degraded communication performance, e.g. latency and packet loss, in order to ensure accurate and reliable DT operation across a wide range of system conditions.

In addition, DT validation is typically confined to software-based simulations, with few reports of realistic testing environments to assess DT performance prior to deployment. Current literature also lacks platforms and tools for examining the impact of communication impairments such as latency, jitter, and sample reordering, despite they are critical factors need to be considered in practice. This gap highlights the need for experimental platforms testing DTs, in order to ensure that DT frameworks and

applications are not only accurate but also resilient to failures in measurement and communication processes, ensuring robust operation under realistic grid conditions.

3.6 Summary

As outlined in Chapter 1, one of the key research gaps lies in the limited application of DTs for real-time frequency services in the power sector. This chapter reviewed the definition and evolution of the DT concept, its applications and the associated TRL levels across different industrial sectors. The focus was then placed on the DTs' applications in the power sector, where a number of example use cases were introduced in detail. Industrial initiatives confirm the growing interest in DTs but remain largely at the demonstration stage. Academic studies demonstrate a wide range of DT functions but also indicate gaps in high-fidelity DER modelling, coordinated control under communication constraints, and validation under realistic conditions. These findings motivate the following chapters, which focuses on modelling for DTs, along the supporting dispatch and control scheme to enable DERs to participate in frequency regulation.

Chapter 4

Creation of DTs for DERs to Enable Frequency Control

This chapter presents the methods for creating DTs of DERs so that they can be used to support frequency control applications. Capturing the dynamic behaviour of DERs with high fidelity is essential for designing fast and coordinated frequency response strategies. Three modelling approaches are explored, i.e. physics-based (white-box), system identification-based (grey-box), and data-driven (black-box). The choice of the approach depends on the available information about DERs and their intended role in scheduling and control for frequency support. Since DTs require live data to reflect actual system dynamics, this chapter also presents techniques for determining the minimum data reporting requirements and for addressing the impact of communication performance on DT accuracy.

To validate DT performance, a real-time HiL testing platform is designed, where physical DERs are represented using a real-time simulator and their corresponding DTs are hosted on dedicated computing devices. The platform also emulates communication effects (e.g. latency and jitter) to reflect real-world conditions. While the DTs are created at the device level, their intended application is system-wide coordination for effective frequency control, and they can be integrated into higher-level network DTs to enable broader applications.

This chapter is organised as follows. Section 4.1.1 presents the three modelling approaches of DTs using physics-based, system identification-based and data-driven approaches, where the assumption of data availability and also the suitable applications are also discussed. Section 4.2 presents a method for determining the minimum data reporting rate to support the created DTs. Section 4.3 describes the design of the testing platform for DT-based applications, where the design considerations are also discussed. Section 4.4 evaluates the performance of the created DTs using the designed HiL test platform. Section 4.5 provides a summary of the chapter.

4.1 Creation of DTs of DERs

4.1.1 Selection of Modelling Techniques

The selection of modelling technique for DT virtual models depends both on the level of knowledge available about the internal structure, parameters, and control characteristics of the DERs, and on the intended application of the DTs. The application requirements influence the necessary level of model fidelity and computational complexity, which in turn affect the selection of modelling methods. There are three different types of models that could be considered, i.e. *white-box*, *grey-box*, and *black-box*, which are terms originated from software [152]. They describe the level of tester's insight into a program's internal logic. This classification has also been widely adopted in power system modelling [153–155], where white-box methods assume full visibility of the system, grey-box methods provide partial insight into the system's structure, and black-box methods rely solely on inputs and outputs. The analogy holds in DT modelling for DERs: depending on the availability of structural and control information, DTs may be built from full knowledge of the physical system, simplified physical assumptions with estimated parameters, or entirely from input–output data. This classification provides a practical framework for selecting appropriate techniques based on system accessibility and data availability.

White-box models are developed using physics-based approaches and constructed from comprehensive knowledge of a system's physical structure and control logics. For

certain DERs with open-source models or detailed manufacturer documentations, parameters and control information allow for accurate physics-based representations of dynamic responses. These models are highly interpretable and reliable, making them well suited for control design and safety-critical studies. However, their development is time-intensive, requiring specialised expertise in areas, e.g. power electronics and dynamic system modelling, and is often limited by restricted access to proprietary information in commercial DERs.

Grey-box models can be created using system identification methods that combine partial physical knowledge with measurement data. This approach is effective when the general system structure is known (e.g. system topology or control layers) but detailed parameters or control logics are unavailable. By making assumptions, e.g. linear time-invariant behaviour, dynamics can be approximated through transfer functions or state-space models. Grey-box models offer a balance between interpretability and flexibility, using available documentation to define the model structure while calibrating unknown dynamics with data. Their accuracy, however, may degrade under operating conditions not represented in the training dataset, particularly in the presence of non-linearities or mode-switching behaviour.

Black-box models can be built using data-driven methods and primarily rely on observable input–output behaviour, without assumptions about internal structure or control logic. This approach is especially suitable for commercial inverters or closed-source controllers where internal details are inaccessible. For DT prototyping, black-box models are applicable when transparency is limited but massive input–output data is available. These models, if constructed using data-driven methods, can typically be made lightweighted and computationally efficient, which make them well suited for real-time applications and large-scale what-if simulations. Despite their flexibility and scalability across diverse DERs, black-box models lack physical interpretability and may show poor performance under operating conditions that not represented in the training data.

In summary, the selection of the model types depends on the accessibility of internal information and the expected application of the DT. Each approach offers a different

Table 4.1: Selection of modelling methods

Classification	Modelling method	Interpretability and reliability	Data dependency	Flexibility
White-box	Physics-based	High	Low	Low
Grey-box	System identification	Medium	Medium	Medium
Black-box	Data-driven	Low	High	High

balance between interpretability, flexibility, and data dependency. In practice, DT prototyping for DERs often involves combining multiple modelling strategies to adapt to the diversity and limited transparency of real-world systems. In this work, all three types of models are investigated, and are discussed in detail in the following subsections.

4.1.2 Physics-Based DTs

In the context of DTs creation, physics-based modelling provides a fundamental framework for reproducing the internal dynamics of DERs with high fidelity. This is the most basic and straightforward approach in terms of methodologies used for modelling, as it directly embeds the governing equations, control logic, and device characteristics that dictate DER behaviour, thereby offering interpretability, reliability, and strong generalisation across operating conditions. To achieve this, several key aspects must be considered in the modelling process:

- Fidelity of system dynamics. The DT must represent the dynamic behaviour of the physical system with sufficient accuracy to capture the relevant dynamic characteristics. This requirement is similar to conventional modelling practices used in power system analysis, where the objective is to reproduce actual system responses to disturbances and control actions. However, in the DT context, fidelity is not only a matter of accurate simulation under a certain operating conditions but also of ensuring that the model remains valid across a wide range of operating conditions encountered in real-time operation.
- Real-time performance. Beyond modelling fidelity and variable selection, physics-based DTs must consider the model efficiency for real time operation. This involves

meeting strict computational deadlines so that the DT can process incoming data, execute simulations, and deliver outputs within the time frames required by the application. Achieving real-time performance requires a careful balance between model complexity and computational burden. Highly detailed models may offer better fidelity but risk being too computationally heavy for real-time use. Therefore, an appropriate balance between accuracy and efficiency is essential.

- Selection of input and output variables. A critical distinction between traditional offline models and DTs lies in their data interfaces. Offline models typically rely on pre-configured parameters, with simulations executed under fixed assumptions. In contrast, DTs must be driven by live measurement data, and continuously adapt to reflect the state of the physical asset. At the same time, the DT is expected to provide real-time outputs that support targeted applications, e.g. frequency control in this thesis. The careful selection of input and output channels is therefore essential, both to ensure that the DT captures the most influential system behaviours and to guarantee compatibility with the measurement and communication infrastructure available in practice.

To illustrate the physics-based modelling methodology, a modified microgrid test system comprising three representative DERs is considered in the following sections: a droop-controlled BESS, an gas turbine-based SG, and a grid-forming converter (GFC) with virtual synchronous machine (VSM) control, adapted from the benchmark system in [156]. Since the targeted application of the DER DTs is frequency control, the primary variables of interest are system frequency and active power. With this consideration, and to balance the trade-off between model fidelity and real-time performance, this work adopts an analytical modelling approach, where transfer functions are used to represent the frequency and active power dynamics of each DER. The corresponding block diagrams illustrating these dynamics for the three systems are shown in Figure 4.1, Figure 4.2, and Figure 4.3, respectively.

Figure 4.1 presents the block diagram of the BESS with a droop controller. The inputs to the model are the grid frequency and the reference power set-point. The

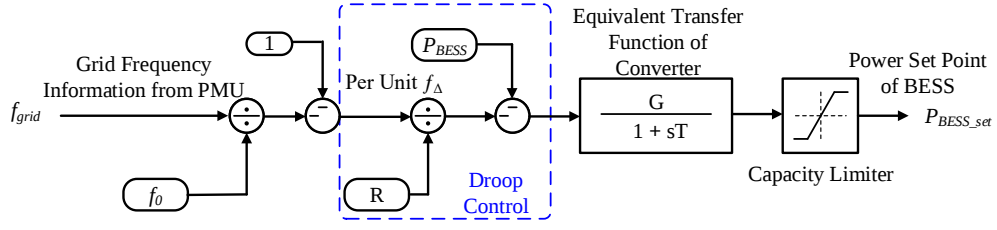


Figure 4.1: Block diagram of droop-controlled BESS [156].

grid frequency is treated as a system-wide variable, which can be measured through a PMU or similar frequency measurement devices, and must be updated continuously in real time. By contrast, the reference power set-point is updated at slower timescales, typically in the order of minutes.

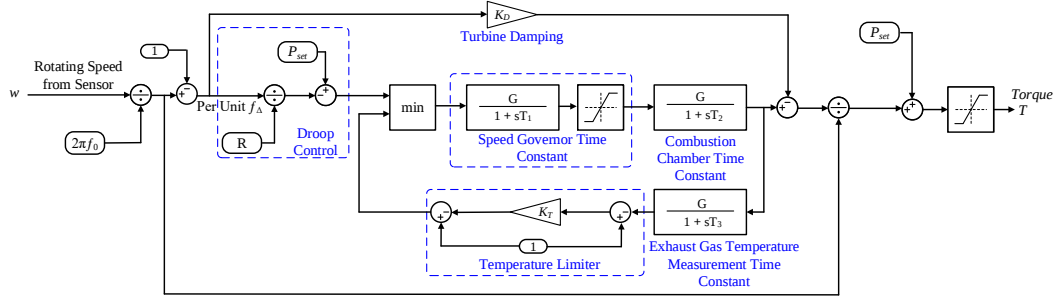


Figure 4.2: Block diagram of GAST [157].

Similarly, the input to the gas turbine SG model, as shown in Figure 4.2, is the measured rotational speed, which is assumed to be equivalent to the system frequency. For droop control implementation, the speed input is first normalised into per-unit frequency and subsequently processed through droop and damping gains. The SG's functional subsystems, including the speed governor, combustion chamber, and exhaust gas temperature limiter, are each represented by first-order transfer functions to capture their essential dynamic behaviour.

For the VSM-based GFC, the control structure is shown in Figure 4.3. The model implements a grid-forming control strategy with a conventional nested controller augmented by an inertia emulator. The converter's output voltage is regulated according to the reference frequency f_{ref} and voltage magnitude v_{dqref} . While the primary variable

of interest is the reference power determined by the droop control algorithm, the contributions of inertia and damping power are also crucial for understanding the system's frequency response and therefore warrant detailed investigation.

4.1.3 System Identification-Based DTs

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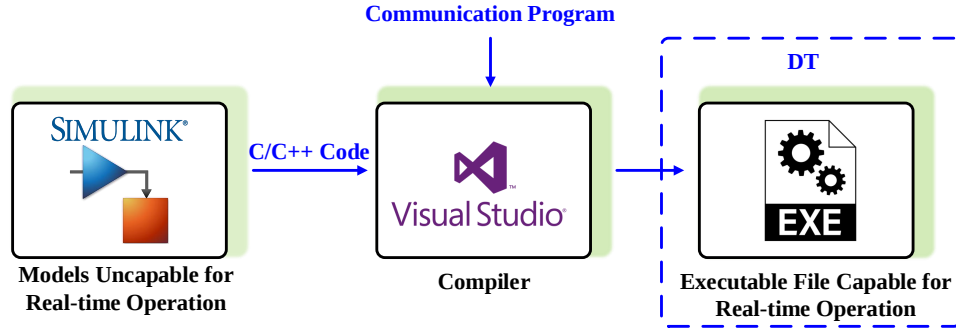


Figure 4.4: The detailed process of DT development

The detailed methodology developed for creating a system identification-based DT is illustrated in the flowchat presented in Figure 4.5. The process begins with applying a step command to the active power reference signal of the targeted DER. This can be performed either on the physical DER itself or on a detailed DER model, including encrypted or black-box models that do not disclose internal design details. Such scenarios are particularly relevant to energy aggregators and other DER asset owners, who may have direct access to physical DERs or be provided with vendor-supplied black-box models.

During the test, the input reference power signal and the corresponding active power response are monitored and recorded as time-series data. These data sets are then imported into system identification tools for model derivation. In this work, the MATLAB System Identification Toolbox is employed, as shown in Stage I of Figure 4.5. The toolbox estimates models by fitting parameterised structures (e.g., transfer functions) to the measured data, typically using prediction-error minimisation algorithms. These algorithms iteratively adjust the model parameters to minimise the difference between the measured output and the model-predicted output across the data set, with the error evaluated in least-squares framework. To initialise the identification process, the expected characteristics of the system must be specified by defining the number of zeros and poles of the transfer function model. This is where partial knowledge of the system is required. Once the candidate transfer function is obtained, it can be simulated using the same input step signal, and its output response is compared against the actual DER

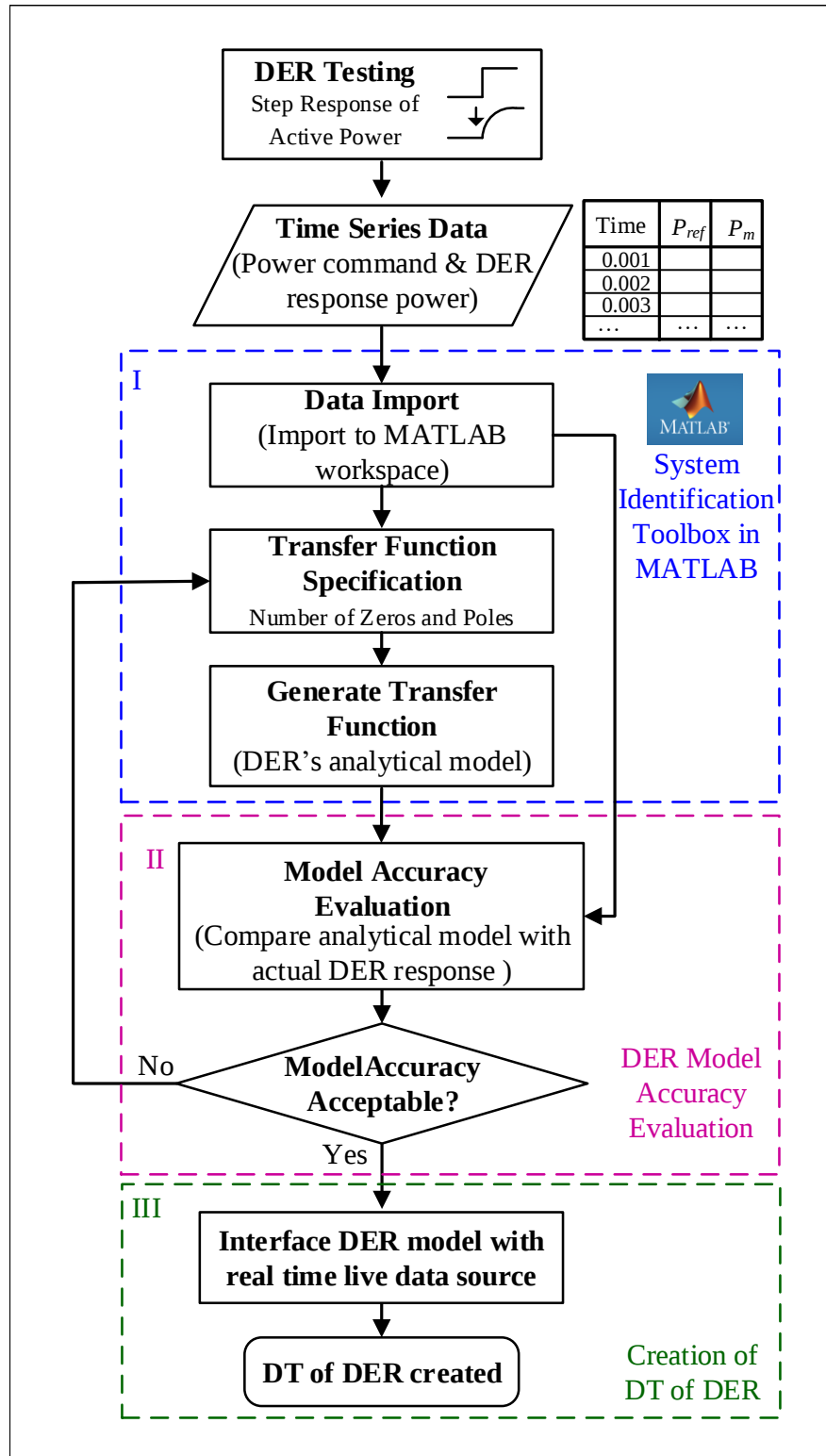


Figure 4.5: The process of implementing DTs for the DERs

behaviour, as illustrated in Stage II of Figure 4.5.

4.1.4 Data-Driven DTs

When there is little knowledge of the internal structure or design of the DERs, it is possible to rely entirely on test data to generate a data-driven model. In such cases, access to the physical DER is required to perform a wide range of tests in order to collect representative datasets. Alternatively, as in the previous approach, detailed black-box models of the DERs can be employed to simulate their behaviour, with the resulting simulation data serving as the training data.

In this work, a data-driven DT is developed using a hybrid convolutional neural network (CNN) architecture [159]. The performance of the trained CNN model is directly linked to the representativeness of the training scenarios. The training dataset is constructed by simulating the behaviours of the DERs under a diverse set of frequency disturbance events. A large number of diverse cases should be designed to capture variations in DER power set-points and the magnitude of power imbalances in the system model. Particular attention is given to scenarios where non-linear dynamics and boundary effects are likely to arise. Extra test cases are executed in these regions to improve model accuracy. Broader operating conditions are also included to ensure generalisation, result in a balanced set of training cases. For each case, the grid frequency time series is recorded as the model input, and the corresponding active power responses of the DERs are collected as output data.

The CNN is implemented as a one-dimensional (1D) architecture, which is well suited for time-series processing such as frequency measurements. The network consists of three convolutional layers that progressively extract features from the input signal. Each convolutional layer is followed by normalisation, which helps stabilise and speed up the training process. A non-linear activation function is then applied, allowing the model to capture complex patterns rather than just linear relations. The output stage contains two additional convolutional layers that map the learned features to the predicted active power trajectory. The CNN is trained to output the change in active power, defined as the deviation between the actual response and the DER's power set-

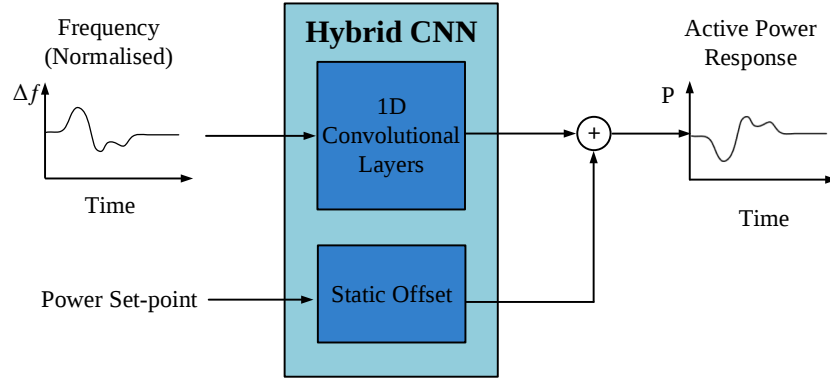


Figure 4.6: Structure of Hybrid CNN Model

point. The set-point is then added back to the model output, making the approach “hybrid” by combining physical knowledge with data-driven learning.

For preprocessing, the frequency input is first shifted so that 50 Hz corresponds to zero, making deviations more obvious for the model to learn. A ± 0.2 Hz deadband would be applied if the CNN model is trained for DERs used in DC services. The output data representing the active power responses of the DERs are retained in their physical units (MW). In this work, each case consisted in the dataset is 8 seconds with 50 Hz sampling rate, represented by a 400-point time window, where the length of time is selected empirically based on a typical frequency event duration. The dataset is divided into 80% for training and 20% for validation. Model training uses an adaptive optimisation algorithm with a small step size (learning rate of 0.001) to update parameters efficiently [160]. The error measure is based on the Smooth L1 loss (also called Huber loss), which behaves like squared error for small differences but switches to absolute error for larger ones, providing robustness against occasional outliers [161]. Finally, an early stopping mechanism with a patience of 100 epochs is applied to avoid over-fitting.

Model performance is evaluated on the validation set by comparing predicted and actual DER responses with new frequency events. During training, the loss on both training and validation data is tracked to ensure convergence and stability. The final trained model is saved once the best validation performance is achieved.

4.2 Data Reporting Rate to Support DTs

Section 4.1 presented several modelling approaches for creating DTs suitable for representing the dynamic behaviour of DERs with respect to frequency control and active power outputs. To ensure that such DTs operate reliably, it is essential to provide input data of sufficient quality to drive their real-time simulations. This section focuses on investigating the required data reporting rate necessary to achieve adequate DT accuracy. This analysis is particularly important as it provides guidance for specifying the measurement and communication infrastructure needed to support DT-enabled applications. For illustrative purposes, it is assumed that all DTs of DERs utilise frequency measurements obtained from PMUs as their primary input. These frequency signals are then used to estimate the broader dynamic behaviour of the DERs, including their active power outputs.

4.2.1 Impact of Data Reporting Rate on DT Accuracy

To illustrate the impact of data reporting rate on DT accuracy, the previously introduced grid-forming converter with VSM control is used as a case study [156]. Both the VSM and the microgrid are implemented as real-time models in RTDS, thereby emulating their physical counterparts. The control strategy of the VSM incorporates a droop controller together with an inertia emulation block, which monitors frequency deviations and produces power proportional to RoCoF [162]. The damping effect is introduced via a damping constant by comparing the VSM angular speed with the frequency estimated using a Phase-Locked Loop (PLL). A DT of the VSM was developed using the physics-based approach as presented in Section 4.1.1 and deployed on a separate hardware platform [163], which is designed to utilise frequency measurements from the grid as inputs to calculate the real-time active power output of the physical system. The frequency measurement is supplied by a PMU model within the RTDS, capable of reporting at up to 5000 Hz over an Ethernet connection (note, physical PMUs are typically not able to output at such a high reporting rate in practice). During frequency events, three dynamic components of the VSM are particularly critical, i.e. droop power,

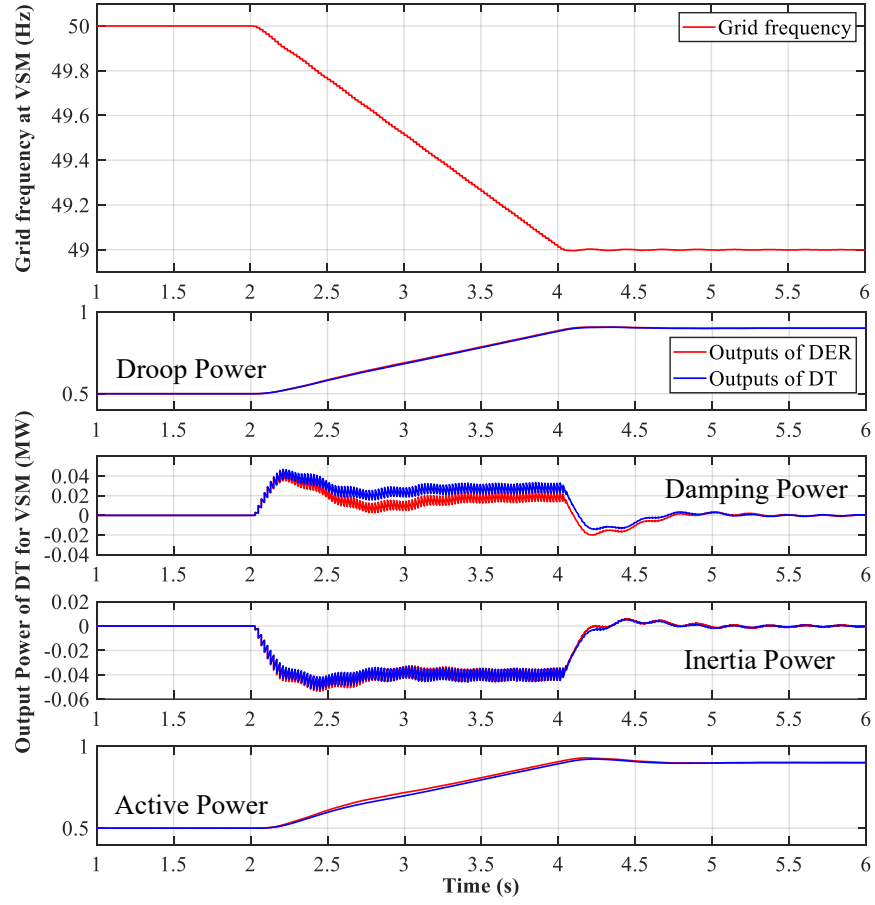


Figure 4.7: The DT accuracy with information source at reporting rate of 5000 Hz

inertial power, and damping power. These three quantities are used in this study as representative metrics to evaluate how the choice of data reporting rate affects the accuracy and effectiveness of DTs.

The VSM DT is expected to accurately track the relevant dynamic behaviours during frequency events. To test this capability, a case study was conducted to simulate frequency deviations in the power grid that can lead to notable responses from the VSM. Initially, the microgrid containing the VSM was connected to the main grid and operating at the nominal frequency of 50 Hz. Due to the droop characteristic, the active power output of the VSM varies proportionally with frequency deviations, while the inertia and damping controllers respond dynamically to changes in system frequency. A frequency event of 6 s duration was triggered using an controllable voltage source driv-

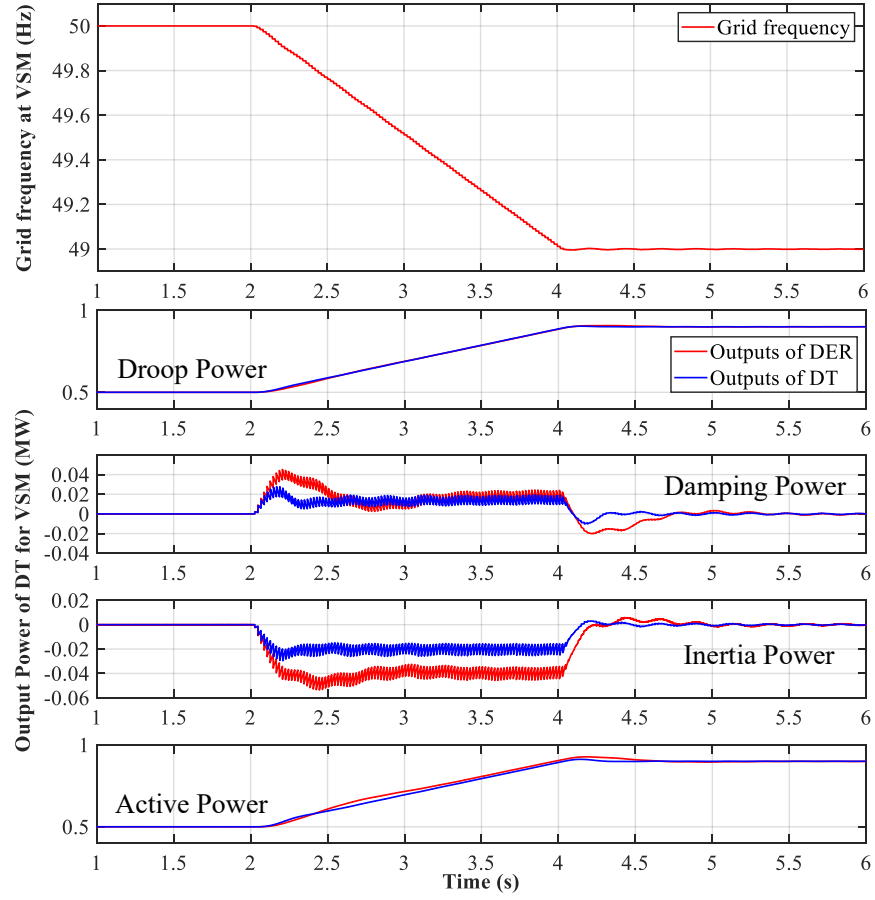


Figure 4.8: The DT accuracy with information source at reporting rate of 500 Hz

ing the microgrid to evaluate DT accuracy under three different input data reporting rates. The results are shown in Figures 4.7 to 4.9. At $t = 2$ s, the main grid frequency experienced a ramped decrease from 50 Hz to 49 Hz with a RoCoF of $-0.5, \text{Hz/s}$, as shown in Figure 4.7. This event is designed to emulate the impact of a generation loss in the main grid. The inputs to the DT consist of PMU measurements provided at three different reporting rates, transmitted via the GTNET-SKT2 card (communication interface hardware on RTDS) to the DT hosted on a separate hardware platform. The corresponding DT outputs are compared against the physical system in Figures 4.7 to 4.9.

From Figure 4.8, it can be observed that the difference of the output between the actual VSM and its DT emerge to be apparent when the reporting rate falls below 500

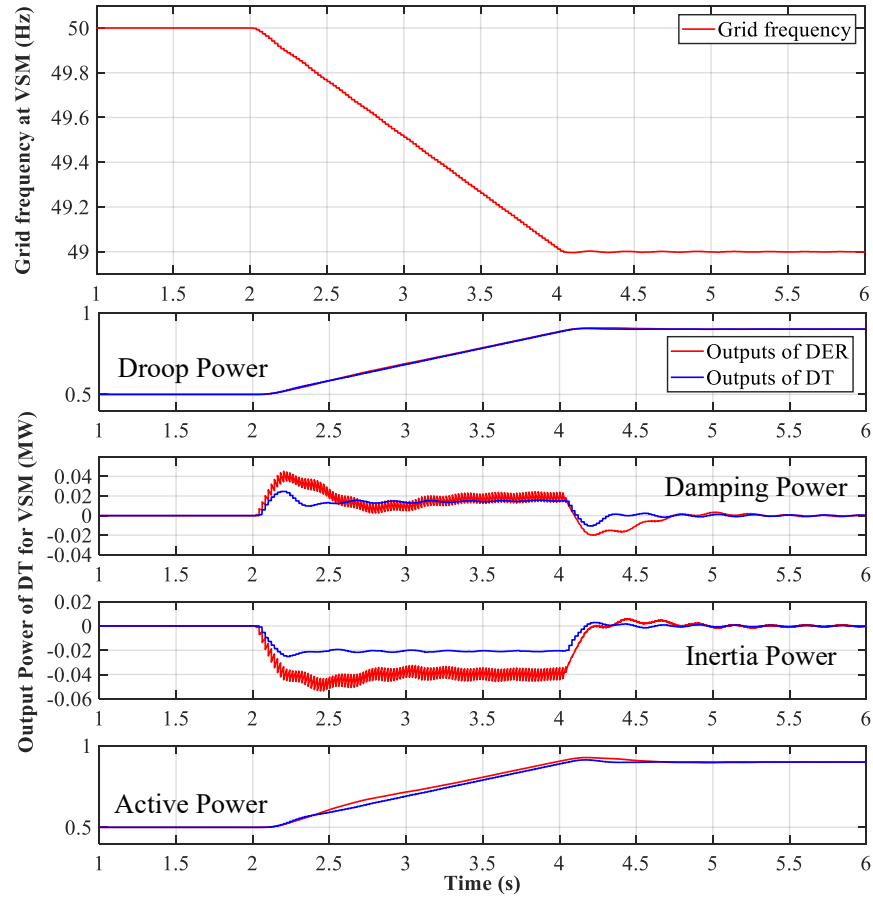


Figure 4.9: The DT accuracy with information source at reporting rate of 50 Hz

Hz. At a reporting rate of 5000 Hz, the DT successfully tracks the dynamic behaviour of the VSM, which confirms the validity of the modelling approach. The discrepancies at lower rates are therefore attributed to limitations in the reporting rate of the measurement data, which serve as the DT inputs. In typical practice, PMUs operate with a default reporting rate of around 50 Hz. However, applying such a rate in this context results in significant errors in the DT's response, as illustrated in Figure 4.9. While some PMUs can be configured to output data at a higher rate, e.g. 200 Hz, it is still inadequate based on the case study. Consequently, DTs of DERs relying on standard PMU configurations are unlikely to achieve the accuracy required for many real-time applications and services. Higher reporting rates are therefore essential to ensure that physics-based DTs deliver reliable outputs for frequency control and other time-sensitive

operations. Therefore, new methods and solutions will be required in order to unlock this limitation.

4.2.2 Mechanism of DT Response Distortion and Solutions

This section analysis the root cause of increased DT error as a result of decreasing data reporting rate. Figure 4.10 illustrates the differences between hardware operating in the physical world and the DT implemented in the virtual space [164]. For a physical VSM, as represented in Figure 4.10(a), the system operates continuously. Its associated properties, e.g. frequency and power outputs also evolve in real time. In contrast, the DT of the VSM can be described by differential equations, as shown in Figure 4.10(b). To interface with the digital model, frequency measurements must first be sampled by an Analog-to-Digital Converter (ADC), which transforms the signal into digital form. This conversion process may introduce distortion, the severity of which can be quantitatively assessed using the Signal-to-Noise Ratio (SNR). The resulting SNR depends on the chosen sampling rate, which determines how accurately the analogue signal is represented in digital form.

According to [164], digital control systems can achieve satisfactory performance if the sampling rate is at least 30 times greater than the closed-loop system bandwidth. This rule of thumb is adopted as a reference benchmark in this work for comparison with the experimental results presented later. This criterion provides a theoretical baseline for determining the minimum reporting rate required to preserve DT fidelity.

To address the low accuracy resulting from insufficient data reporting rates, discretisation can be applied to the virtual model in order to mitigate the negative effects introduced by low sampling. Discretisation refers to the process of converting continuous functions, models, variables, and equations into discrete equivalents, making them suitable for implementation on digital computing platforms [165]. In the modelling process, the integrators of the DER models are converted into discrete form using the Zero-Order Hold (ZOH) method. ZOH is a sample-and-hold operation in which the input signal is held constant over each sampling interval, producing a piecewise-constant output that approximates the continuous input signal. This process is illustrated in Fig-

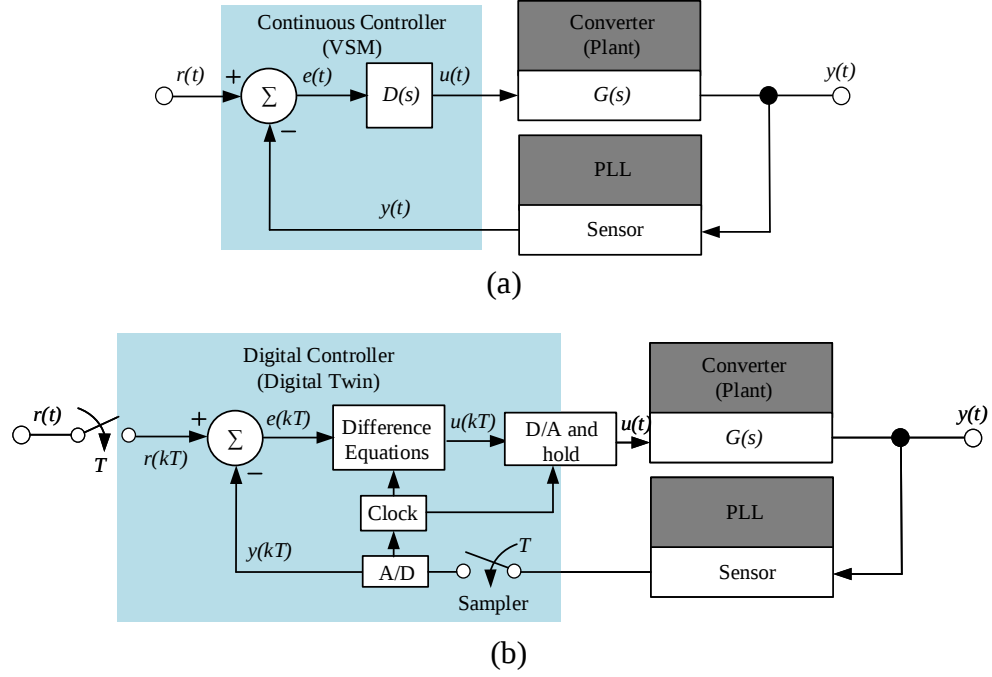


Figure 4.10: Continuous controller to digital controller: (a) VSM (b) DT of VSM

Figure 4.11, which resembles the behaviour of step signals. To ensure accurate monitoring of intermediate variables, e.g. damping power and inertia power, all continuous-time blocks within the DT's virtual model must be discretised using the ZOH approach.

Three additional scenarios were studied to evaluate the performance of the DT after discretisation under different data reporting rates. In the RTDS, which simulates the VSM to emulate the physical system, the input signal of the VSM is updated every $50\mu\text{s}$, so it can be approximately considered as continuous. By contrast, the DT input signal is supplied at discrete reporting rates, with 50 Hz (i.e. at a time interval of 20 ms) used as the baseline case. Despite the large difference between these reporting rates, the DT's ability to track system dynamics improved significantly after discretisation, even at the relatively low rate of 50 Hz, as shown in Figure 4.12. The tracking capability gradually weakens as the reporting rate decreases from 50 Hz (Figure 4.12) to 8 Hz (Figure 4.14). Further analysis revealed that un-damped oscillations occur when the reporting rate is reduced to 7 Hz, indicating that 8 Hz is the minimum requirement for stable DT operation with acceptable accuracy. This case study showcases that applying the ZOH-

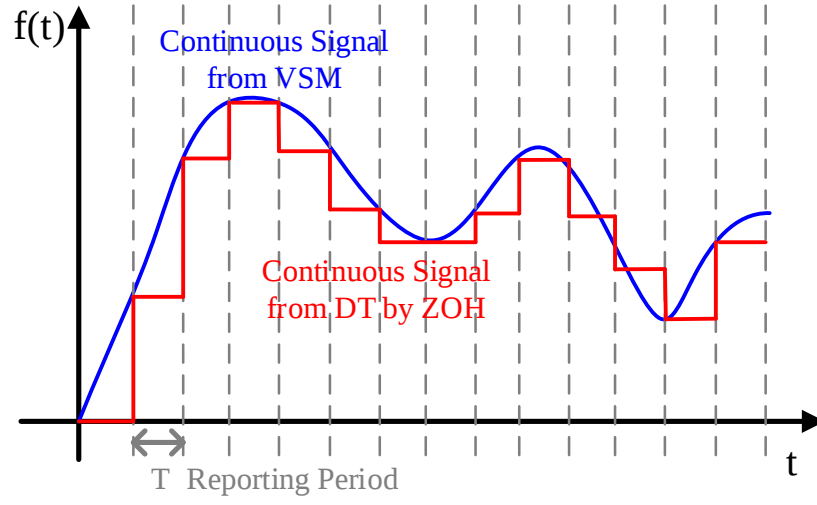


Figure 4.11: Discretisation of DT model by ZOH method.

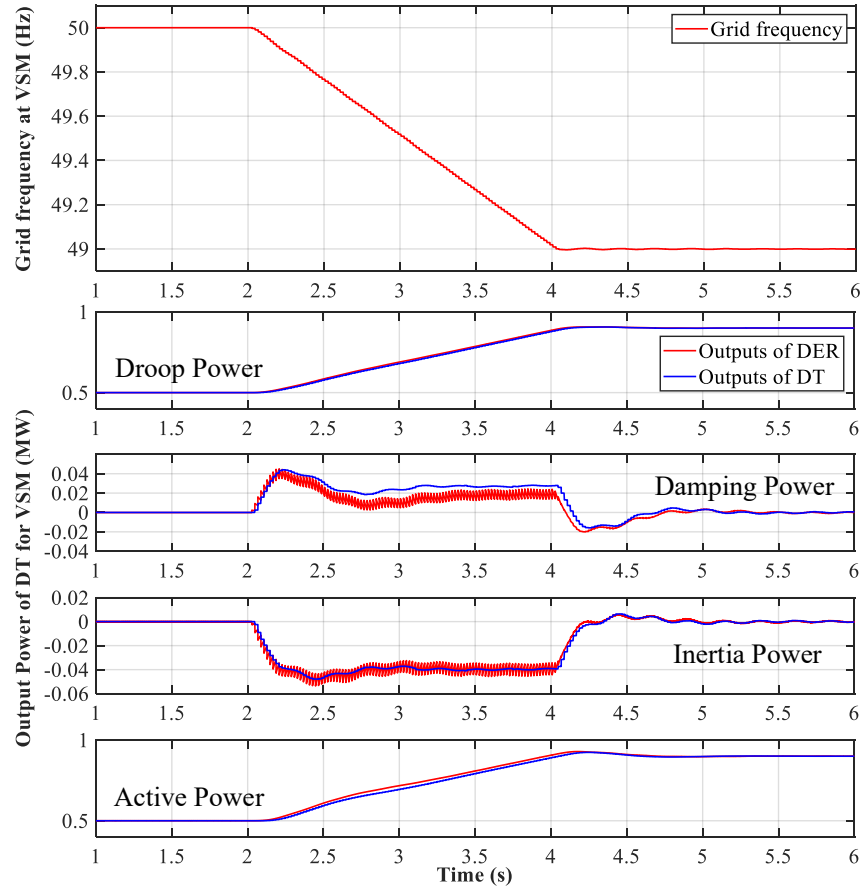


Figure 4.12: DT performance after discretisation at reporting rate of 50 Hz

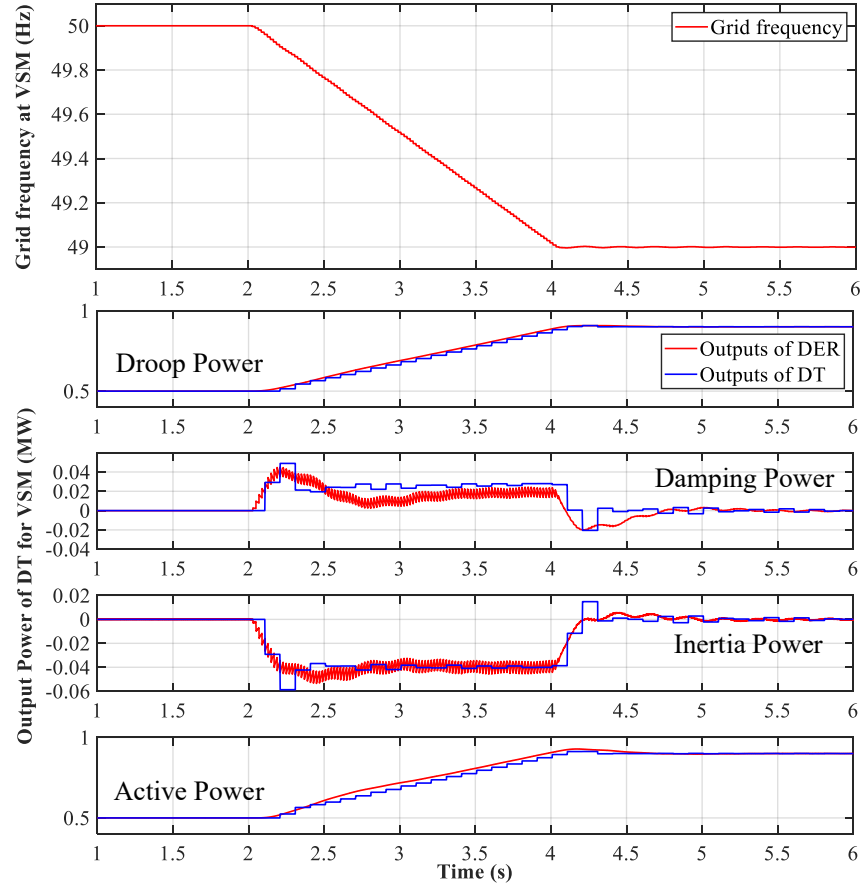


Figure 4.13: DT performance after discretisation at reporting rate of 10 Hz

based discretisation method to the DT model can substantially improve accuracy, even when data rates are low. In other words, the minimum required data reporting rate for a DT can be relaxed by incorporating ZOH discretisation. Nonetheless, as shown in Figure 4.12, noticeable errors still appear when the reporting rate is reduced to 10 Hz as shown in Figure 4.13. To systematically determine the minimum reporting rate required for real-time monitoring applications, this paper proposes two estimation methods, which are introduced in the following section.

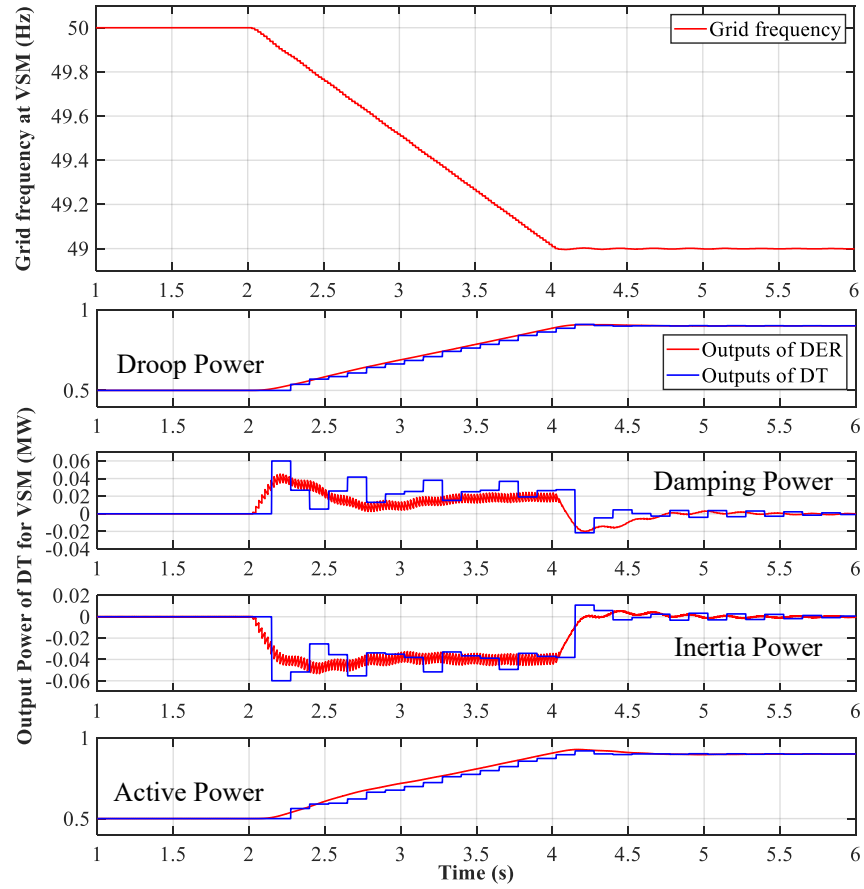


Figure 4.14: DT performance after discretisation at reporting rate of 8 Hz

4.2.3 Methods of Determining Minimum Required Data Reporting Rate

As mentioned in Section 4.2.2, the bandwidth of a closed-loop system determines the requirements of input signals reporting rate. Therefore, frequency-domain analysis is essential for identifying the data reporting rate needed to support DT operation.

Estimation of Minimum Required Data Reporting Rate for Physic-Based DTs

For physics-based DTs, frequency-domain analysis provides a direct way to assess the dynamic characteristics of the system model. This can be carried out using commercially available software tools, e.g. the Model Linearizer application available in In

MATLAB/Simulink [166]. The first step is to define the open-loop input and output points in the Simulink model. This is necessary because the toolbox performs local linearisation around an operating point, and it requires a clear signal path to compute the small-signal transfer function. By dividing the loop at a chosen location, the tool isolates the response of the model to a small variation at the input without interference from feedback controllers.

Once the open-loop path is defined, a linearised representation of the system is computed at the chosen operating point. This produces a state-space model that approximates the system dynamics locally, which is then used to generate the Bode plot. The plot shows both the magnitude and phase response as a function of frequency, which provides information of the system's ability to track or reject disturbances.

The -3 dB bandwidth, also known as the closed-loop bandwidth, is identified on the magnitude plot at the frequency where the gain falls to 70.7% of its steady-state. This point represents the effective speed of the system: signals within this bandwidth are tracked with minimal attenuation, while higher-frequency variations are increasingly filtered out. According to Franklin et al. [164], ensuring that the reporting rate is at least 30 times this bandwidth avoids aliasing and distortion when the DT processes input data in discrete time. This establishes a practical lower bound on the digital sampling rate required to preserve fidelity in DT outputs.

Estimation of Minimum Required Data Reporting Rate for System Identification-Based DTs

For System Identification Based DTs, the initial steps of this process follow the same system identification workflow introduced in Section 4.1.3 (Figure 4.5), including the collection of input-output time series, model fitting using the MATLAB System Identification Toolbox, and accuracy validation. For reporting rate estimation, however, the focus shifts to ensuring that the data set contains sufficient frequency content to capture the DER dynamics. As illustrated in Figure 4.15, frequency disturbance events of varying magnitudes and durations are applied, and the resulting time-series data are pre-processed (e.g., DC filtering and dataset splitting). Transfer function models are

then estimated and validated as before.

Once a model of acceptable accuracy is obtained, the next stage departs from the previous workflow. Instead of proceeding directly to DT implementation, the validated transfer function is used to derive the frequency response of the DER. A Bode plot is generated, and the -3 dB bandwidth is identified. According to established practice [164], multiplying this bandwidth by a factor of thirty provides the minimum reporting rate required for DT input data. This step translates operational measurements into a quantitative reporting requirement for data-driven DTs. This methodology is later demonstrated through a VSM-based GFC case study, where the minimum reporting rate is derived and validated on the HiL platform.

It should be noted that the CNN-based DT's minimum reporting rate is not investigated in detail in this work for two main reasons: 1) it is primarily used for running live what-if scenarios to support DER dispatch rather than for real-time control; and 2) the closed-loop bandwidth of the CNN cannot be directly measured, as its dynamics are embedded in the data-driven representation rather than expressed in an explicit transfer function, so the proposed method is not directly applicable.

4.3 Design of a Realistic Hardware-in-the-Loop Testing Platform for DTs

4.3.1 Design Considerations

By nature, DT is a multidisciplinary technology that integrates a wide range of techniques, including physical system modelling, sensing, and communications. Consequently, the design of a testing platform for DTs must account for these unique characteristics. As previously shown in Figure 3.3, the general structure of a DT system, comprises five key elements: 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 support various applications. The key design considerations for addressing these elements are discussed below.

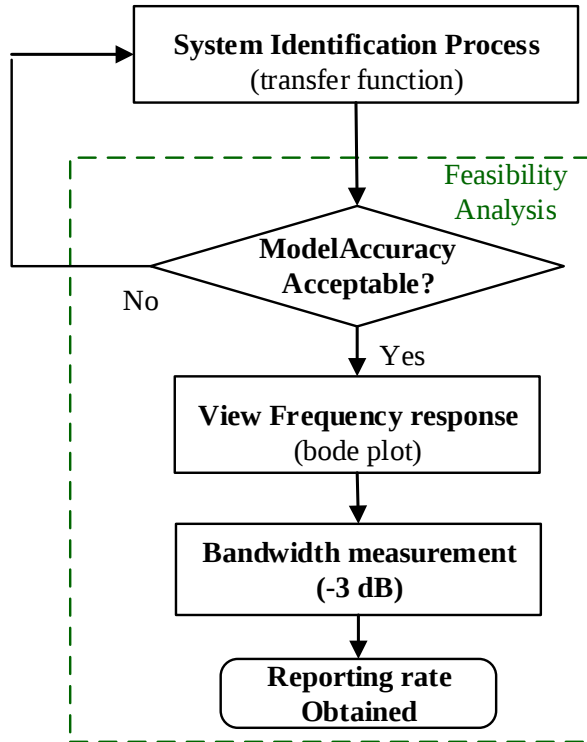


Figure 4.15: Determining minimum data reporting rate for system identification-based DTs

- **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. the 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 potential 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 behaviours.

- 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.

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 following section will

focus on designing a testing platform specifically for DTs of DERs to enable frequency control ancillary services.

4.3.2 Overview of the DT Testing Platform

With the consideration factors for DT-based systems listed in Section 4.3, 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 4.16, comprises the five key elements typically required for demonstrating and testing DT-based solutions. The key characteristics of these elements are summarised as follows:

- The physical DERs are represented with real-time DERs models simulated in an RTDS simulator. One of the DERs are represented by a power converter interfaced with RTDS.
- 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 established via the GTNET card and an Ethernet switch, together with a dedicated software-based communication delay emulator implemented in this platform (see Section 4.3.5). User Datagram Protocol (UDP) is adopted for these channels, as it is well suited to real-time, high-rate streaming where minimising latency is prioritised over guaranteed delivery.

- 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 as the DTs.

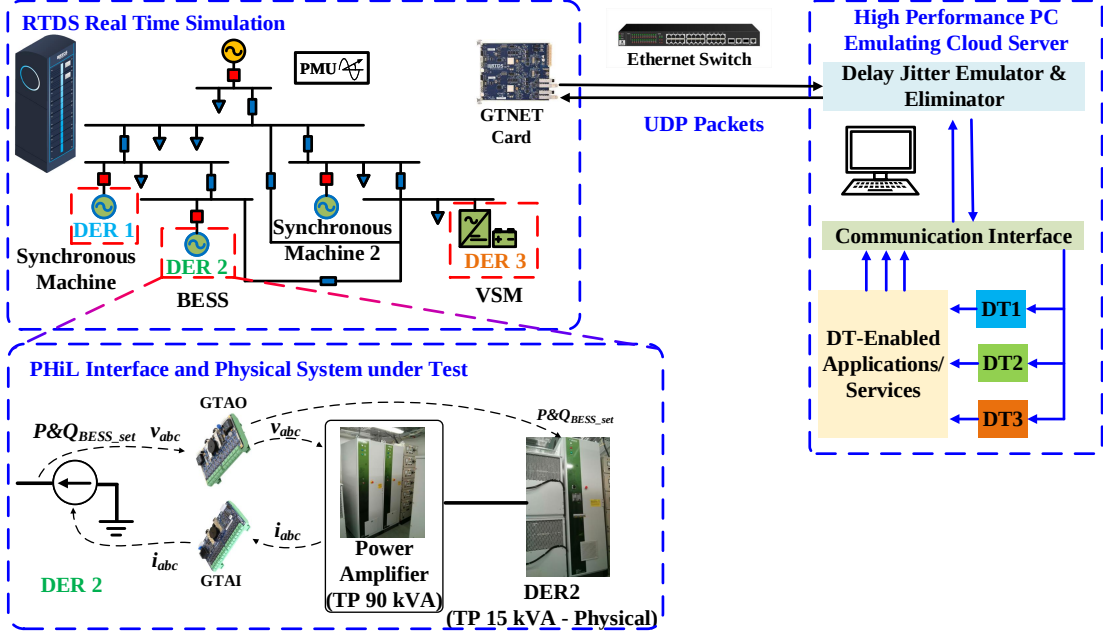


Figure 4.16: Lab set-up of the DT-based real-time HiL platform.

4.3.3 Physical DERs being Simulated

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 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. For illustration purpose, an SG and a battery-based VSM are hosted on RTDS as illustrated in Figure 4.16 as an example.

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 the designed platform, the actual physical hardware system incorporated into this PHIL is a back-to-back Triphase 15 kVA (TP15 kVA) power converter, which is utilised to represent the droop-controlled BESS.

4.3.4 Execution and Host of DTs

Selecting an appropriate platform for hosting and executing the DT is highly depends on the target application and the modelling detail-level. In general, the platform must be capable of processing input measurement data and executing the DT logic within the required time step. For instance, DT-based monitoring of power electronic devices is typically hosted on FPGA platforms, as such models must operate in parallel with physical hardware at microsecond or sub-microsecond timescales.

In this work, DTs were created and tested on a standard PC, which provided sufficient computational capacity for light-weight model development, training, and validation. To investigate practical deployment, two hosting scenarios were considered. For cloud-hosted DTs, the PC was used as the execution environment. For edge-hosted DTs, Raspberry Pi devices were selected as representative low-cost embedded platforms, given their balance between computation capability and accessibility for prototyping [167].

4.3.5 Emulation of Communications

DTs require the real-time system measurement data from the physical world in order to replicate the physical system's behaviour. 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.

In this designed platform, the dynamic behaviours of DERs are packaged by a

GTNET-SKT2 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. The package sizes depend on the number of floats, each extra float will increase the package size by 4 bytes. User Datagram Protocol (UDP) is adopted to set up communication channels as it is suitable for real-time and high reporting rate streaming communications [168]. 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 utilise the reserved port to listen to incoming messages from the sending end.

The accuracy of the DTs in reflecting the physical systems' behaviour highly depends on the data that are transmitted through the communication network. 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. It was found in this work that communication jitter, if not dealt with appropriately, could significantly compromise the DTs' accuracy. As reported in [169, 170], 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 would be required in DT development.

In this work, a software-based communication emulator, as shown in Figure 4.17, has been developed to introduce an artificial random delay to the DT signals to emulate unstable communication channels. It 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. The working mechanism of the developed communication emulator does not introduce actual delay to

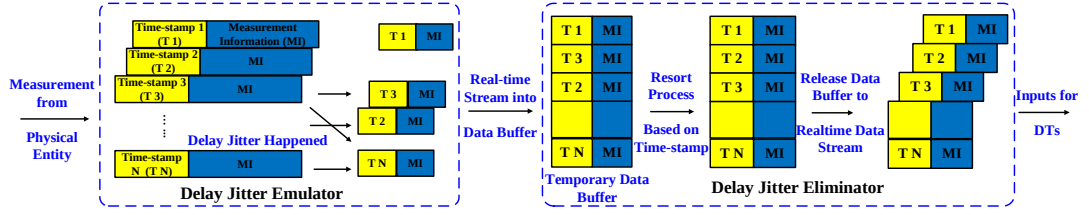


Figure 4.17: A representation of the design criteria of the delay jitter emulator and eliminator

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.

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.

4.3.6 Measurements for DTs

This DT platform aims at tracking the active power outputs of DERs with limited communicated data. As highlighted in Section 4.1, 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. PMUs. The reporting rate of PMU can be selected based the method presented in Section 4.2. 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 test and

validate the minimum sufficient reporting rate that is required for specific applications. The example applications for estimating DERs' active power output based on frequency measurement using the platform is demonstrated in the case studies in Section 4.4.

4.3.7 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 optimisation and behaviour prediction can potentially be further realised. 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 Chapter, 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.

4.4 Case studies: HiL Simulation and Validation of DT Tracking Capability

This section presents case studies that demonstrate the use of the proposed DT testing platform for validating and showcasing DTs for DERs. Although the platform is developed specifically for DTs of DERs to support frequency control, the methodology and approach are expected to provide valuable reference for similar DT-based applications.

The tracking capability of DTs is validated in Section 4.4.1, 4.4.2, and 4.4.3 by comparing their outputs with those of RTDS-based DERs. The impact of communication delay jitter and the effectiveness of the proposed jitter elimination method are assessed in Section 4.4.4.

4.4.1 Validation of Physic-Based 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 shown in Figure 4.16 is initially

connected with the main grid and operates at the nominal 50 Hz frequency. The main grid is represented using an controllable voltage source, which can be configured to drive ramped frequency changes for testing purposes. 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 4.18 and 4.19.

1. **Frequency deviation in grid-connected mode (50 Hz to 49 Hz).** At $t = 2\text{ s}$, upon the activation of the first scenario, the main grid frequency witnesses a significant drop from 50 Hz to 49 Hz with a 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 emulate an under-frequency event 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 emulate an over-frequency event in the islanded microgrid.

As illustrated in Figure 4.18, the DT tracking performance for SG is highly effective under these scenarios. As demonstrated by Figure 4.19, the overall tracking capability

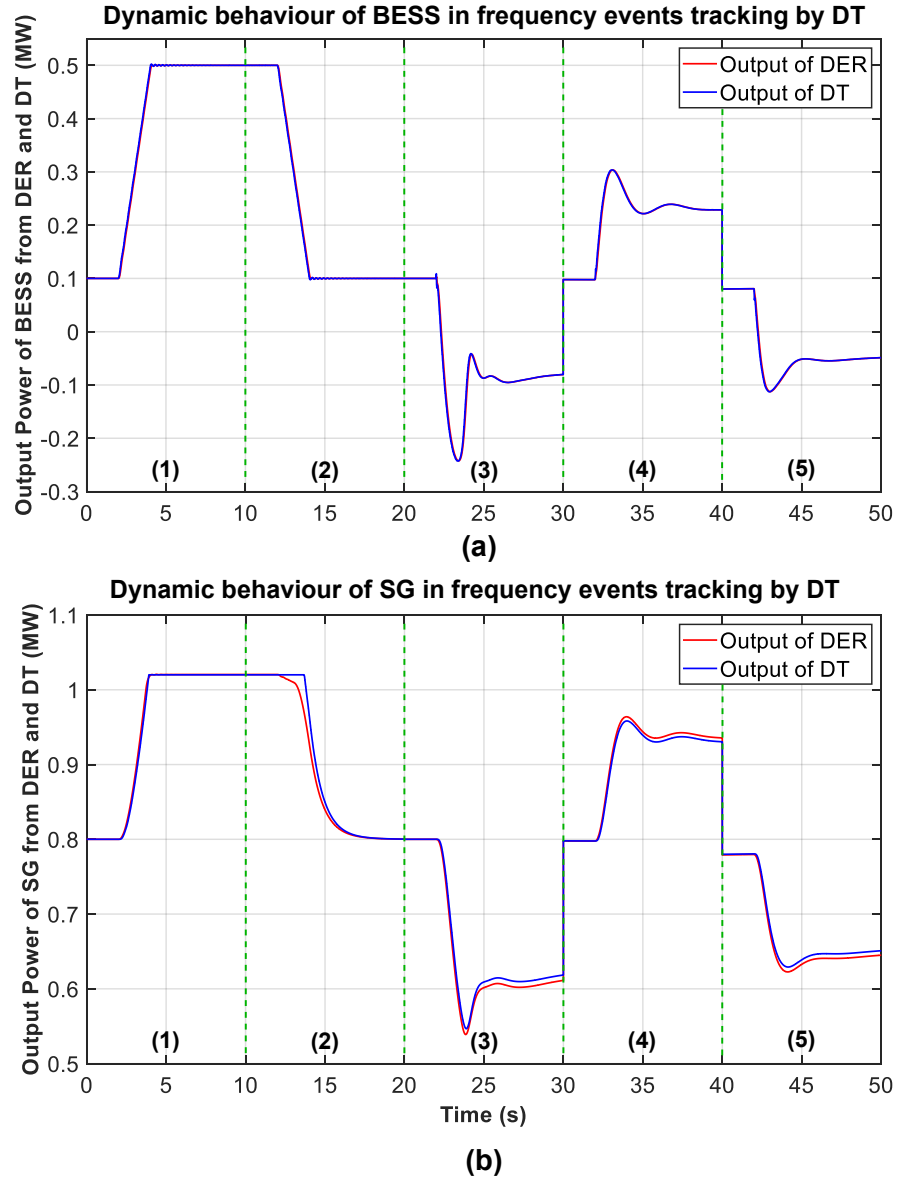


Figure 4.18: DTs of BESS and SG validation under five scenarios: (a) DT of BESS; (b) DT of VSM.

of DT for VSM is also reliable, but there are some oscillations on inertia response and damping power, which are relatively more apparent in when the microgrid is in the islanded mode. Part of the reason is the particular characteristic of these dynamic behaviours and the different time-steps between RTDS-hosted DERs and PC-hosted DTs, which is analysed in detail in Section 4.2.1. Another potential reason could be the change in system equivalent impedance due to transition to the islanded mode, which is outside of the scope of this paper and requires further investigation in the future. In general, the test results show the developed physics-based DTs provide satisfactory tracking capability to reflect the dynamic behaviour of DERs.

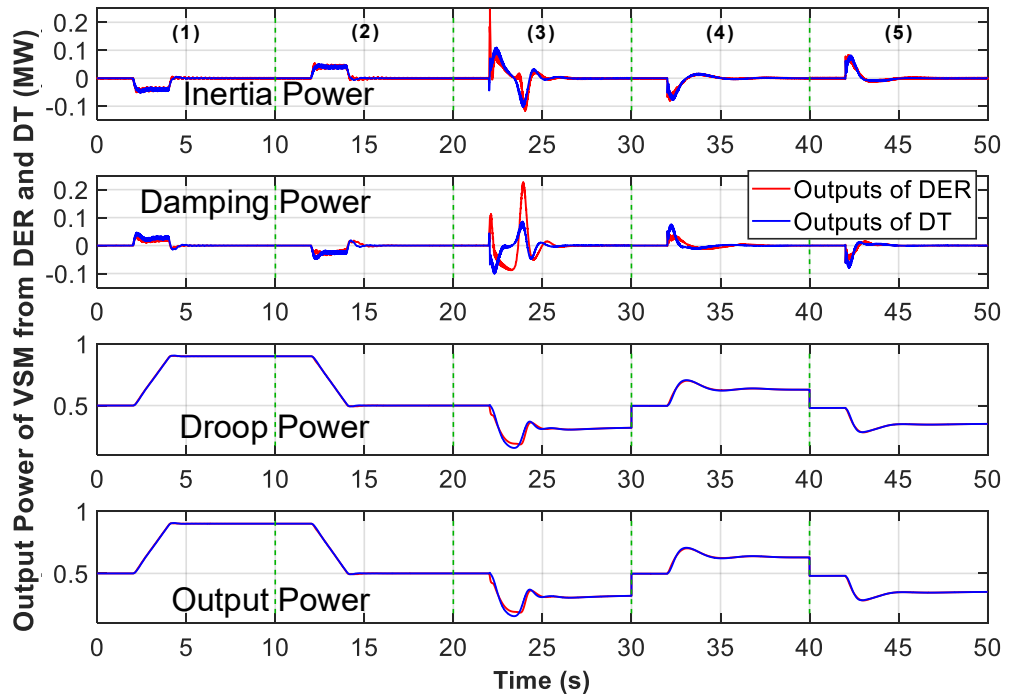


Figure 4.19: DT of VSM validation under five scenarios.

4.4.2 Validation of System Identification-Based DTs' Real-Time Tracking Capability

In this section, the DT of the VSM-based GFC is created using the system identification-based approach. Firstly, the system identification-based approach in reflecting the actual transfer function the system is evaluated. Figure 4.20 shows the validation results

of the transfer function model. The model achieved a best fit of 93.25%, demonstrating that the grey-box model have a satisfactory representation of the VSM dynamics with acceptable accuracy.

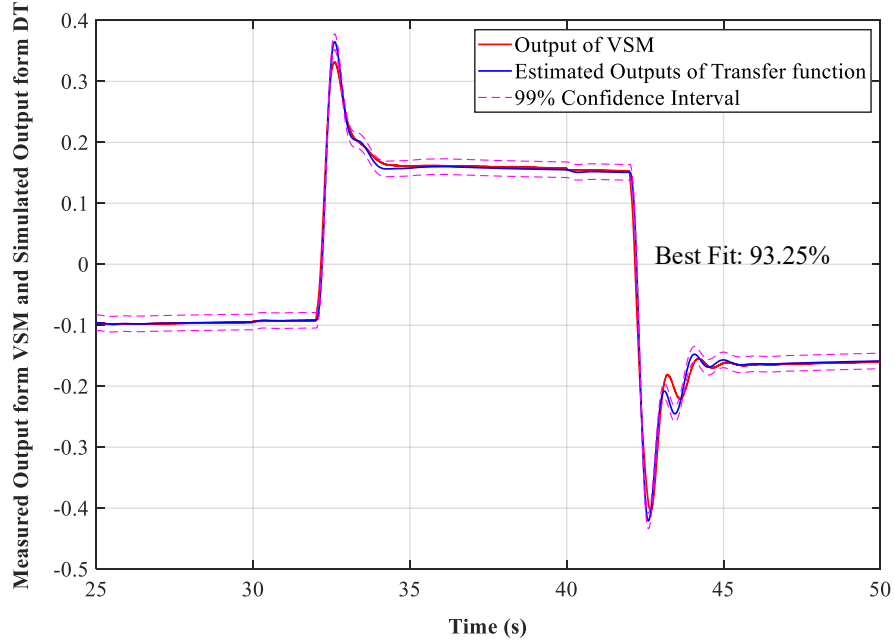


Figure 4.20: Comparison between VSM and the corresponding transfer function

Based on this transfer function, the corresponding Bode plot is presented in Figure 4.21 to determine the minimum reporting rate for input measurements. The bandwidth of the closed-loop response is identified as 2.08 Hz (13.06 rad/s), which defines the frequency range within which the VSM can effectively follow system disturbances. This bandwidth is then used as a reference for determining the minimum reporting rate required for the DT. Using the identified bandwidth, the minimum reporting rate of the DT information source is estimated as 30 times the closed-loop bandwidth, corresponding to 62.4 Hz.

To test its performance of the DT in time domain with the determined data reporting rate, five frequency events were applied to an islanded grid by creating power imbalances. This is achieved by varying the load level during the islanded model sequentially at 3.3 MW, 3.1 MW, 3.5 MW, 2.9 MW, and 3.7 MW. Each scenario lasted for 10 seconds, with the disturbance introduced at $t = 2$ s. The corresponding input and output power

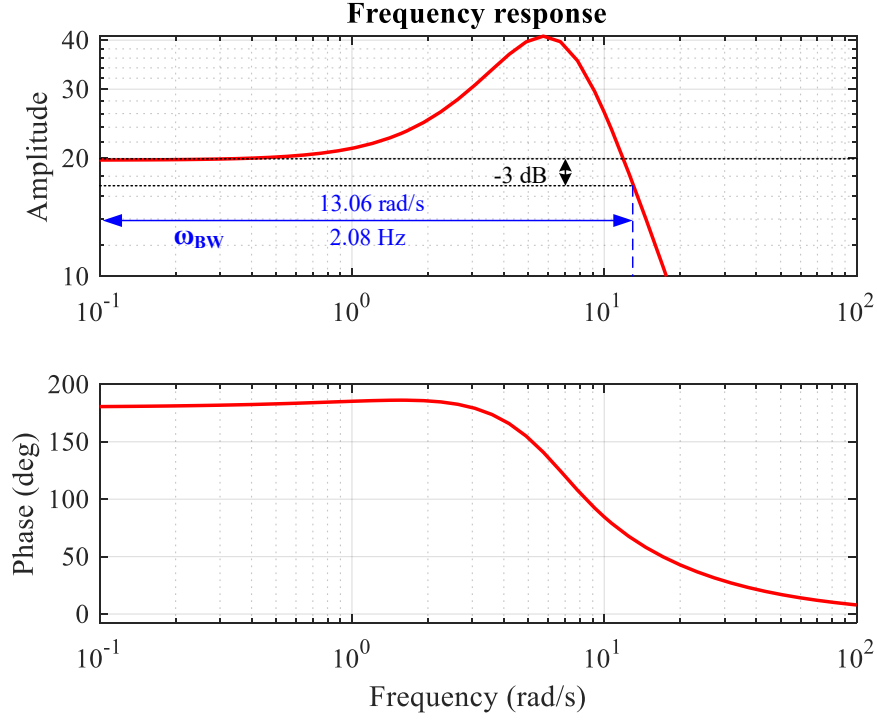


Figure 4.21: Bode plot of estimated transfer function

of the VSM-based GFC were recorded in real time using automated scripts to ensure continuity of data. To illustrate the difference between hardware measurements and DT outputs under the minimum reporting rate, only the final scenario is shown in Figure 4.22. Fluctuations in the real-time tracking can be observed, indicating that the DT is operating near its reporting limit, but can still represent the dynamic behaviour of the DER at a satisfactory level.

4.4.3 Validation of Data-Driven DTs' Real-Time Tracking Capability

In this case, the performance of a data-driven DT using a CNN model is tested. Unlike the grey-box approach, which relied on five disturbance scenarios for system identification, the CNN requires a substantially larger training dataset. In the present analysis, 275 frequency events were simulated to provide adequate coverage of system dynamics. For grey-box models, the sampling rate of input signals can differ from the training data, provided it exceeds 30 times the closed-loop bandwidth to ensure accurate reproduction of dynamics. By contrast, the CNN model requires that the input time-steps at the

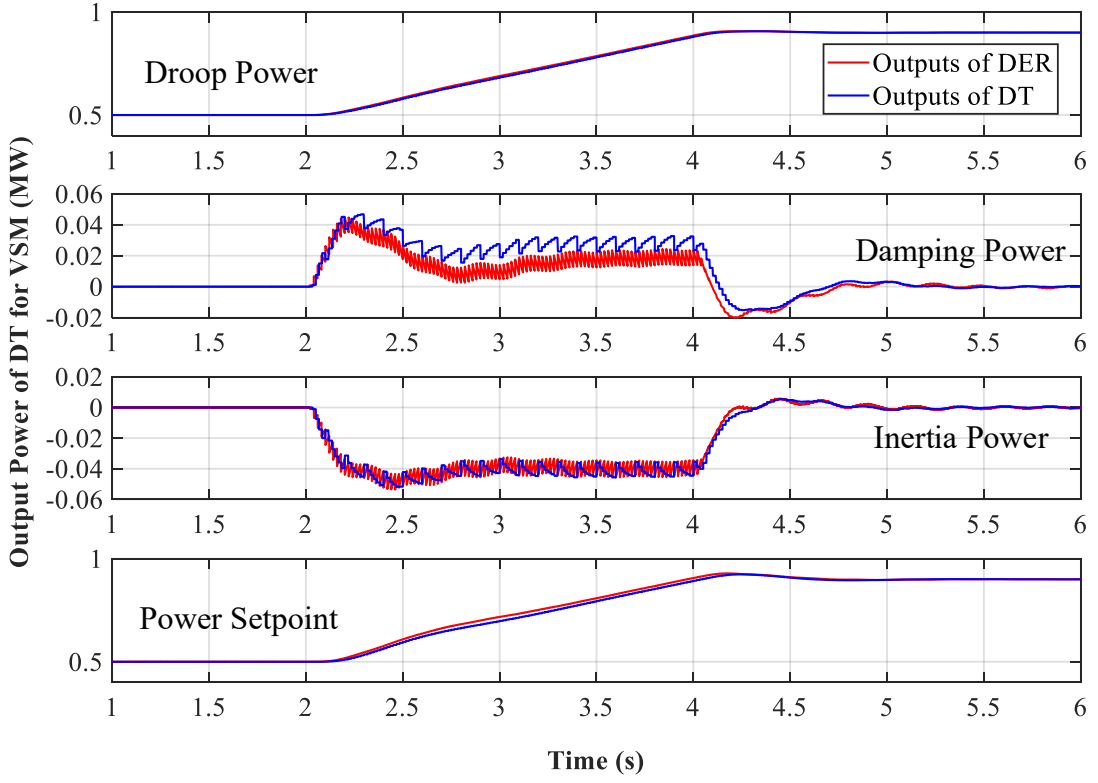


Figure 4.22: The performance of DT in real-time monitoring with estimated minimum reporting rate (62.5 Hz)

application stage remain identical to the training dataset. Furthermore, the closed-loop bandwidth of the CNN cannot be directly measured, as its dynamics are embedded in the data-driven representation rather than expressed in an explicit transfer function.

To assess the tracking capability of the CNN-based DTs, a set of representative case studies is carried out. Two types of DERs are considered: a droop-controlled BESS providing DC response and a VSM-based GFC delivering primary response response. For each service, three operating conditions are tested to evaluate the performance of the DTs with different set-points and grid disturbances.

For the droop-controlled BESS, the DT of DER is validated against DC service scenarios under the following three conditions:

1. Set-point = 0.0 p.u., main grid disturbance $\Delta P = -0.55$ GW
2. Set-point = 0.0 p.u., main grid disturbance $\Delta P = +0.55$ GW

3. Set-point = 0.5 p.u., main grid disturbance $\Delta P = -1.8$ GW

For the VSM-based GFC, the DT is tested in primary response service mode under the following three conditions:

1. Set-point = 0.5 p.u., main grid disturbance $\Delta P = -1.8$ GW
2. Set-point = 0.5 p.u., main grid disturbance $\Delta P = +0.5$ GW
3. Set-point = 0.9 p.u., main grid disturbance $\Delta P = -1.8$ GW

In each case, the DT output is compared with the measured response of the physical system. The validation dataset was collected using the same procedure as the training dataset. A total of 275 events were triggered, and the corresponding DER responses simulated on the RTDS were recorded in comma-separated values (CSV) format for comparison. As illustrated in Figures 4.23 and 4.24, the results demonstrate that the CNN-based DTs are capable of reproducing the dynamics of both droop-controlled and VSM-based devices under realistic frequency events. For the droop-controlled BESS providing DC service, the DT achieves a mean absolute error (MAE) of 0.0083 p.u., a root mean square error (RMSE) of 0.0191 p.u., and a coefficient of determination (R^2) of 0.996 across all tested samples, indicating an almost perfect reproduction of the reference response with only negligible deviations. In contrast, the DT of the VSM under primary response service produces an MAE of 0.0077 p.u. and an R^2 of 0.949, which reflects a strong overall correlation with the physical system. The corresponding RMSE of 0.0764 p.u. is higher compared with the BESS case, highlighting larger deviations at certain operating points. The differences in output of measured and predicted arises because the CNN model has difficulty capturing the damping and inertia characteristics that define VSM dynamics, resulting in less accurate reproduction of oscillatory behaviour. Nevertheless, the overall accuracy is sufficient for enabling the DER dispatch application targeted in this thesis, as the DT successfully captures the essential shape, timing, and magnitude of the response under frequency disturbances.

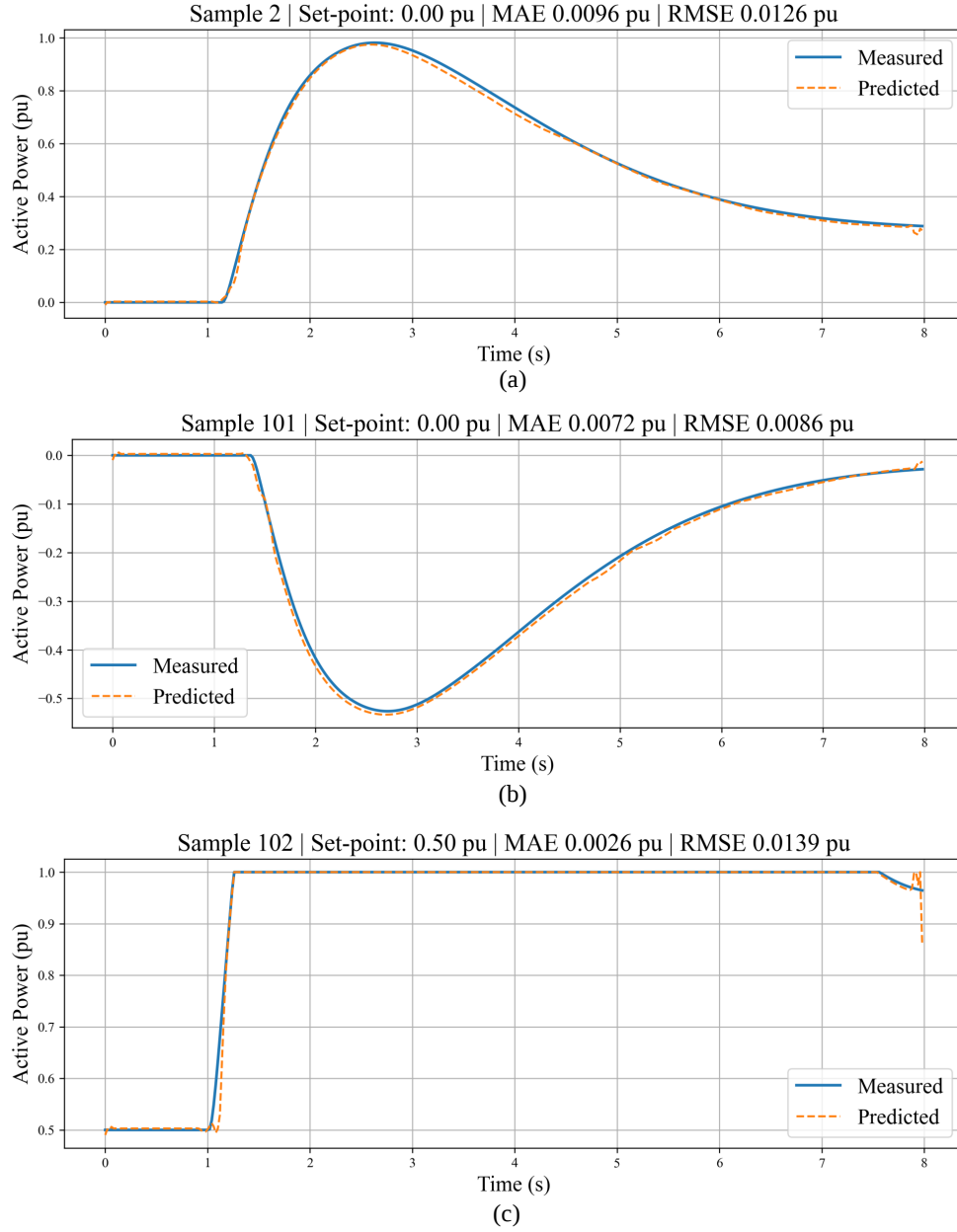


Figure 4.23: The performance of DT for droop-based BESS in real-time monitoring

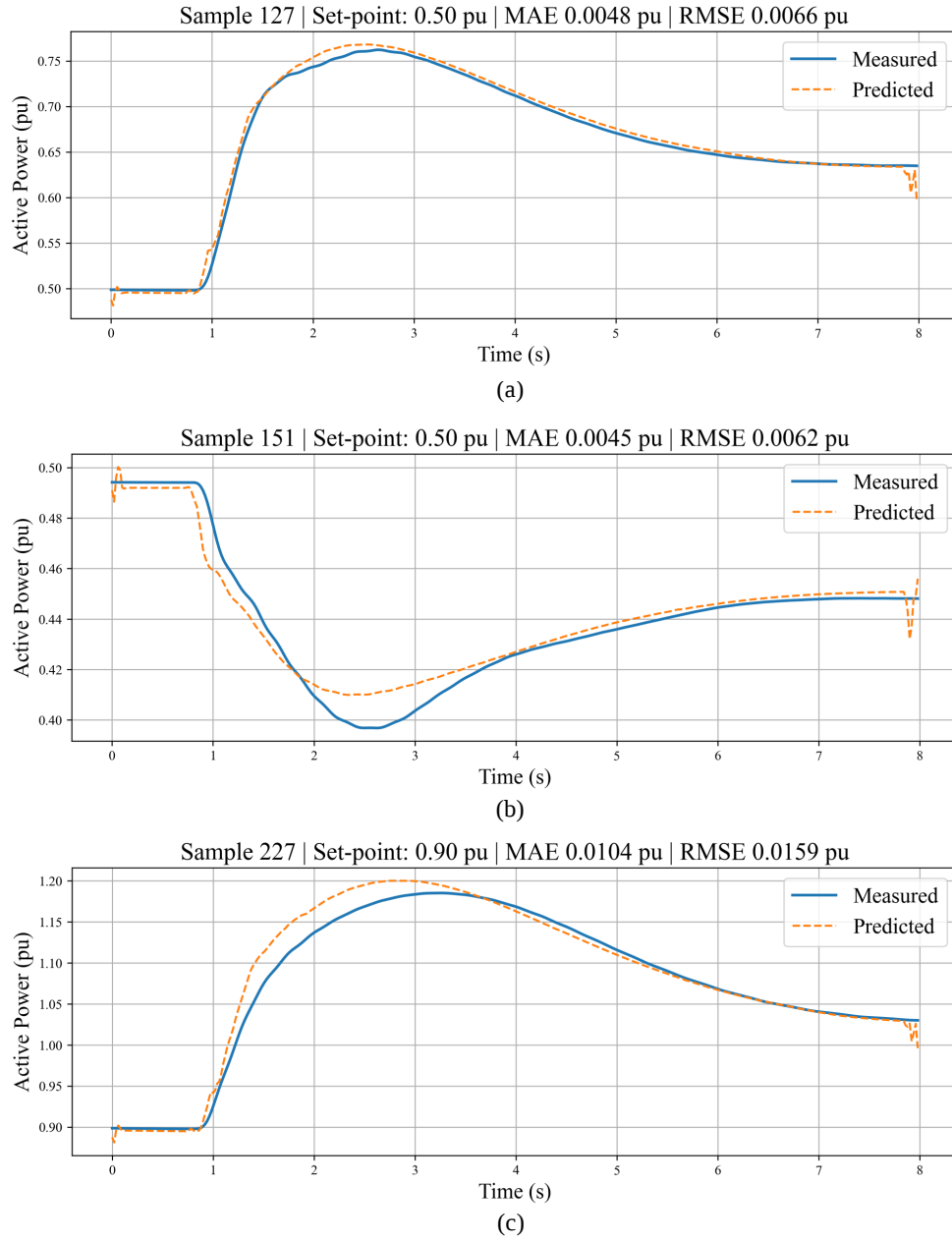


Figure 4.24: The performance of DT for VSM-based GFC in real-time monitoring

4.4.4 Impact of Communications on DTs

In this case, 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 4.25a, 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 4.25b demonstrates the output signal of DT (with delay jitter eliminator) after jitter elimination is enabled. Compared with the DT output in Figure 4.25a, 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 4.26a, 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 4.26b presents less oscillations than that as presented in Figure 4.26a. A better tracking performance between the DT output and RTDS output has been achieved by enabling the delay jitter eliminator.

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.

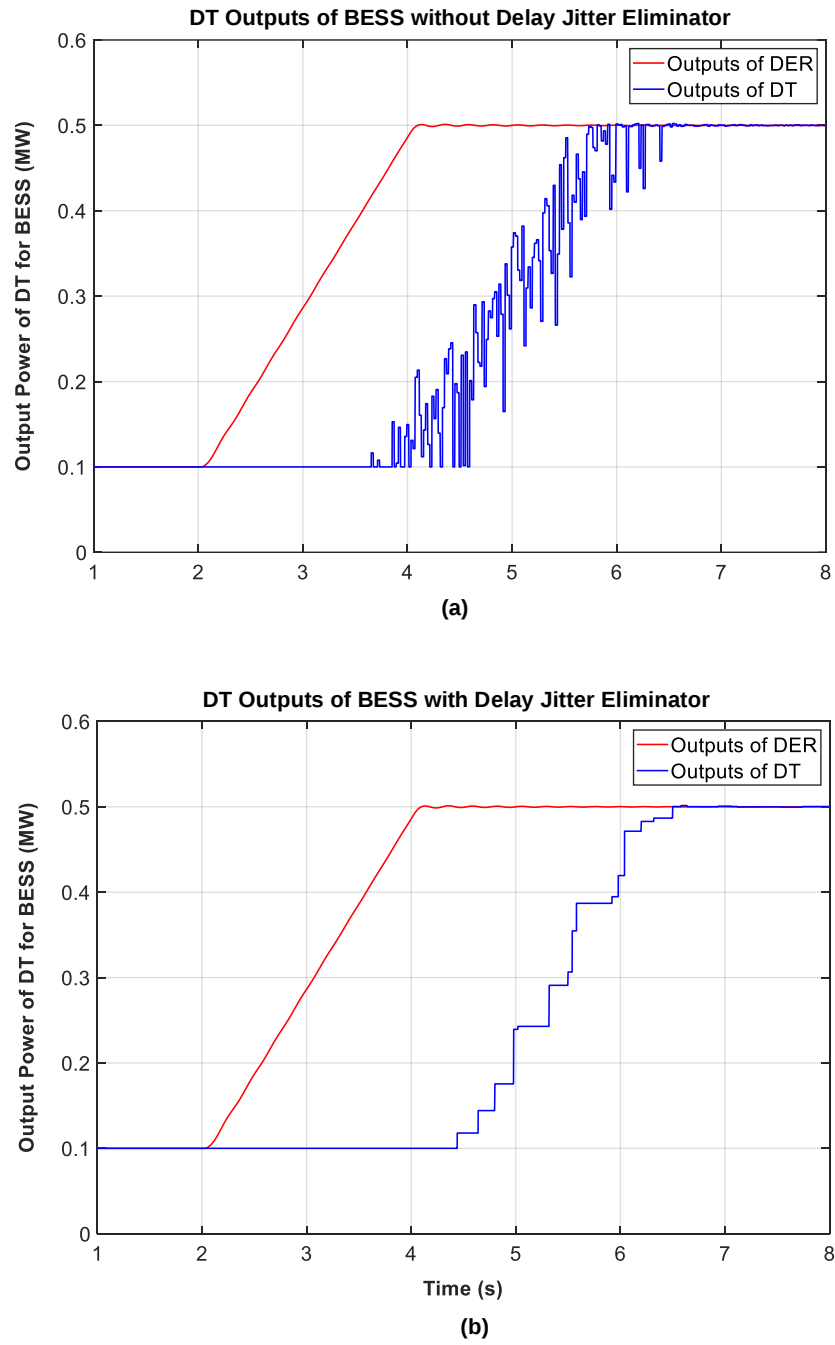


Figure 4.25: Effectiveness validation of jitter elimination on DT of BESS: (a) Comparison of original signal and signal with communication jitter (b) Comparison of original signal and signal after jitter elimination.

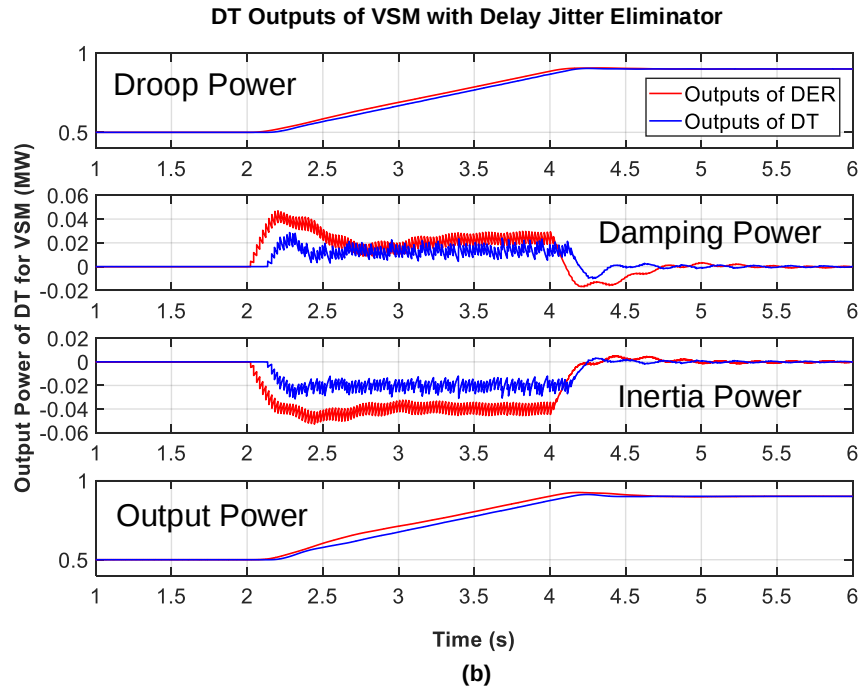
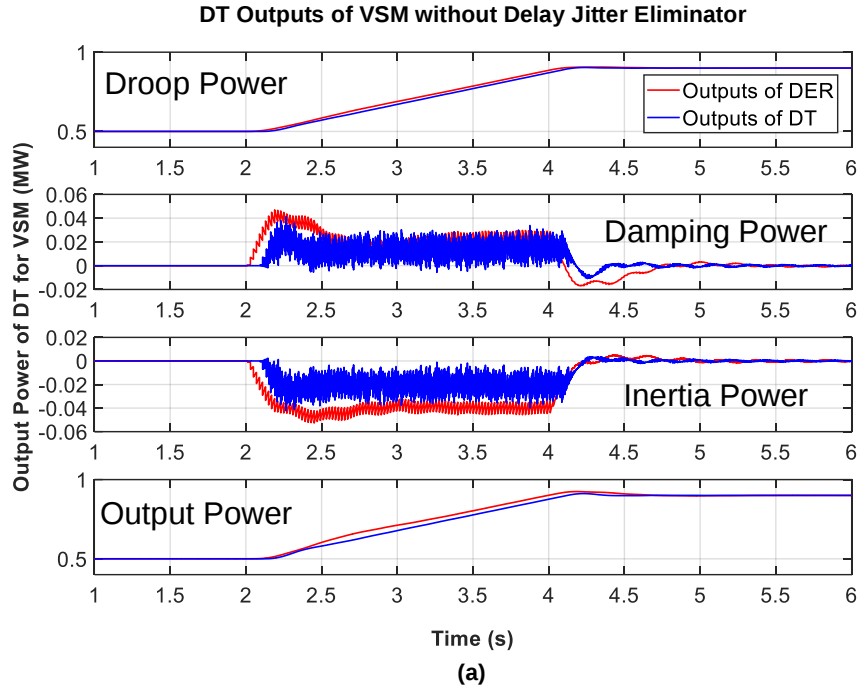


Figure 4.26: Effectiveness validation of jitter elimination on DT of VSM: (a) Comparison of original signal and signal with communication jitter (b) Comparison of original signal and signal after jitter elimination..

4.5 Summary

This chapter has presented the creation of DTs of DERs for frequency control applications, focusing on accurately capturing device dynamics and ensuring reliable real-time performance. Three modelling approaches are explored: physics-based (white-box), system identification (grey-box), and data-driven CNN (black-box). Each offers different trade-offs between interpretability, flexibility, and data dependency, and all three are implemented for DT prototyping.

To ensure reliable operation, the impact of data reporting rates on DT accuracy has been analysed. A method has been developed for estimating the minimum required reporting rate using frequency-domain analysis and validated through case studies, with discretisation methods shown to relax reporting requirements. The impact of communication performance has also been examined, with a software emulator used to introduce delay and jitter effects, alongside a jitter elimination method to improve DT accuracy.

A HiL testing platform has been designed to validate DT performance under realistic conditions. It integrates RTDS-based physical system emulation, cloud- and edge-hosted DT execution, and configurable communication interfaces. Case studies have demonstrated the tracking capabilities of physics-based, system identification-based, and data-driven DTs, evaluated the impact of communication constraints, and validated the effectiveness of mitigation techniques. Overall, the work establishes a practical methodology for creating and validating DTs of DERs, ensuring their suitability for real-time monitoring and frequency support services.

Chapter 5

DT-Based Dispatch of DERs for Frequency Response

Presently, DERs mainly provide frequency control ancillary services either individually to the system operator or through DERs aggregators. The system operator typically relies on offline simulations to estimate the required amounts of different ancillary services to contain the frequency deviation within the required limits, which assume that the procured services will deliver consistent technical performance across a wide range of system events. However, the representation of DERs in such offline models is often simplified and does not accurately capture their limitations under specific operating conditions. As a result, the system operator may over- or under-procure DER capacity, leading to discrepancies between the expected and actual effectiveness of frequency control.

This chapter introduces a DT-based DER dispatch framework, which utilise the ability of DTs to run live “what-if” scenarios. By doing so, it provides a more accurate assessment of the services that DERs can realistically deliver, enabling the system operator to schedule and dispatch the correct amount of DERs for frequency control with greater confidence.

This chapter is organised as follows. Section 5.1 introduces the general process and framework currently adopted by the system operator to determine the required

frequency ancillary services and discusses its limitations, particularly with the consideration of the diverse capabilities of DERs in providing frequency control. Section 5.2 presents the proposed DT-based DER dispatching framework, where DTs are employed to perform live what-if simulations for accurate estimation of DERs' capability to deliver frequency response. Section 5.3 provides case studies that demonstrate the operation of the proposed DT-based DER dispatch framework and illustrate how frequency ancillary services can be more accurately determined using this approach. Section 5.4 discusses the distinctive features, operational implications, and scalability of the proposed framework. Finally, Section 5.5 summarises the key findings of this chapter.

5.1 Existing Approach for Scheduling and Dispatching DERs for Frequency Control

Unlike large SGs or renewable plants, system operators currently have very limited knowledge of the DERs providing frequency response services. As noted earlier, they rely on offline simulations with assumed DERs' behaviour to determine the amount of DERs' capacity required to support frequency control. This section uses NESO as an example for illustrating the current process of scheduling and dispatching DERs for frequency control ancillary services and discusses their limitations.

NESO employs Dynamic Security Assessment (DSA) platforms to inform both real-time decision-making and offline planning studies. These platforms must balance computational feasibility with operator usability, a compromise that introduces several critical challenges. Figure 5.1 presents a general process that is adopted by NESO for supporting offline planning studies and real-time decision-making. In this process, an online simulation tool, i.e. Dynamic Security Assessment (DSA) in this example, is used as the core for supporting the process.

The DSA involves two main processes, i.e. online and offline. The online DSA is designed to provide rapid situational awareness. It relies on low-rate SCADA inputs and a 15-minute computation cycle, and only provides a simplified representation of system dynamics.

Frequency stability is excluded from this online functional scope, and DER responses are represented through aggregated models. These simplifications risk failing to capture fast transients and the heterogeneous behaviour of inverter-based resources, both of which are increasingly significant in a low-inertia grid. In addition, abstracting outcomes into categorical risk indicators supports operator interpretation but reduces complex dynamic interactions to low-resolution risk signals, which may not reflect the underlying stability margins.

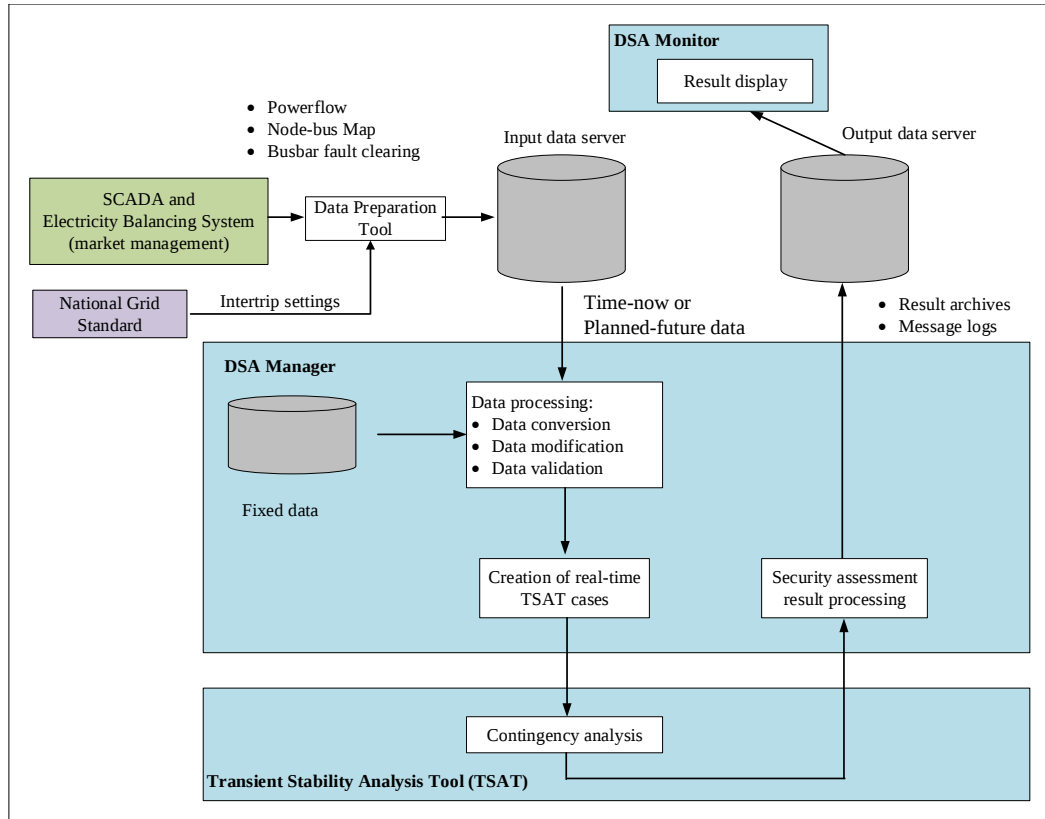


Figure 5.1: NESO online DSA architecture [171]

The offline DSA provides greater modelling detail by simulating contingencies with dynamic models, typically use simulation packages like PowerFactory, although this capability is constrained by its offline nature. Simulations are performed on assumed system conditions, meaning that rapid changes in dispatch, renewable output, or network topology may invalidate results before they can be operationally applied. The computational burden also limits the scale and diversity of cases that can be explored

within acceptable runtimes. As a result, offline studies can provide understanding of typical system behaviours but struggle to enable real-time responses to emerging events.

These limitations highlight structural issues in current security assessment practice: restricted frequency stability assessment, over-simplification of DER behaviour, dependence on low-rate data, and delays in producing actionable outputs. In current implementations, NESO relies on simplified models to predict the frequency trajectory following extreme events such as the single largest infeed loss. These models assume that the full volume of active power procured on DC market will be delivered strictly as required once a frequency excursion occurs. In practice, the deliverable power can be lower due to the absence of real-time monitoring of DER operating conditions. For example, insufficient state of charge may prevent discharge, high power set points may result in reaching inverter limits, and charging rate constraints can restrict the achievable response. Communication delays further add uncertainty to the timing and scale of delivery. Such gaps create the risk that critical instability dynamics remain undetected or are addressed too late to support secure operation.

5.2 DT-Based Framework for Dispatching DERs

5.2.1 Overview of the Proposed DERs Dispatch Framework

To address the challenges of the existing DERs dispatching process that might over- or under-procure the required amount, this section proposed a revised framework, as illustrated in Figure 5.2, which utilises the DTs' real-time what-if simulation capability for accurate understanding of the DERs' capability, thus determine accurately the required DERs response. The proposed a DT-based framework is a structured method for dispatching and verifying and DER capacity for frequency response, which ensures that scheduling decisions are based on deliverable capability rather than contractual assumptions.

As shown in Figure 5.2, at the highest level, the system operator firstly evaluates the system condition (e.g. system demand, inertia level, etc.) using existing tools to obtain an initial allocation of the required frequency response. A power system model, typically

an offline model at present, but potentially a system-level DT in the future, is then used to simulate the most extreme event (usually the largest credible contingency, currently a 1.8 GW infeed loss in GB [59]) to determine whether the resulting frequency trajectory satisfies key requirements (e.g., frequency nadir, RoCoF, etc.). If the trajectory does not meet the requirements, the allocation of ancillary services is adjusted (e.g. by procuring additional DERs for dynamic containment). This process is repeated until the frequency trajectory meets the requirements. Importantly, this conventional approach assumes that all service providers can deliver ideal technical performance. As noted earlier, if this assumption is retained for the final dispatching decision, it may lead to either overestimating or underestimating the actual control effectiveness.

The proposed DT-based dispatching framework extends this process by adding an additional validation layer. Once the frequency trajectory from the existing procedure is deemed satisfactory, it is passed to DER aggregators, which host the DTs of the DERs. Using these DTs, the aggregators run what-if simulations to evaluate the expected active power response under current operating conditions. These local simulations capture dynamic behaviours that are often overlooked by the existing process, such as delivery speed, ramping limits, and saturation. The aggregated active power responses are then returned to the system operator and integrated into the overall system model to verify whether the actual DER capabilities, as estimated by the DTs, align with the original expectations. If the estimated response does not align, e.g. due to constraints such as ramp rates, overloading limits, or saturation, the system operator adjusts the ancillary service allocation and repeats the process until sufficient DERs are scheduled.

5.2.2 Selection of DTs for the Proposed Framework

As reported in Chapter 4, this research has investigated three approaches for developing DTs: physics-based, system identification-based, and data-driven. For the DER dispatch application, the data-driven approach is considered as the most desirable option. This is because system aggregators may not have access to fully transparent DER models, and the iterative nature of the dispatching process requires light-weighted models, which can be most effectively achieved through data-driven methods.

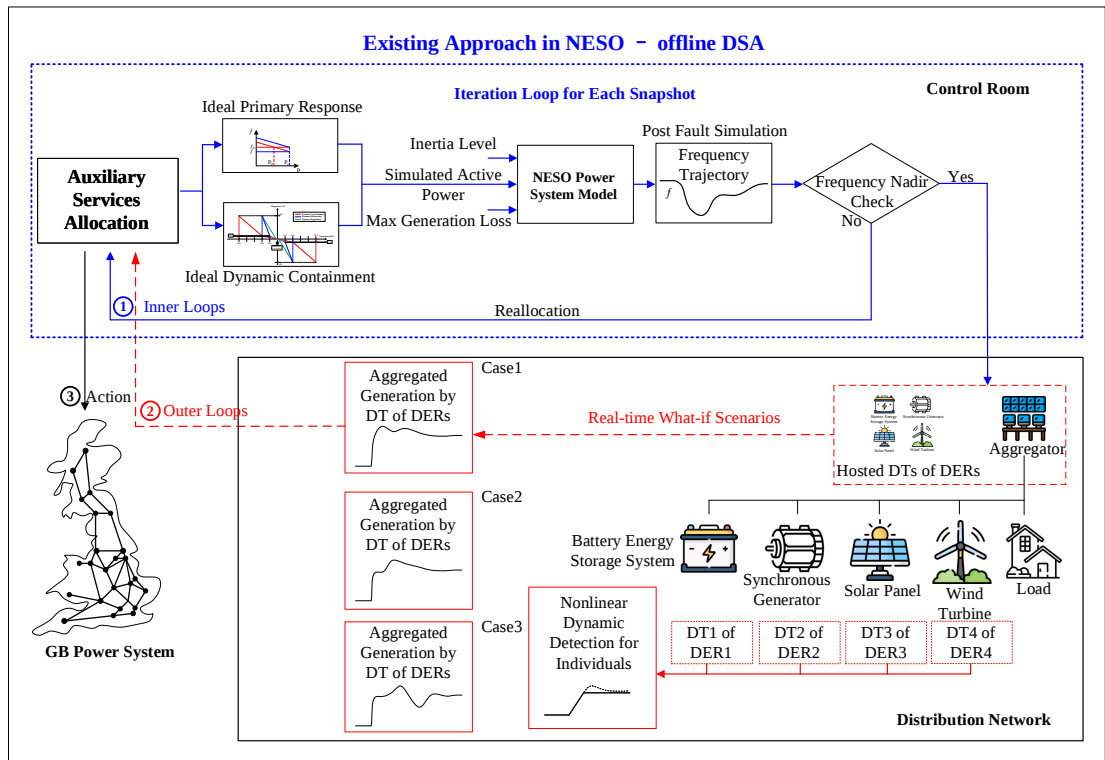


Figure 5.2: DT-based dispatch framework for DERs using real-time what-if simulations

In this work, the CNN model is selected as the data-driven representation of DERs for several reasons. Firstly, CNNs are well suited to learning temporal patterns in time-series data while maintaining computational efficiency. By applying convolutional filters across the input frequency trajectory, the model can automatically extract dynamic features, e.g. rate of change, overshoot, and recovery characteristics without requiring prior assumptions about system structure. This capability is particularly valuable for DERs whose dynamics are non-linear or difficult to represent through simplified transfer functions.

Secondly, the CNN offers scalability and generalisation. Once trained on a sufficiently large dataset of frequency events, the model can reproduce responses across a wide range of operating points and disturbance conditions, making it appropriate for real-time scenario evaluation where diverse cases must be assessed rapidly. Unlike recurrent neural networks, which may capture long-term dependencies but are prone to vanishing gradients and higher computational burden, the CNN achieves a balance between accuracy and inference speed, enabling deployment within the sub-second response requirements of low-inertia systems.

Finally, CNNs provide robustness to noisy or incomplete input signals. In real-world frequency measurements, sensor noise, missing data, or communication delays are unavoidable. Convolutional architectures are inherently resilient to such disturbances because feature extraction using sliding windows rather than relying on individual measurements. This makes CNN-based DTs more reliable for operational use, where stable and low SNR data cannot always be guaranteed.

5.2.3 Implementation of CNN-Based DTs for the Proposed Framework

Within the proposed framework, each DER-level DT hosted by the aggregator uses a CNN model, which receives the reference frequency trajectory, provided by the system-level DT, along with the locally accessible set-point of the DER. It processes these inputs to predict the active power change trajectory, denoted $\Delta P(t)$, under the current operating conditions.

The frequency signal is pre-processed with a symmetric dead band centred at the nominal frequency f_0 . This ensures that small fluctuations within the tolerance band are disregarded, and only effective deviations contribute to the response. The resulting normalised signal $f_{\text{norm}}(t)$ is then used as the CNN input, which is defined as:

$$f_n(t) = \text{sign}(f(t) - f_0) \cdot \max(|f(t) - f_0| - \Delta f_{\text{db}}, 0) \quad (5.1)$$

where $f(t)$ is the system frequency at time t , and Δf_{db} is the half-width of the dead band.

The CNN prediction $\Delta P(t)$ is added to the steady-state set-point to obtain the raw active power trajectory. Saturation limits are then applied to reflect physical capacity constraints, and the deliverable power change is obtained as $\Delta P_{\text{actual}}(t)$, where $\Delta P_{\text{actual}}(t)$ represents the clipped output relative to the set-point.

Aggregators repeat this process for all contracted DERs. The resulting $\Delta P_{\text{actual}}(t)$ trajectories are aggregated into a portfolio-level response and returned to the system-level DT. This enables the operator to update the frequency trajectory using verified DER capabilities rather than assumed values. Because the CNNs are used purely in an inference mode, the computation is lightweight and fast enough to support the iterative re-dispatch loop. Each time a new frequency trajectory is issued or local set-points are updated, the aggregator reruns the CNN models to produce updated deliverability estimates.

$$\Delta P_{\text{agg}}(t) = \sum_{k=1}^{N_{\text{types}}} n_k \cdot \Delta P_{\text{actual},k}(t) \quad (5.2)$$

where $\Delta P_{\text{agg}}(t)$ is the aggregated deliverable power change, n_k is the number of units of DER type k , and $\Delta P_{\text{actual},k}(t)$ is the deliverable response of an individual unit of that type.

The summation extends over all N_{types} of DERs considered in the aggregator portfolio. This workflow integrates the CNN-based DTs seamlessly into the framework. The system-level DT defines the reference condition, aggregators execute the detailed validation, and the verified responses $\Delta P_{\text{actual}}(t)$ are fed back to the system-level DT for

re-dispatch.

5.3 Case Studies

5.3.1 System Frequency Simulation Model

As noted previously, the system operator typically uses a reduced offline system model, incorporating primary response, demand response, and new dynamic response services, to simulate the frequency behaviour of the system during credible contingency events [171]. For illustration of the proposed DT based DER dispatching framework, this work uses the analytical model as shown in Figure 5.3 for emulating system operator's model [172]. This analytical model is based on the swing equation, where system inertia is represented as an equivalent inertia constant and frequency-sensitive resources are included as aggregated first-order response blocks.

In this case study, the analytical model is configured to represent a power system with 25GW demand which is operating at minimum inertia level of 102 GVAs, corresponding to an equivalent inertia constant of 2s. This is configured based on the minimum system inertia condition in GB system. The contribution from DC is represented as an idealised proportional service, assumed to deliver the contracted active power instantaneously following a frequency event. Descriptions of the parameters as presented in Figure 5.3 are provided in Table 5.1.

Table 5.1: Description of the parameters in grid model

Parameters	Description	Value
F_H	Fraction of power generated by the turbine	0.1
T_R	Reheat time constant in seconds	4 s
K_m	Mechanical power gain factor	0.95
ΔP_m	Change of mechanical power output in p.u	variable
ΔP_{event}	Change of power caused by events in p.u	variable
H_s	Inertia constant	2 s
R	Droop constant	0.05
D	Damping constant	1.0
f_n	Nominal frequency in p.u	1.0
Δf	Change of grid frequency in p.u	variable
f_{grid}	Normalized grid frequency in p.u	variable

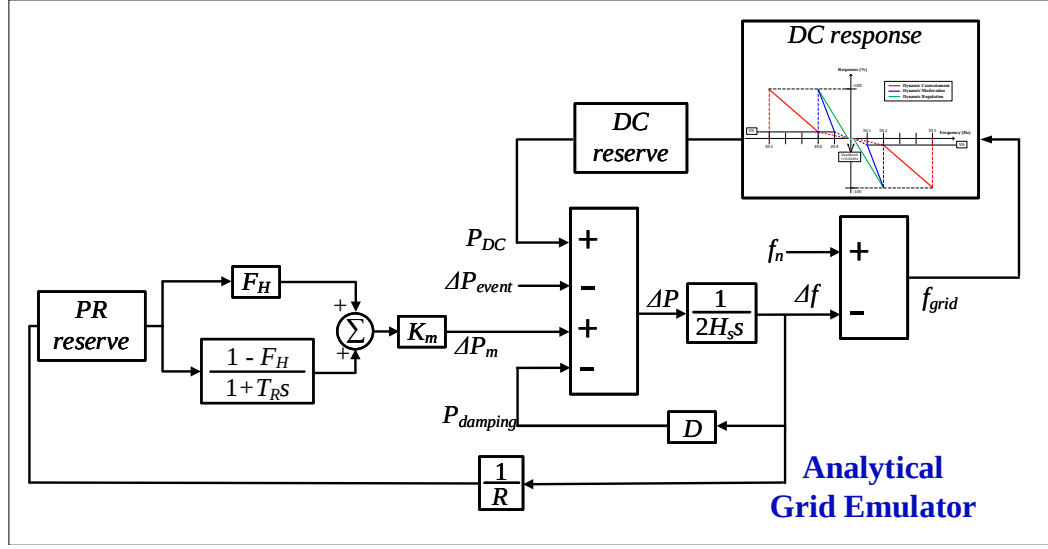


Figure 5.3: Frequency Trajectory Model [172]

To highlight the impact of DC support on frequency stability, a simulation is carried out under the loss of 1.8 GW infeed at a system inertia of 102 GVAs. Figure 5.4 compares two frequency trajectories produced by the model: one assuming no DC support, and the other assuming the full contracted DC volume is delivered. Without DC, the frequency nadir falls below the statutory limit, demonstrating the inadequacy of inertia and primary frequency response to contain the disturbance. When DC is included, the frequency trajectory recovers within secure bounds, with the nadir remaining above 49.2 Hz and the RoCoF contained below 0.5 Hz/s.

This example highlights both the value and the limitation of the current trajectory model. On the one hand, it provides a quick and transparent tool to assess the sufficiency of procured DC capacity. On the other, it assumes perfect and instantaneous delivery of contracted services, without consideration of DER operating states or physical constraints. This presents the need for DT-based DER dispatch framework as demonstrated in the following sections.

5.3.2 Estimation of Actual DERs' Frequency Response Based on DTs

Using the CNN-based DT developed in earlier sections, the next step is to employ them to estimate the aggregated active power from multiple DERs under a given frequency

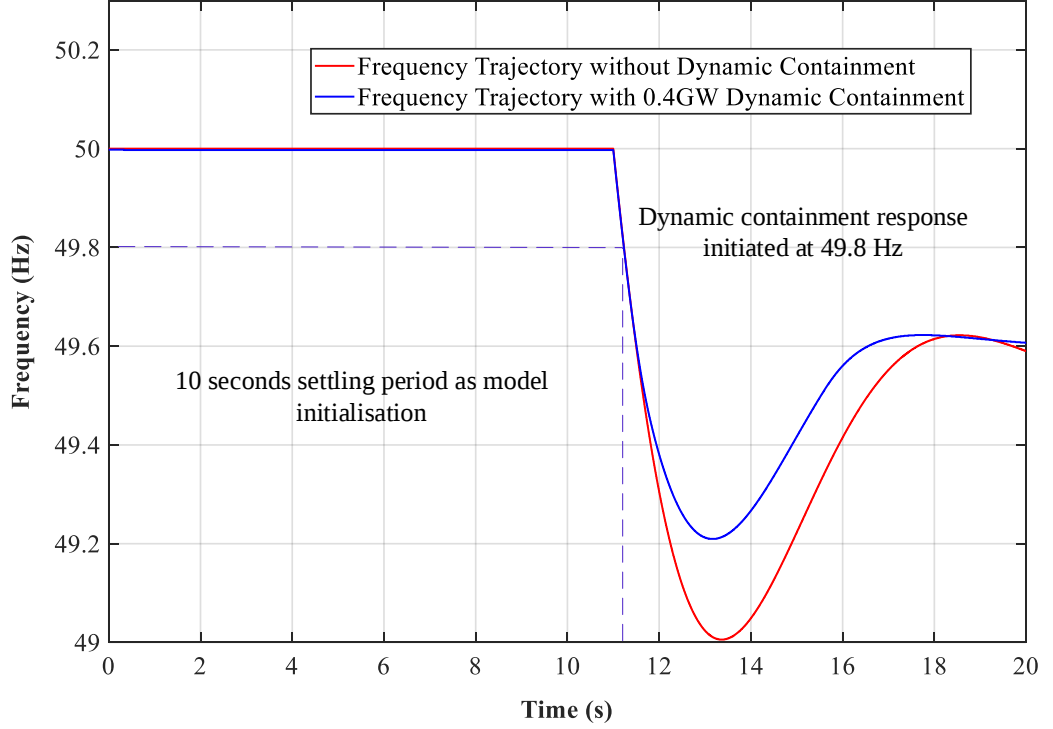


Figure 5.4: The Frequency Response with or without dynamic containment in max single loss event

trajectory. This will provide more accurate view of the actual DERs' capability as it considers the live status and limitation of the DERs. In this process, the frequency profile generated by the system-level DT is applied as the common input signal to the DTs of different DER types. The resulting responses are then scaled according to the number of deployed units within each aggregator, and subsequently combined to obtain the total aggregated change in active power, ΔP .

To validate that the DTs can accurately reflect the DERs' frequency responses, HiL tests are conducted. In this validation, DERs hosted on the RTDS are considered as hardware references, while their corresponding DTs run in parallel to produce estimated responses. As shown in Figure 5.5, the aggregated ΔP obtained from the DTs is compared with that derived from the RTDS-based hardware to assess consistency. This comparison ensures that the aggregation process retains the fidelity of individual DTs when scaled up, providing confidence that the proposed framework can be applied

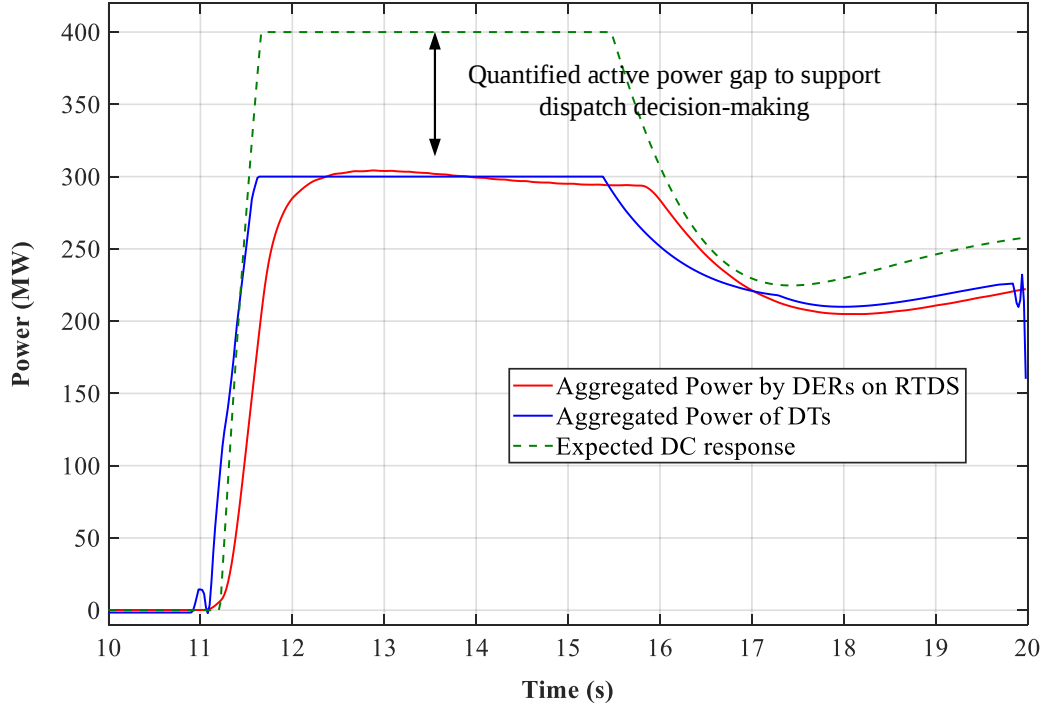


Figure 5.5: Evaluation of Aggregated Power: DT Predictions versus DER Output and Expected Value

reliably in real-time system studies.

As shown in the results presented in Figure 5.5, the aggregated ΔP estimated from DTs is compared with the response of DERs hosted on RTDS. It is important to emphasise that such aggregated power from real DERs cannot be measured directly in practice, and is available here only due to the HiL configuration. The comparison indicates that the active power trajectories from DTs and DERs are in close agreement, providing sufficient accuracy for scenario evaluation. This confirms that the DT-based aggregation preserves the accuracy of individual models when scaled up to system level.

It is also observed that, with the power set-point of the DER fixed at 0.5 p.u., insufficient headroom prevented the full delivery of the procured volume. Although 400 MW of active power was expected, only about 300 MW were actually provided. This outcome reflects the non-linear saturation behaviour of dynamic containment services under high set-points, where their extreme sensitivity to frequency is constrained by physical op-

erating limits. The discrepancy between the DT-generated aggregated power and the expected DC response therefore represents a quantifiable shortfall that can be utilised to trigger real-time re-dispatch actions. By capturing such practical delivery limitations, which are often neglected in market assumptions, aggregated DTs strengthen the value of the proposed framework for validating frequency response services under realistic operating conditions.

5.3.3 Updated Frequency Trajectory Based on Frequency Response Estimated by DERs

The estimated aggregated frequency response ΔP using DTs, which has a clear difference from the expected response, can be fed back to the system operator to evaluate how the actual DERs' capability frequency control and the frequency trajectory will be recalculated. The updated trajectory is illustrated in Figure 5.6, which shows that the system frequency drops to 49.16 Hz, below the statutory limit of 49.2 Hz. This outcome demonstrates that the current dispatch strategy is not effective and must be adjusted through additional procurement or re-dispatch actions to restore frequency security.

The breach of the 49.2 Hz statutory limit indicates that the system is operating outside the secure boundaries. Such a condition may activate automatic low frequency demand disconnection to arrest further frequency decline but creates undesirable disruption for consumers. The gap between contracted and deliverable response volumes highlights a structural weakness in the current procurement framework and market assumptions.

Updating the frequency trajectory in this iterative DT framework serves to provide system operators with a more quantifiable and intuitive warning compared with the simple indicators used in current practice. By explicitly showing how deliverable DER responses alter the system frequency trajectory, the framework enables operators to identify shortfalls in real time rather than relying on assumed delivery. All steps of this process, i.e. the initial frequency trajectory generation by the system-level DT, the aggregated power estimation by DER-level DTs, and the subsequent update of the trajectory are completed within 10 seconds. This rapid evaluation is considerably faster

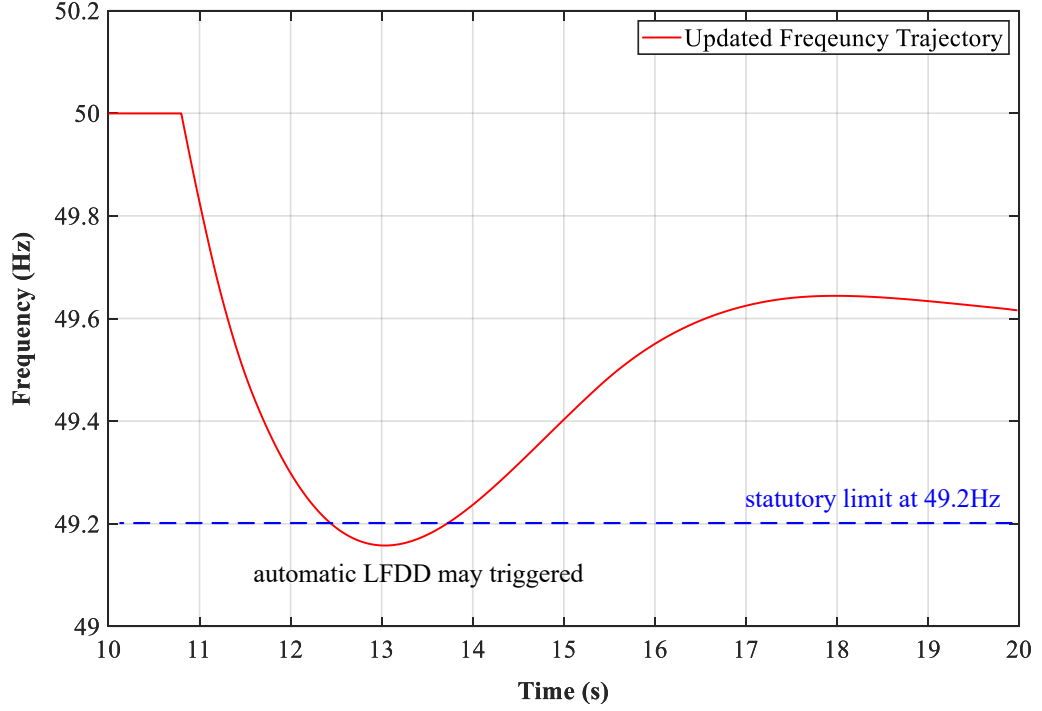


Figure 5.6: Updated frequency trajectory with actual aggregated power from DERs

than current dispatch processes, which typically operate on a minute-scale, and therefore supports more effective corrective actions in low-inertia power systems.

5.3.4 Real-time Re-dispatch of DERs Based on DTs and Evaluation

In the final step of the iterative process, re-dispatch was applied in order to contain the system frequency within statutory limits. The active power gap identified in the previous analysis amounted to approximately 100MW. To compensate this gap, an additional 100MW of BESS capacity was procured in the ancillary service. The DTs of BESS were then used to generate the corresponding new aggregated ΔP , which was fed back into the system-level DT to produce an updated frequency trajectory.

The results are shown in Figure 5.7, where the new trajectory is compared with both the original profile based on expected DC delivery and the updated trajectory based on actual DER responses, which drops to 49.16 Hz. With the additional dispatch, the frequency nadir remains above the statutory limit of 49.2 Hz, demonstrating that the

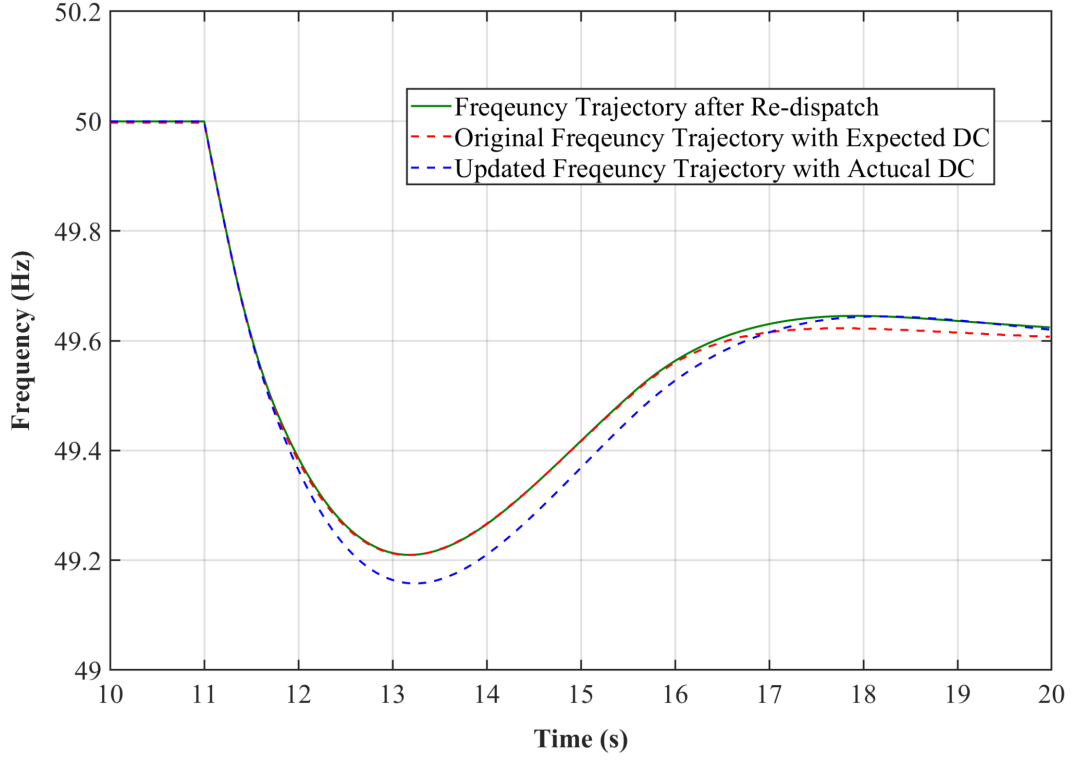


Figure 5.7: Comparison between all the frequency trajectories

system is returned to secure operation.

The evaluation shows that the DT-based iterative process is able to detect when contracted services cannot be fully delivered, quantify the resulting shortfall, and implement re-dispatch actions to restore system security. Compared with existing approaches, the framework produces explicit frequency trajectories that reveal how re-dispatch affects system dynamics. The complete loop of frequency prediction, DER-level response estimation, trajectory update, and re-dispatch runs within about ten seconds, which is significantly faster than conventional re-dispatch processes that typically operate on a minute-scale.

5.4 Discussions

The proposed DER dispatch framework can be featured by four key advantages.

Firstly, it employs a hierarchical structure, linking system-level assessment with

aggregator-level validation and DER-level dynamics. The use of DTs introduces a verification layer into the dispatch process. Instead of assuming that DERs can deliver contracted volumes, their responses are explicitly tested against the reference frequency trajectory. The DERs' delivery limits, which include headroom availability, partial response, and saturation effects that constrain the maximum active power contribution, are fully considered with the application of DER DTs. Furthermore, the dynamic response from DTs captures rise time, settling behaviour, and rate-of-change, providing valuable insights on how quickly and effectively DERs can deliver full contracted power.

Secondly, the framework performs distributed computation by offloading intensive simulations to aggregators, thereby ensuring scalability and fidelity without overloading either the control room or individual DER devices. In conventional practice, most dynamic assessments are performed centrally in the operator's control room, which creates a bottleneck when analysing large DER portfolios. In contrast, the proposed framework delegates these computations to aggregators. This approach distributes the workload and improves scalability: each aggregator runs simulations only for its contracted resources, allowing the system to scale seamlessly across thousands of DERs without overwhelming a central platform. Furthermore, aggregators generally possess greater computing capacity than edge-hosted DER devices, making it feasible to perform data-driven dynamic simulations that would otherwise be impractical at the device level. Under this design, the system operator concentrates on system-wide trajectory updates and dispatch actions, while aggregators handle the intensive validation of DER responses, enhancing both the speed and fidelity of the overall assessment.

Thirdly, it provides predictive assurance, validating responses before instability occurs and giving the operator confidence in dispatch sufficiency. These features have clear operational implications. For the system operator, the framework replaces simplified risk indices with explicit frequency trajectories, offering transparent and quantifiable evidence of stability margins. For aggregators, it establishes a mechanism to demonstrate the real capability of their portfolios, supporting more efficient utilisation of DERs. For DER owners, it ensures that dispatch decisions respect physical constraints, reducing the risk of overcommitment.

Finally, the framework enables iterative re-dispatch, dynamically adapting to active power gaps so that secure operation is always ensured. It is also inherently scalable: each aggregator simulates only its own portfolio, allowing thousands of DERs to be assessed in parallel. With lightweight but accurate DTs, simulations can be completed within a few seconds, considerably faster than re-dispatch processes that typically operate on minutes scale. Furthermore, the framework can be integrated with existing market structures, where capacity is already procured through aggregators in blocks. By adding real-time validation to these processes, it strengthens frequency control without requiring fundamental redesign of the market.

5.5 Summary

This chapter investigates the role of DTs in enhancing the dispatch of DERs for frequency response services. At present, system operators determine the required ancillary services mainly through offline simulations that assume uniform and consistent performance across different operating scenarios. Such an approach overlooks the operational diversity and limitations of DERs, which can lead to significant mismatches between expected and actual performance, and result in inefficient procurement of reserves.

To overcome these limitations, the chapter develops a DT-based real-time dispatch framework. The key innovation lies in the ability of DTs to perform live what-if scenarios, providing system operators with real-time awareness of the actual capability of DERs under current conditions. This allows for a more precise and adaptive allocation of resources, reducing the risks of over- or under-procurement while improving confidence in frequency control outcomes.

Case studies have been presented, which demonstrate how the method can dynamically capture DER behaviour and deliver more reliable estimates of available services. The chapter concludes with a discussion on the distinct benefits of incorporating DTs into system operation, including enhanced accuracy in ancillary service determination, improved operational efficiency, and the potential for greater system reliability in future grids with high DER penetration.

Chapter 6

DT-Based Coordinated Control of DERs for Frequency Response

In addition to the application in supporting the scheduling of DERs for frequency control, DTs can also provide valuable solutions for real-time DER control, particularly in coordinating multiple DERs to deliver effective collective responses that are difficult for individual units to achieve. This chapter focuses on a DT-based coordinated control scheme that enables DERs to provide fast and effective responses while minimising the need for real-time communication.

The chapter begins by analysing the need for coordinated control of DERs in Section 6.1, which highlights the limitations of uncoordinated responses from DERs during frequency events, and how they can lead to slower aggregated dynamics and instability. Section 6.2 reviews the conventional approaches for DER coordination, such as centralised and distributed schemes, with particular attention to their reliance on high-bandwidth real-time communication. Section 6.3 presents the concept of DT-based coordinated control. Two design approaches are presented: (i) cloud-hosted DTs that allow a central controller to estimate the real-time outputs of multiple DERs, and (ii) edge-hosted DTs located alongside individual DERs, enabling coordination without continuous communication. In both cases, the use of DTs is shown to reduce dependence on communication infrastructure while maintaining fast and effective response. Finally,

case studies are presented to evaluate the performance of the DT-based approaches against conventional methods, demonstrating their capability to enhance system frequency support in low-inertia conditions.

6.1 Need for Coordinated Control of DERs

DERs encompass a wide variety of technologies, including converter-based renewable generation, BESS, demand-side resources, and hybrid solutions. Their inherent diversity means they exhibit very different dynamic behaviours. Some DERs, such as batteries and flywheels, are capable of delivering fast active power injections within fractions of a second, while others, such as demand response or small-scale thermal units, operate on much slower timescales.

If these resources act individually and without coordination, their responses are fragmented and often misaligned with system needs. Fast-acting DERs may quickly saturate their limited energy capacity, while slower units may fail to react in time to arrest frequency deviations. This lack of coordination can reduce the overall effectiveness of frequency response, introduce inefficiencies, and in some cases even exacerbate system instability.

Coordinated control frameworks allow different DERs to complement one another, combining fast-acting resources that arrest the initial frequency deviation with slower, higher-energy resources that sustain the response. In the absence of such coordination, the system cannot reliably harness the full potential of distributed resources.

To illustrate these challenges, example results of incoordination are presented in the Section 6.4.2, showing how uncoordinated DERs respond under disturbance conditions compared with coordinated strategies.

6.2 Coordinated Control of DERs and its Conventional Implementation

In this section, a coordinated control scheme is presented followed by two options for its conventional implementation in real world, i.e., centralised and distributed approaches, which will serve as the reference for comparison of the DT-based design and implementation, which is presented in Section 6.3.

6.2.1 Coordinated Control Method For DERs

Considering an example network, representing either a low voltage feeder or a microgrid, with N controllable DERs (denoted by $i = 1, 2, \dots, N$) as shown in Figure 6.1, we assume that M DERs, $M \subset N$, are contracted by an aggregator to provide ancillary services to the system operator at the point of common coupling (PCC). Given a disturbance within the network, P_M is the total reserve activation requested by the aggregator from the M contracted DERs, which can be represented as:

$$P_M = \sum_{i=1}^M p_{i_{sp}}(t) \quad (6.1)$$

where $p_{i_{sp}}$ is the set point of the i^{th} participating DER.

If there is no additional coordinated control implemented, the DERs will simply follow the set points sent by the aggregate purely with their PQ controllers. However, it will be demonstrated in Section 6.4 that the overall aggregated DERs response can be undesirable due to the significant differences in DERs capabilities and characteristics.

Improving Local Response

A set point modulation technique can be employed for improved local response of the DER, i.e. purely based on each DER's own actual power output without considering other DERs. The set point of the i^{th} DER can be modified as:

$$p'_{i_{sp}}(t) = p_{i_{sp}} + u_i^I(t) \quad (6.2)$$

where u_i^I is the modulation factor defined as

$$u_i^I(t) = m_i \times \hat{e}_{i_{pred}}(t). \quad (6.3)$$

where m_i is the weighting factor of error, $\hat{e}_{i_{pred}}$ is the predicted active power output error from a linear error trajectory predictor used in this work.

The weighting factor m_i determines the degree to which the predicted error influences the corrective action applied to each DER. A higher value of m_i increases the sensitivity of the modulation, which can accelerate error correction but may also introduce oscillations if over-emphasised. Conversely, a lower m_i results in smoother but slower adjustments, which can reduce the effectiveness of the coordinated response. In the present case study, all five DERs have identical power ratings, so a uniform weighting factor was applied across the fleet. Parametric testing showed that the best overall performance was obtained when $m_i = 0.5$, providing a balance between responsiveness and stability. This choice ensures that errors are corrected quickly enough to improve both local and global responses, without compromising the aggregated performance at the PCC.

The error in power over prediction horizon T_{pred} is

$$\hat{e}_{i_{pred}}(t_0 + T_{pred}) = e_i(t_0) + r(t_0)T_{pred} \quad (6.4)$$

where $r(t_0)$ is the average rate of change of error calculated over past measurements based on least squares error.

The measured error e_i in active power output of DER i is calculated as

$$e_i(t) = p_{i_{sp}} - p_{i_m} \quad (6.5)$$

where p_{i_m} is the measured active power output of DER i .

Improving Global Response

A global improved dynamic response, i.e. an improved aggregated response from all DERs, can be obtained if the DERs participating in ancillary service provision coordinate their individual responses. The coordinated control aims to improve a DERs' individual response using other $M - 1$ participating DERs in order to ensure fast and optimised dynamic response from all participating DERs at the PCC. The set point of the i^{th} DER is therefore modified as:

$$p''_{i_{sp}}(t) = p_{i_{sp}} + u_i^I(t) + u_i^{II}(t) \quad (6.6)$$

where u_i^{II} is the modulation factor of coordinated control:

$$u_i^{II}(t) = m_i \sum_{j=1, j \neq i}^M \hat{e}_{j_{pred}}(t) \quad (6.7)$$

where $\hat{e}_{j_{pred}}(t)$ is the predicted output power error of j^{th} DER. Substituting Equation (6.2) to (6.6), the DERs' set points become:

$$p''_{i_{sp}}(t) = p'_{i_{sp}}(t) + u_i^{II}(t) \quad (6.8)$$

The coordinated control is complementary for each DER, i.e., the response of each DER is adapted to ensure the global response (at point of common coupling) is improved.

It should be noted that the presented coordinated control in this section is an example control scheme for demonstration purpose only to illustrate the advantage of the DT-based design and implementation, and the coordinated algorithm itself is not a contribution of the chapter. The main contribution of the chapter is the new design and implementation approaches in realising the coordinated control with the DTs of DERs hosted in the cloud and edge for minimising the reliance on real-time communication with effective overall control performance.

6.2.2 Conventional Implementation: Centralised Coordinated Control

The coordinated control presented in Section 6.2.1 can be realised via a centralised approach with a conventional implementation as illustrated in Figure 6.1.(a). In the conventional centralised approach, it is assumed that the coordinated control is implemented within the aggregator. The coordinated controller, as evident from Equation (6.7), requires the knowledge of the predicted output power error ($\hat{e}_{i_{pred}}$) of DERs and therefore each DER sends its measured power output (P_{i_m}) in real time to the aggregator for its calculation. The coordinated controller will use the desired set points requested by the aggregator and the real-time communicated power output (P_{i_m}) to optimise the set points to be sent to the DERs. Consequently, as opposed to the aggregator sending the individual power set point ($p_{i_{sp}}$) to the i^{th} DER, the modified power set point ($p''_{i_{sp}}$) is sent instead. It can be seen that, in this approach, it requires bi-directional real time communications between the DER aggregator and the individual DERs, and this represents $2M$ communication links for M DERs participating in the ancillary service. Furthermore, for each time step, the control algorithm relies on the real-time output from DERs (P_{i_m}) to send the modified power set point ($p''_{i_{sp}}$), therefore, the performance of the communication channels will have a significant impact on the overall performance. It will be demonstrated in Section 6.4 that the communication delay could lead to highly unstable response from the DERs.

6.2.3 Conventional Implementation: Distributed Coordinated Control

An alternative to the centralised implementation of the coordinated control is to implement the controller in a distributed manner. Figure 6.1.(b). presents the conventional implementation of the distributed coordinated control for the DERs. As can be observed, instead of having a single coordinated controller hosted in the aggregator site, each of DERs participating the ancillary service will have one coordinated controller implemented in its site (i.e. the edge), i.e. there are M coordinated controllers in the

M DER sites distributed across the network. One of the main benefits for which is implemented within each of the distributed approach is that it avoids the total failure of the overall scheme when one coordinated controller fails (as it will be the case of the centralised approach presented in Section 6.2.2). In this approach, individual DERs will still need to receive the power set points (p_{isp}) from the aggregator, and then the DERs will start exchanging their predicted error ($\hat{e}_{i_{pred}}$) for the calculation of the modified reference power set point (p''_{isp}) via communications with other DERs. Therefore, each DER will need bi-directional communication with the rest of the $M - 1$ DERs, representing a total of $M(M - 1)$ links among DERs and another M links between individual DERs with the aggregator for the set point. Similar to the centralised approach, with the distributed implementation, it will be demonstrated in Section 6.4 that the communication delay could significantly compromise the overall aggregated response from the DERs.

6.3 Proposed DT-Based Coordinated Control

In a step change to conventional control implementation, this work proposes the use of DTs of DERs to estimate the predicted output power error of each participating DER to realise the proposed coordinated control scheme thereby largely mitigating the need for real-time communications.

6.3.1 DT-based Implementation: Centralised Coordinated Control

The proposed design and implementation of coordinated control with the centralised scheme using DTs of the DERs is illustrated in Figure 6.1.(c). The coordinated controller and the DTs of the DERs are all implemented within the cloud platform of the aggregator (analogous to the conventional centralised implementation). However, in contrary to the conventional centralised approach that requires bi-directional real-time communication between the central coordinated controller and individual DERs for exchange of measured power output p_{im} and modified power set point (p''_{isp}), in this approach, dynamic behaviour of DERs can be estimated by their DTs at the cloud based

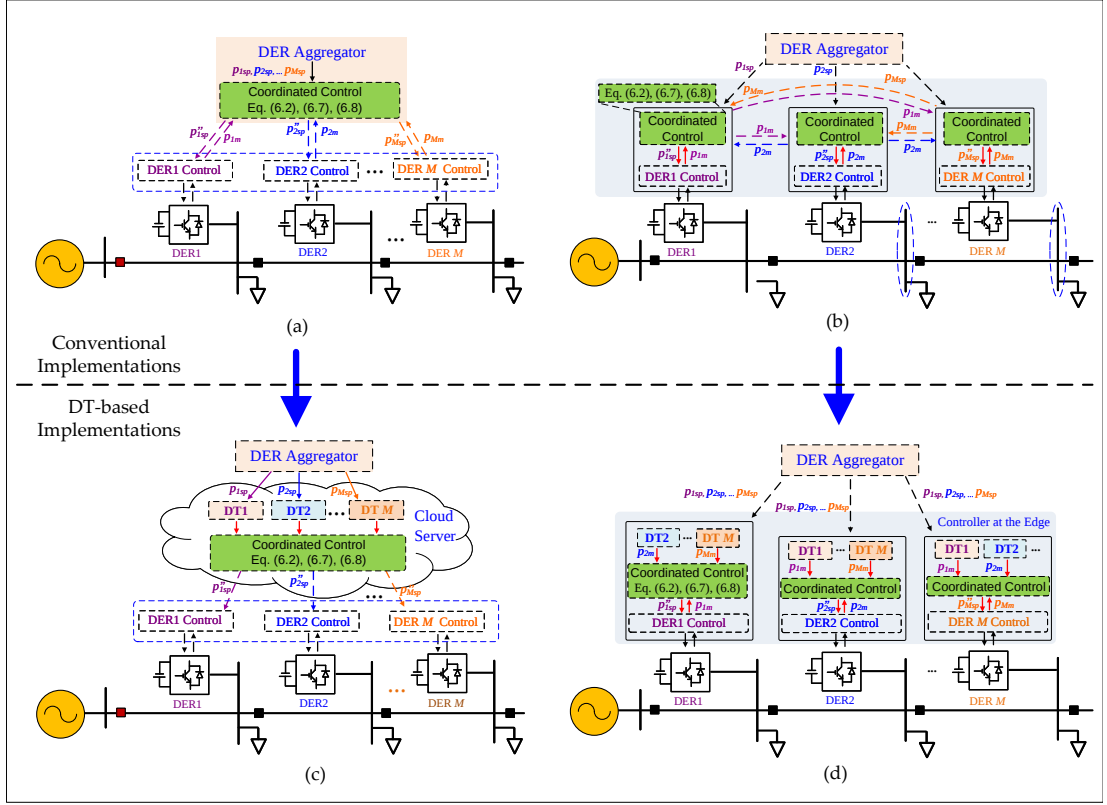


Figure 6.1: Conventional and proposed DT-based coordinated control of DERs: (a) conventional implementation: centralised; (b) conventional implementation: distributed; (c) DT-based implementation: centralised; (d) DT-based implementation: distributed.

on the inputs set point inputs from the aggregator's commands rather than relying on real-time information exchange with DERs.

As the coordinated control is mainly concerned with the active power dynamic behaviour of the DERs in response to the set point comments, analytical models of the DERs that can accurately represent such dynamic characteristics can be used to served as the the DERs's DTs. Section 6.4.1 presents the details of the development of DTs of the DERs. The DTs of the DERs are hosted in the could server, enabling access to the real-time estimated behavior of the DERs to be readily utilised by the coordinated control strategy. The outputs from the coordinated controller are modified power set point ($p_{i_{sp}}''$) based on the estimated DERs' real time power rather than actual power, and they will be sent from the cloud to the M individual DERs via communication links, and the need for communication channel is reduced from $2M$ to M . This approach has

the advantage of using the computation capability provided by the cloud for running the coordinated control scheme while largely mitigating the real-time communications required.

6.3.2 DT-based Implementation: Distributed Coordinated Control

The proposed design and implementation of coordinated control with the distributed scheme using DTs of the DERs is illustrated in Figure 6.1.(d). In this case, both of the DTs and the coordinated controllers are hosted at the edge in DERs' sites (analogous to conventional distributed control implementation). In contrast to conventional distributed implementation where the predicted output power error ($\hat{e}_{i_{pred}}$) is exchanged through real-time communications, in this approach, for the i^{th} DER, the DTs of all other $(M-1)$ participating DERs will be incorporated in its local site. This allows for estimation of the real-time behaviour of other DERs purely using a set points sent by the aggregator, thus enabling the coordinated control without the need for real-time communications with other DERs. As illustrated in Figure 6.1.(d), communications between the aggregator and the DERs will still be required, but this approach eliminates all the real-time communications among DERs, which largely mitigates the reliance on communications. This effectively presents an approach that transforms a distributed control implementation to a decentralised control implementation requiring no real-time communications. However, this approach will present relatively high requirement on the DER controllers' computation capability as the DTs and coordinated controllers are run in real time at the edge.

6.4 Case Studies

6.4.1 Test Network for the Studies

In this work, the modified benchmark low voltage network by Conseil International des Grands Réseaux Electriques (CIGRE) task force C6.04.02 has been chosen as the test AC network [173,174] and is illustrated in both Figure 6.3 and Figure 6.8. The network comprises of a number of feeders that supply residential, commercial and industrial loads

with a nominal voltage of 20 kV. Therefore, five DERs in the network, all participating the frequency response ancillary service via a commercial aggregator. The DERs 1-3 represent BESS units, rated active power of 100 kW, 150 kW, and 200. DERs 4 and 5 represent electric vehicle charging stations with rated active power of 250 kW and 300 kW respectively. For the purpose of demonstrating the DT-based coordinated control (via both centralised implementation at the cloud and the distributed implementation at the edge), it is assumed that all DERs are capable of sourcing and sinking power to/from the grid.

The modelling workflow follows the general process described in Section 4.1.3 and illustrated in Figure 4.5. Step tests are applied to the active power reference, and the resulting input–output time series are used for transfer-function estimation. Model parameters are iteratively tuned until the simulated response matches the measured behaviour within the desired accuracy.

Once the accuracy of the model is considered as acceptable, the model can be implemented on appropriate platforms and interfaced with the live data sources so that it can be updated in real-time as a DT to reflect the actual behaviour of the DER. Figure 6.2 presents the responses from the DTs created based on the process illustrated in Figure 4.5. In comparison of the actual behaviour of the DERs, Figure 6.2 shows that the DTs can accurately reflect the DERs' dynamics with the supplied set point signals.

6.4.2 Case Study 1: Testing of DT-Based Coordinated Control: Centralised Approach

As illustrated in Figure 6.1.(c), in the case of the DT-based coordinated control with the centralised approach, the DTs of the DERs and the coordinated controller are hosted in the cloud server. Figure 6.3 presents a realistic HIL setup, which includes a RTDS simulator for simulating the network with five DERs as discussed in Section 6.4.1 and a desktop PC acting as a cloud server. The real-time simulation in RTDS is communicated with the sever via an Ethernet switch to exchange information using the UDP protocol. During a simulated frequency disturbance event, the commands $p_{i_{sp}}$ from the aggregator are sent to DTs without any communication delay because

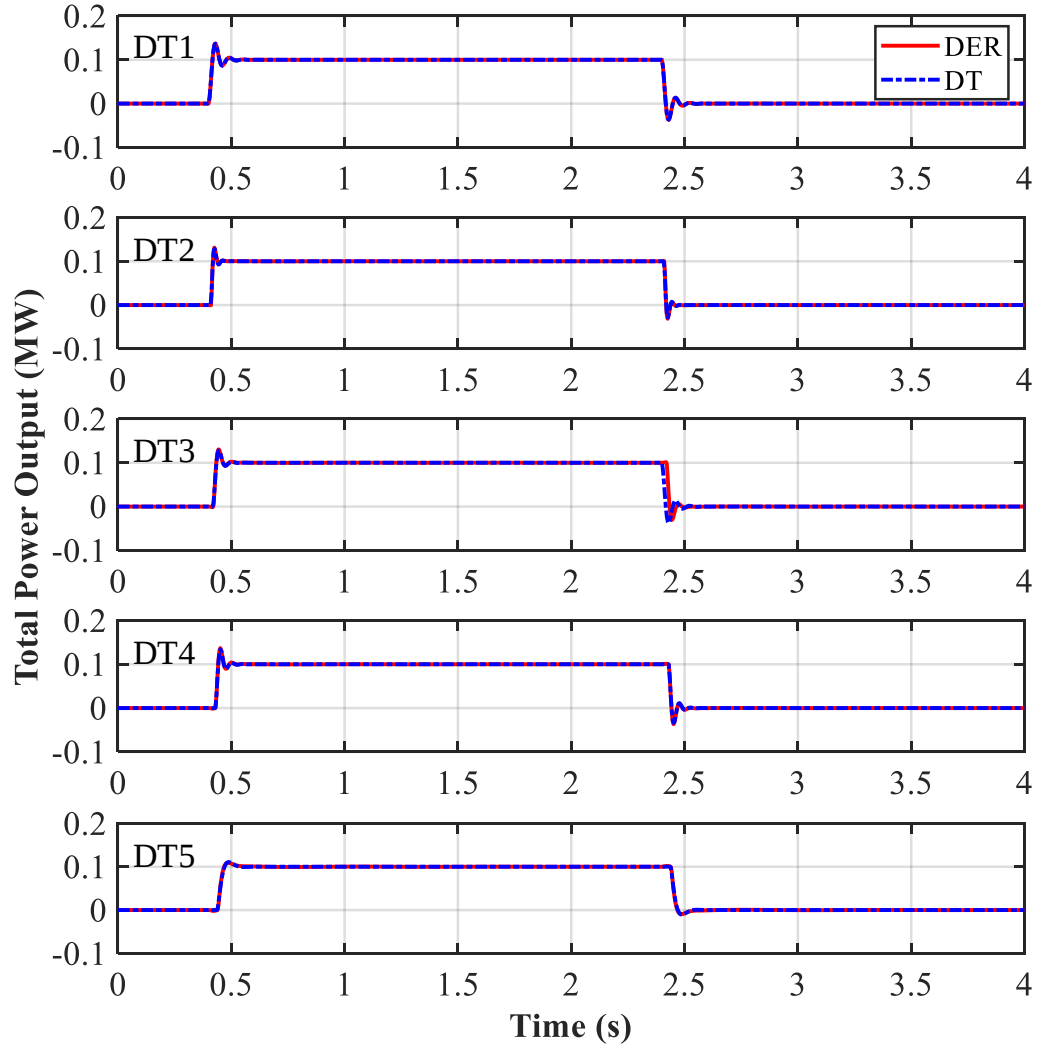


Figure 6.2: Comparison of the responses from DTs and DERs

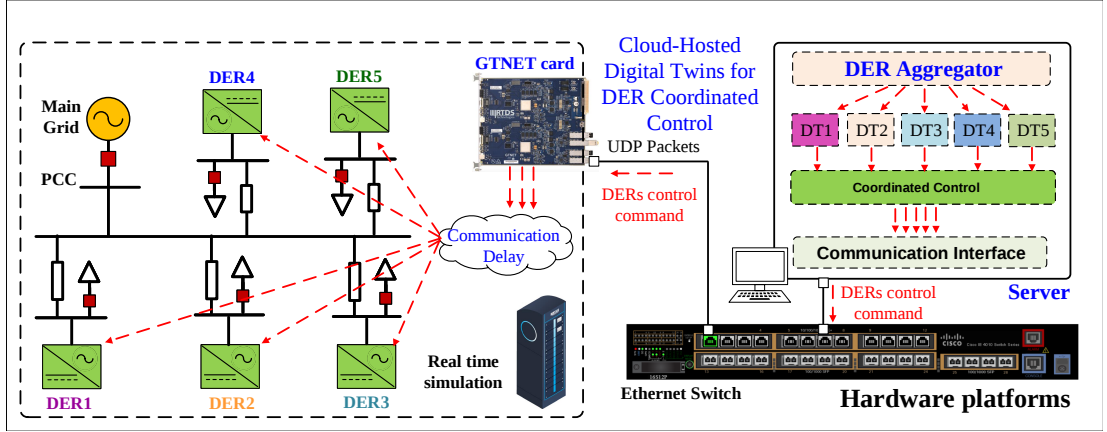


Figure 6.3: Test setup for DT-based implementation: centralised coordinated control of DERs

DTs are located at the same cloud server as the aggregator functions. A key benefit of this approach is that the communication required for sending active outputs from the DERs to coordinated controller in the cloud can be avoided. Based on the set points of the aggregator, DTs are used to estimate the real-time power outputs of the DERs, which are used by the coordinated controller to generate the modified set points $p''_{i_{sp}}$ for optimising the overall response as discussed in Section 6.2. Any error exists in the DTs can be detected and compensated by the coordinated controller. In the test setup, a function block emulating communication delays has also been created in RTDS for testing the impact of the communication latency between the aggregator and the DERs on the proposed DT-based centralised coordinated control for DERs. In the tests presented in this section, the communication delay is set as 50 ms, which is considered to be realistic to be realised with low-cost communications based on the work reported in [175]. In Chapter 4, a testing platform was established for more detailed evaluation of impact of communication performance on DT-based solutions.

Simultaneous Change in the Set Points of DERs

In this case, it is assumed that the aggregator detects a frequency event and sends power set points to all of the five DERs simultaneously to request a same amount of increase in active power output (i.e. 100 kW) at 0.4 s. A 50 ms communication delay is

assumed which is consistent with values reported in prior study of PMU communication in power systems [176]. Therefore, the overall aggregated increase of active power from the five DERs is expected to be 500 kW. Figure 6.4 and Figure 6.5 present the individual and overall aggregated responses of the DERs with their inherent PQ control (i.e. no coordinated control deployed), conventional coordinated control, and the DT-based coordinated control.

It can be clearly seen from Figure 6.4 that different DERs have very different responses to set points sent by the aggregator for requesting the increase in active power. With the inherent control of the DERs (i.e. no coordinated control), as shown in Figure 6.5, the aggregated overall response is relatively slow with a certain level of overshoot. This could be problematic for the system operator when there are large number of aggregator with a significant capacity of DERs providing the ancillary service to the grid.

With the conventional implementation of coordinated control, due to the communication delay and its high reliance on communication performance, significant errors between the reference power and the actual output for each DER response can be observed, thus leading to an undesirable overall response. Furthermore, due to the communication delay, it appears that the coordinated controller experiences stability issues with severe oscillations in active power, which will contribute negatively to the overall system frequency regulation.

In the case of DT-based coordinated control, since the coordinated controller receives data from the corresponding DTs located in the cloud, rather than relying on active power communicated from the DERs, the overall response from has significantly improved with faster response and shorter settling time as shown in Figure 6.5. Examining the individual DER responses as shown Figure 6.5, the DT-based coordinated control refines the individual responses (e.g. DER 2 responds faster with an overshoot and DER 5 responds slowly compared to other DERs) so that they can complement with each other to form an improved overall response.

It is also important to consider the performance under larger communication delays. In this case study, the 50 ms assumption means the set-points reach the DERs at 0.45

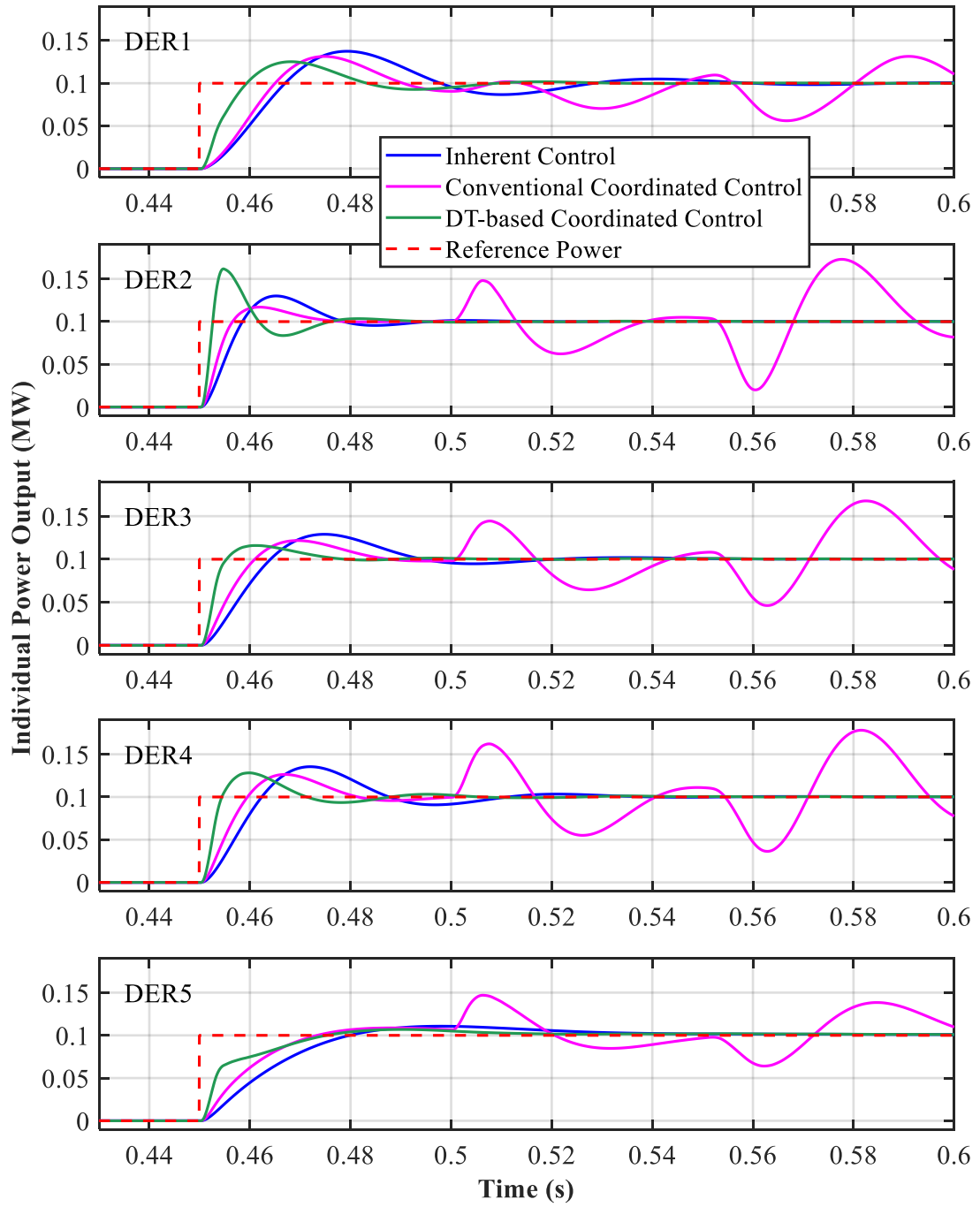


Figure 6.4: Individual responses of DERs with simultaneous set point change - same amount of power requested from all DERs

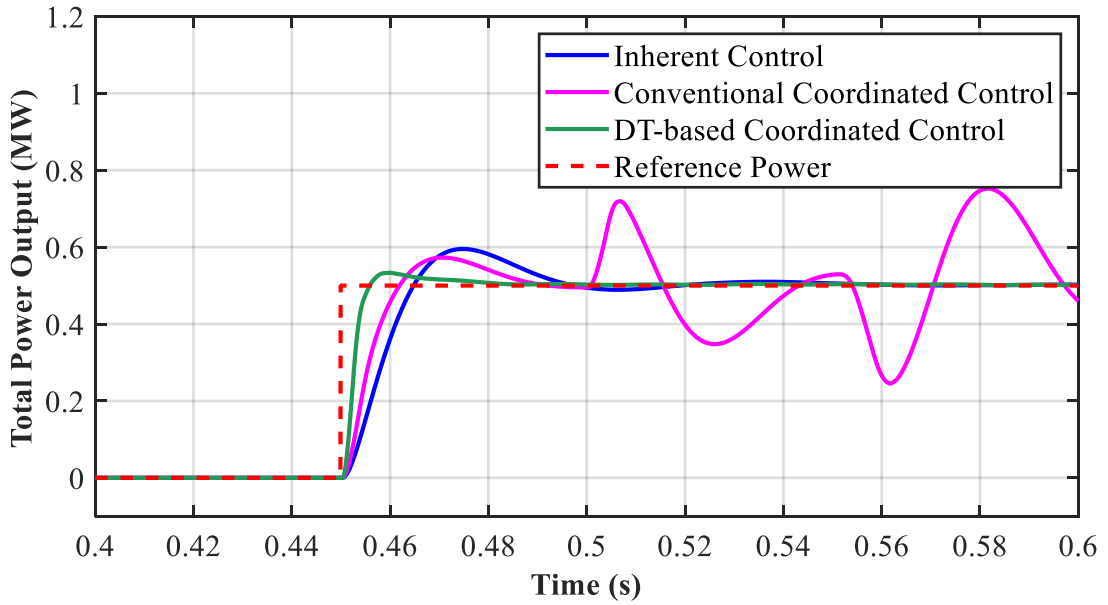


Figure 6.5: Aggregated responses of DERs with simultaneous set point change - same amount of power requested from all DERs

s, and the DT-based controller enables full delivery by 0.46 s, well within the DC requirement of initiating within 0.5 s and achieving full delivery within 1 s. If the one-way delay were increased to 300 ms in 4G condition [177], the set-points would arrive at 0.70 s and full delivery would occur at 0.71 s. The initiation time of 0.30 s and full delivery time of 0.31 s after the event both remain comfortably within the limits. This highlights that the proposed DT-based approach maintains compliance with grid service requirements even under less favourable communication conditions.

Similar observations as described above with the case presented in Figure 6.6, where the DERs are commanded to output different amounts of active power to deliver a total of 1 MW response against a frequency event. As it can be seen that the DT-based coordinated control presents an improved response compared with the case with DERs inherent controllers. It should be noted that the case with conventional implementation approach has been demonstrated to be unstable in Figure 6.5, thus not being shown again in Figure 6.6.

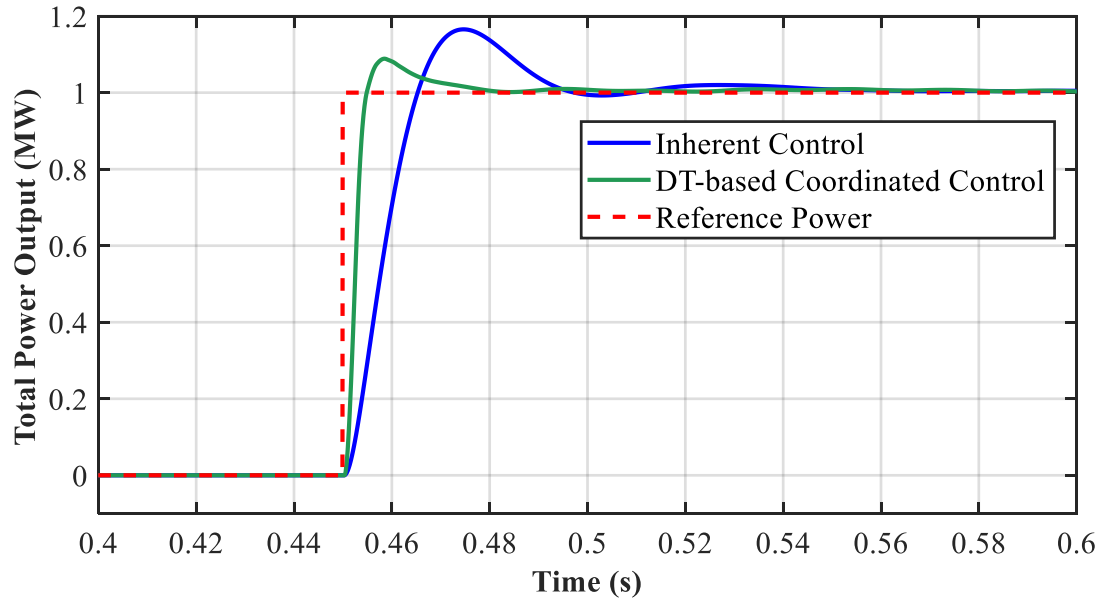


Figure 6.6: Aggregated responses of DERs with simultaneous set point change - different amounts of power requested from all DERs

Staggered Change in the Set Points of DERs

Similar to the previous case, the aggregator detects a frequency event and sends power set points to all of the five DERs to request the same amount of increase in active power output (i.e. 100 kW), but in this case, at different time (emulating a more realistic case where the set points are not sent precisely simultaneously by the aggregator). The overall aggregated increase of active power from the five DERs is still expected to be 500 kW but not at the same time. The overall aggregated coordinated control responses for the DERs inherent control and DT-based coordinated control are presented in Figure 6.7.

In the inherent control of the DERs, as shown in Figure 6.7, the aggregated overall response from the DERs is relatively slow and less effective. However, in the case of DT-based coordinated control, the overall response is comparably faster and more effective in tracking the reference power compared with the inherent control of the DERs.

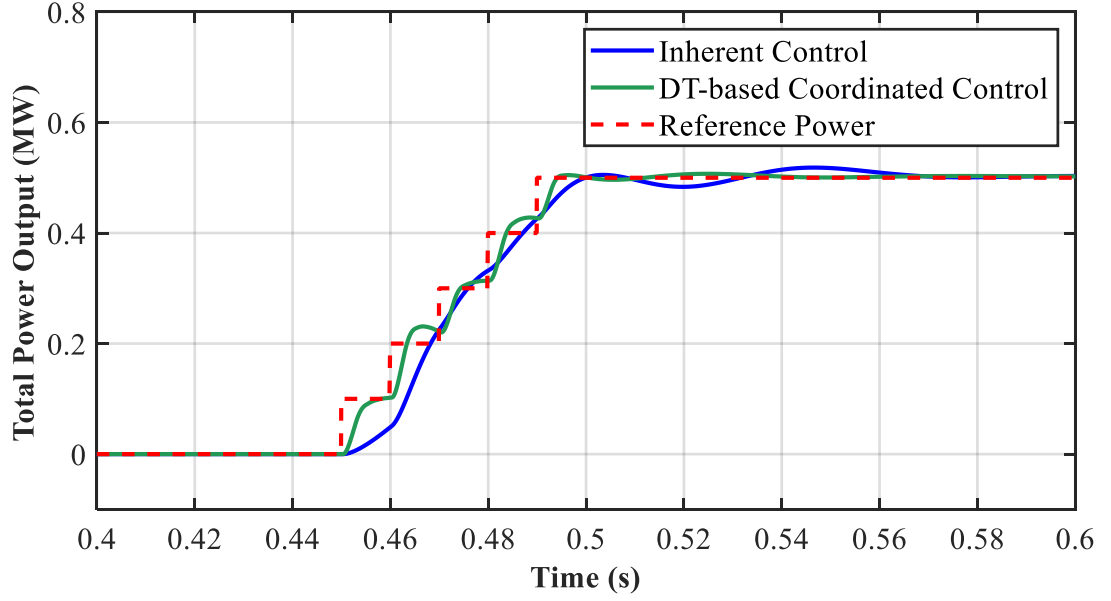


Figure 6.7: DERs' Power output with applying staggered power reference inputs

6.4.3 Case Study 2: Testing of DT-based Implementation: Distributed Coordinated Control

The DT-based distributed coordinated control is illustrated in Figure 6.1 (d), from which it can be seen that the DTs of the DERs are hosted in DERs' sites. The test setup for evaluating the DT-based distributed coordinated control is illustrated in 6.8, which includes the test network with the five DERs participating in the ancillary service, a functional block emulating the aggregator, and the corresponding DTs of the DERs installed at the DERs sites along with the coordinated controllers. In this setup, in order to estimate the dynamic behaviours of other DERs, while avoiding the need for bi-directional real-time communication with them, each DER hosts DTs of the other four DERs locally. The DTs are updated based on the set point signals for all DERs sent by the aggregator.

Once a frequency event is detected, the aggregator will send requests of active power changes via power set points $p_{i_{sp}}$ to DERs and their hosted DTs of other DERs. Different from the DT-based centralised approach, each DER in this case receives all the power set points $p_{i_{sp}}$ rather than the designated one for themselves in order to provide inputs

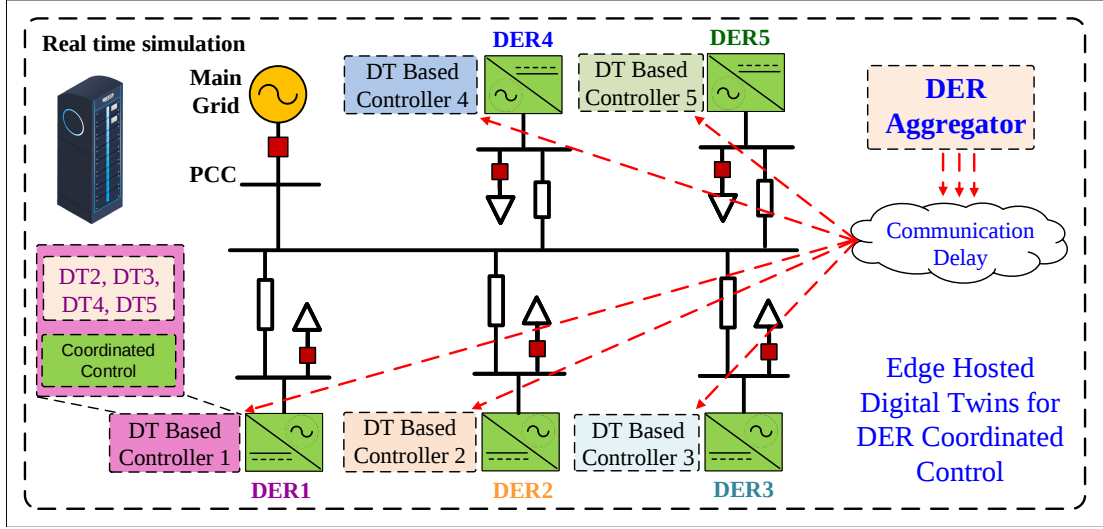


Figure 6.8: Test setup for DT-based implementation: distributed coordinated control of DERs

for local DTs for estimated other DERs' outputs. These estimated DERs' outputs are used by the coordinated controllers installed at each DER site to generate modulated reference power $p''_{i_{sp}}$ for DER and DTs. The DER and DTs will then output certain power according to the received $p''_{i_{sp}}(t)$. As this process only involves the use of the set points communicated from the aggregator without the need for communication with other DERs, the performance of the proposed DT-based coordinated control scheme can largely mitigate the reliance on the communications, which is demonstrated in the following sections.

Simultaneous Change in the Set Points of DERs

In this test case, the aggregator sends power set points to all of the five DERs simultaneously to request a same amount of increase in active power output (i.e. 100 kW) at 0.4 s. The results for this case are presented in Figure 6.9 and Figure 6.10 for individual DER responses and overall aggregated responses respectively. For the comparison purpose, DERs inherent control, conventional coordinated control and DT-based coordinated control responses are presented in the same figures.

As it can be seen form Figure 6.9 and Figure 6.10 that, in the case of inherent

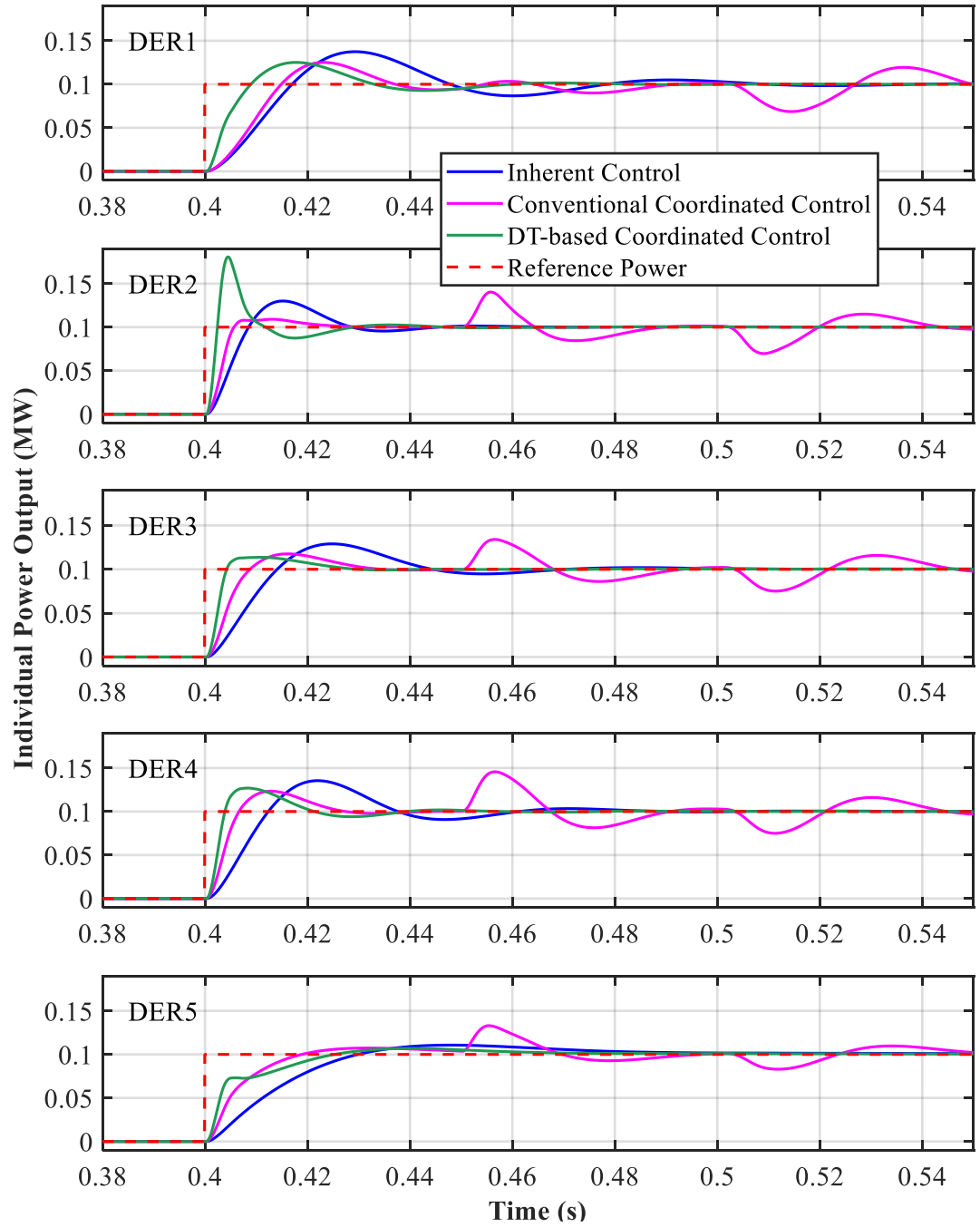


Figure 6.9: Individual responses of DERs with simultaneous set point change - different amounts of power requested from all DERs

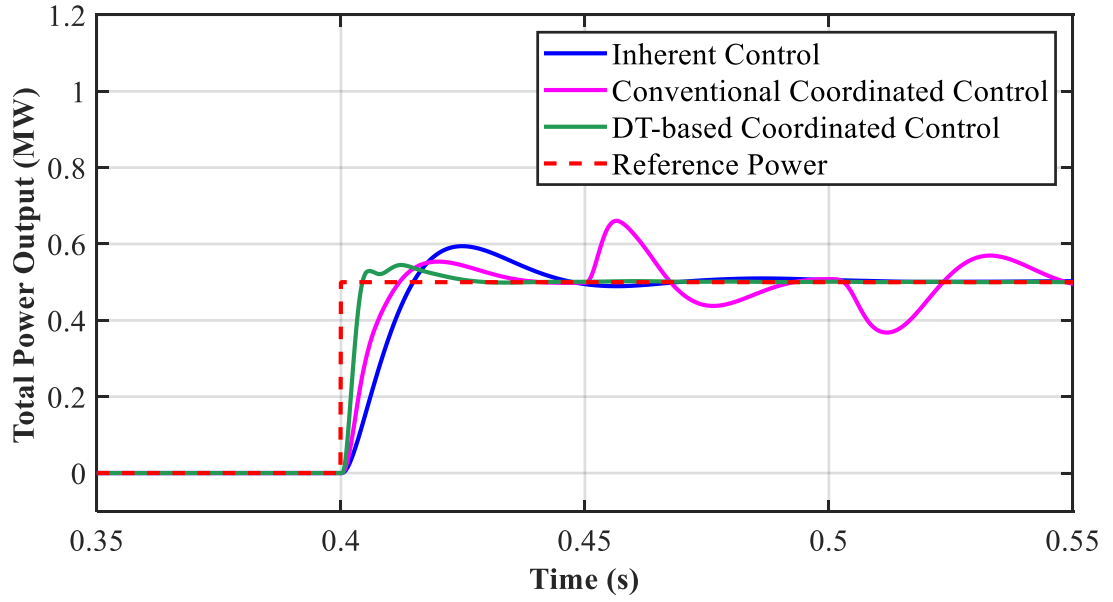


Figure 6.10: Aggregated responses of DERs with simultaneous set point change - same amount of power requested from all DERs

control, the aggregated overall response is relatively slow due to slow responses from each DER, along with a certain level of overshoot and relatively long settling time. Such behaviour is not ideal for the overall frequency regulation especially with large number of aggregators and a large capacity of participating DERs.

With the conventional coordinated control, significantly large errors between the reference power and the actual power output for each DER can be observed due to communication delay between the among the DERs (as illustrated in Figure 6.1.(c)). These errors also lead to an oscillation in the overall response of the DERs, which might could severely comprise the system's frequency control performance.

In the case of DT-based distributed coordinated control, due to the DTs are located in the DERs sites without the need for communication with other DERs, it has significantly faster response and shorter settling time compared to the other two approaches.

Figure 6.11 present another case that has been tested with 1 MW total active power requested simultaneously by the aggregator but with different amounts for each DER. The results along with comparison between inherent and DT-based coordination control are shown in Figure 6.11. Similar observation as motioned above for Figure 6.10 can

be made for both DT-based coordinated control and the inherent DER control, where DT-based coordinated control shows significantly improved response.

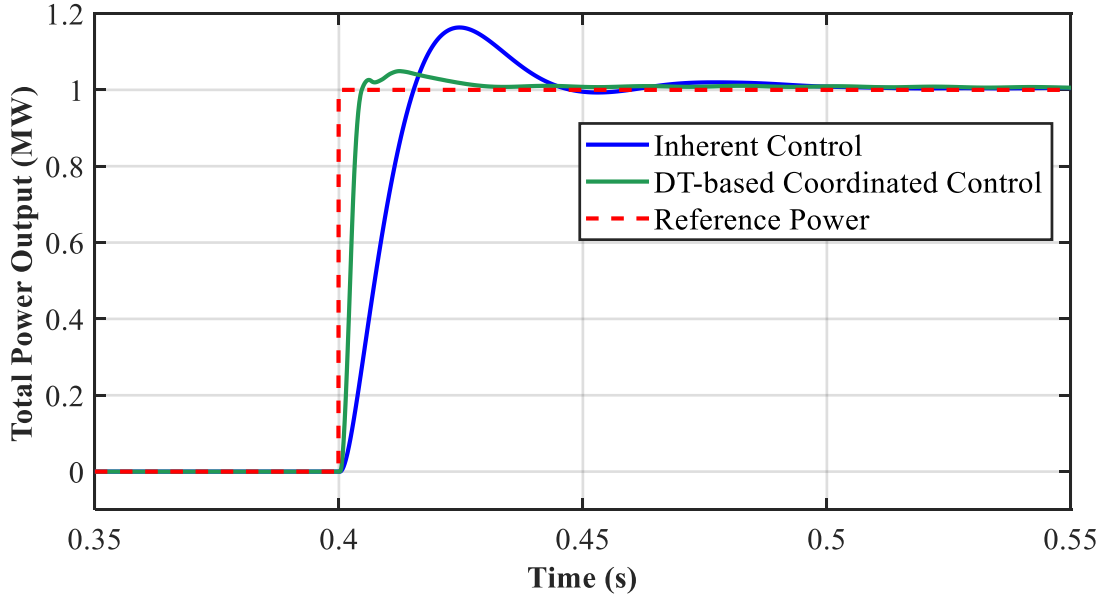


Figure 6.11: Aggregated responses of DERs with simultaneous set point change - different amounts of power requested from all DERs

Staggered Change in the Set Points of DERs

In this case, the aggregator sends power set points to all of the five DERs to request a same amount of increase in active power output (i.e. 100 kW) but at different time rather than sending signal simultaneously. The results for this case are shown in Figure 6.12. It can be observed that the overall response from the DT-based coordinated control is faster with more effective tracking of the reference power compared to the inherent control of the DERs.

6.4.4 Case Study 3: Effectiveness of DT-Based Coordinated Control in Supporting Grid Frequency Regulation

In practice, electricity system operators are required to maintain the frequency close to its nominal value, which is 50 Hz in the GB network. The ultimate objective of the coordinated control using DTs of DERs either hosted in the cloud (centralised) or at the

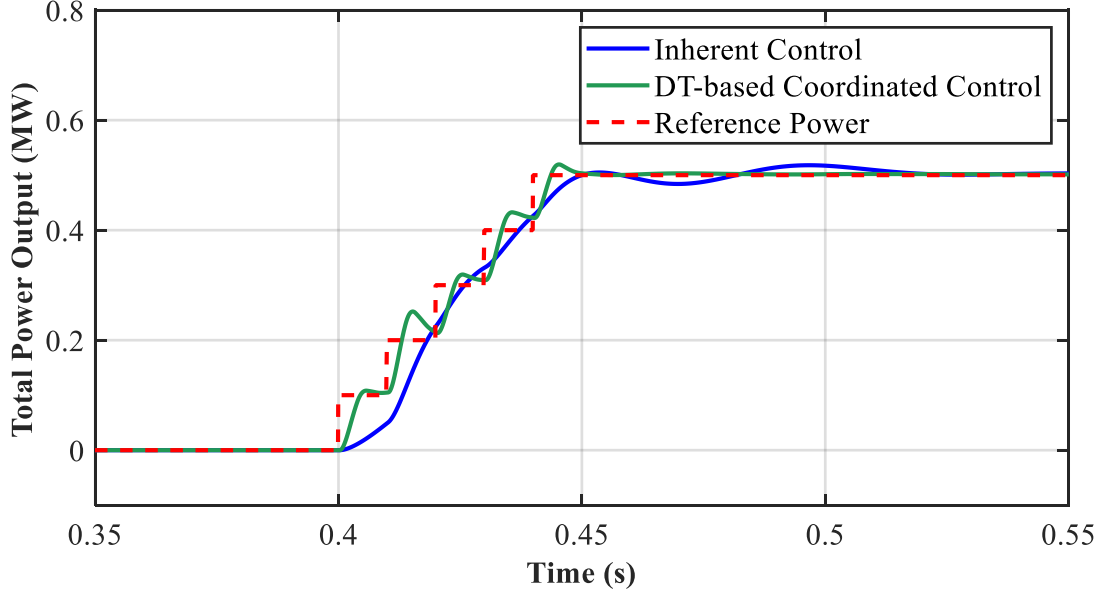


Figure 6.12: Power output with coordinate control by applying staggered inputs

edge (distributed) as demonstrated in Section 6.4.2 and 6.4.3 is to support the control of grid frequency, which can deviate from its nominal value during power imbalance events. Based on the current National Electricity Transmission System Security and Quality of Supply Standard [178], the statutory frequency limit should be maintained between 49.5 Hz – 50.5 Hz. In this case study, it will be shown how conventional frequency control methods can be inadequate in containing frequency deviation in future low inertia conditions and how the DERs with DT-based coordinated control can significantly improve the frequency regulation performance.

As shown in Figure 6.13, under-frequency events can be emulated by changing the power imbalance value (ΔP_{event}) in the analytical power grid model, which can be used for representing power grid frequency behaviour during power imbalance events [179]. The model is used to emulate the frequency profile during a disturbance. The frequency will then be applied to the controllable voltage source connected to the microgrid, acting as a grid emulator. The DER aggregator will monitor the frequency and trigger frequency response from DERs when the frequency drops below 49.8 Hz. As the aggregated DERs' active power within a single microgrid or a distribution network within a certain area is relatively small compared with the overall grid loading, in this case

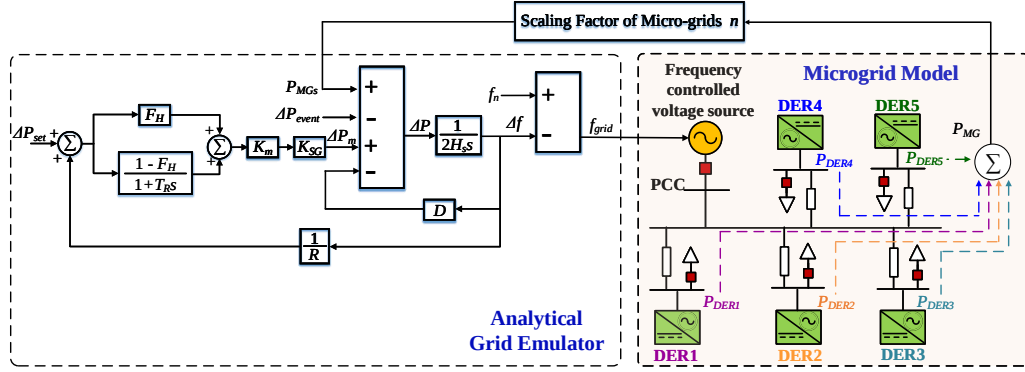


Figure 6.13: Test setup for evaluating DT-based coordinated control in supporting grid frequency regulation

Table 6.1: Description of the parameters in Case 3

Parameters	Description	Value
ΔP_{set}	Change of synchronous generator's power set point in p.u.	Variable
F_H	Fraction of power generated by the turbine	0.1
T_R	Reheat time constant in seconds	4 s
K_m	Mechanical power gain factor	0.95
ΔP_m	Change of mechanical power output in p.u	Variable
ΔP_{event}	Change of power caused by events	Variable
H_s	Inertia constant	2 s
R	Droop constant	0.05
D	Damping constant	0.06
f_n	Nominal frequency	50 Hz
Δf	Change of grid frequency	Variable
f_{grid}	Normalised grid frequency	Variable

study, the total response of all DERs (i.e. P_{MG}) is scaled up to emulate an scenario, where the proposed DT-based coordinated control is deployed by many DER aggregators across the system, to test the effectiveness of the proposed approach in supporting future grid frequency regulation when it is rolled out at a large scale. A scaling factor of micro-grids n is introduced to control the level of scaling of the frequency response from DERs being controlled. Descriptions of the parameters as presented in Figure 6.13 are provided in Table 6.1.

Grid Frequency Regulation with DT-Based Centralised Coordinated Control (Cloud-Hosted)

In this test case, a 1000 MW loss of generation is emulated with 25 GW system loading and an overall system inertia of 50 GVAs. It is assumed that there are five DERs with four of them representing conventional distributed SGs with relatively slow response and one representing converter-based source (e.g. BESS) with a faster response. The scaling factor for the DERs is set as 100, i.e. assuming there are 100 DER aggregators with same DERs available providing the ancillary service. Three scenarios are designed to illustrate the effectiveness of DT-based coordinated control: 1) the grid only relies on conventional primary frequency response without support from DERs; 2) DERs purely use their own inherent controllers to provide support to main grid without coordinated control; 3) DERs provide support to main grid with the proposed DT-based coordinated control.

The test results are shown in Figure 6.14 and Figure 6.15. In the case where there is no DERs' support, the grid frequency decreases severely to 49.29 Hz. In the second scenario, where there is DERs support but no DT-based coordinated control is used, the frequency nadir is improved to 49.48 Hz due to additional active power from participating DERs. In the third scenario, where DERs are deployed with the DT-based coordinated control, the frequency deviation is effectively contained with a frequency nadir of approximately 49.6 Hz. The improvement of the frequency is due to the coordinated actions from DERs with different responding capabilities, which lead to an overall faster response to contain frequency deviation as illustrated in Figure 6.15.

Grid Frequency Regulation with DT-Based Distributed Coordinated Control (Edge-Hosted)

In this test case, the same test scenario as Case 3.1 is adopted, but with the edge-hosted DT-based distributed coordinated control. The test results are presented in Figure 6.16 and Figure 6.17.

Similar to the observations made in Case 3.1, the coordinated control using DTs hosted at the edge also provide significant improvement to the frequency regulation

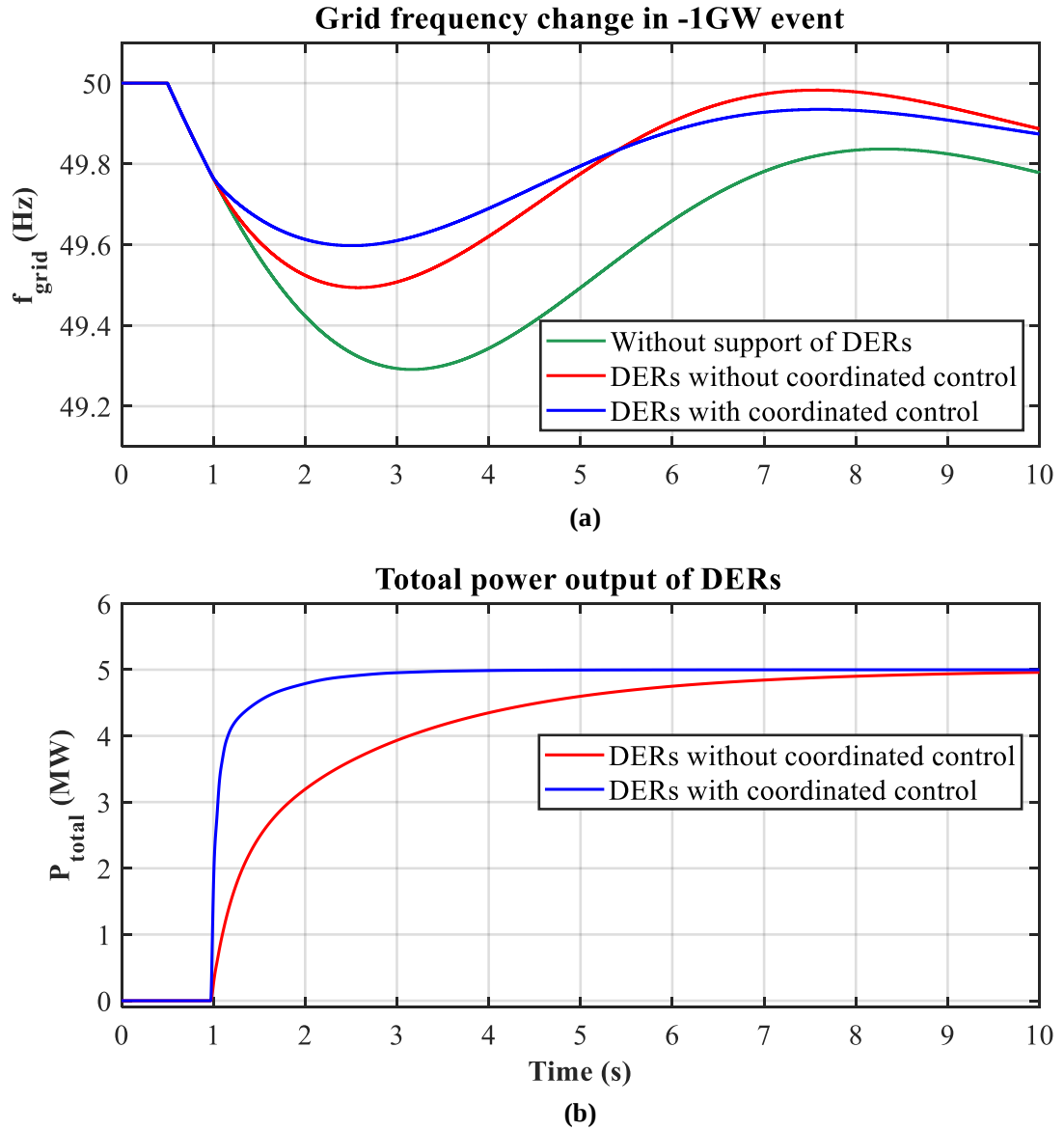


Figure 6.14: Performance of frequency regulation comparison with and without DT-based centralised coordinated control (cloud-hosted): (a) frequency profile; (b) total active power provided by DERs

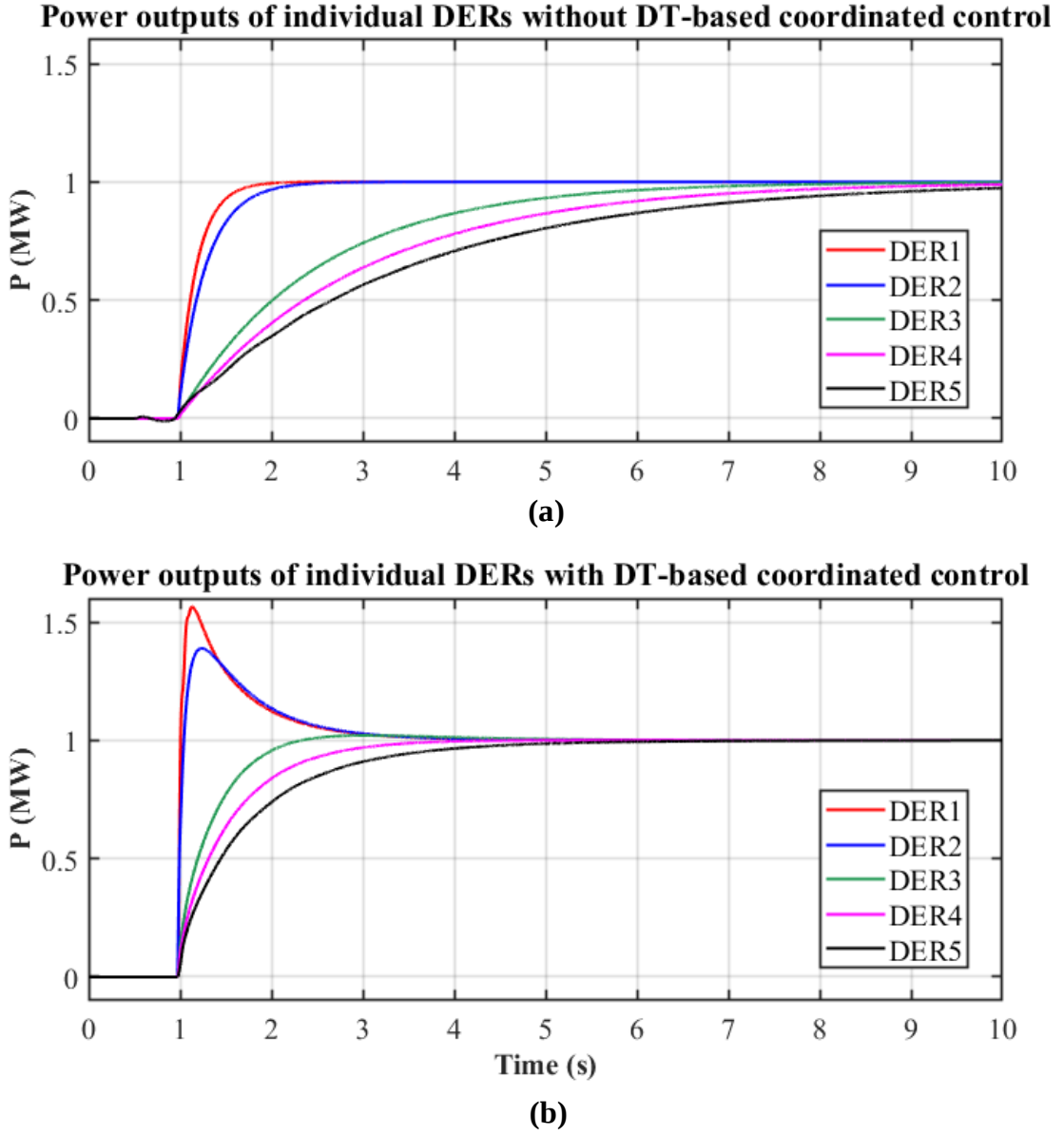


Figure 6.15: Active power outputs of individual DERs: (a) with DT-based centralised coordinated control; (b) without coordinated control

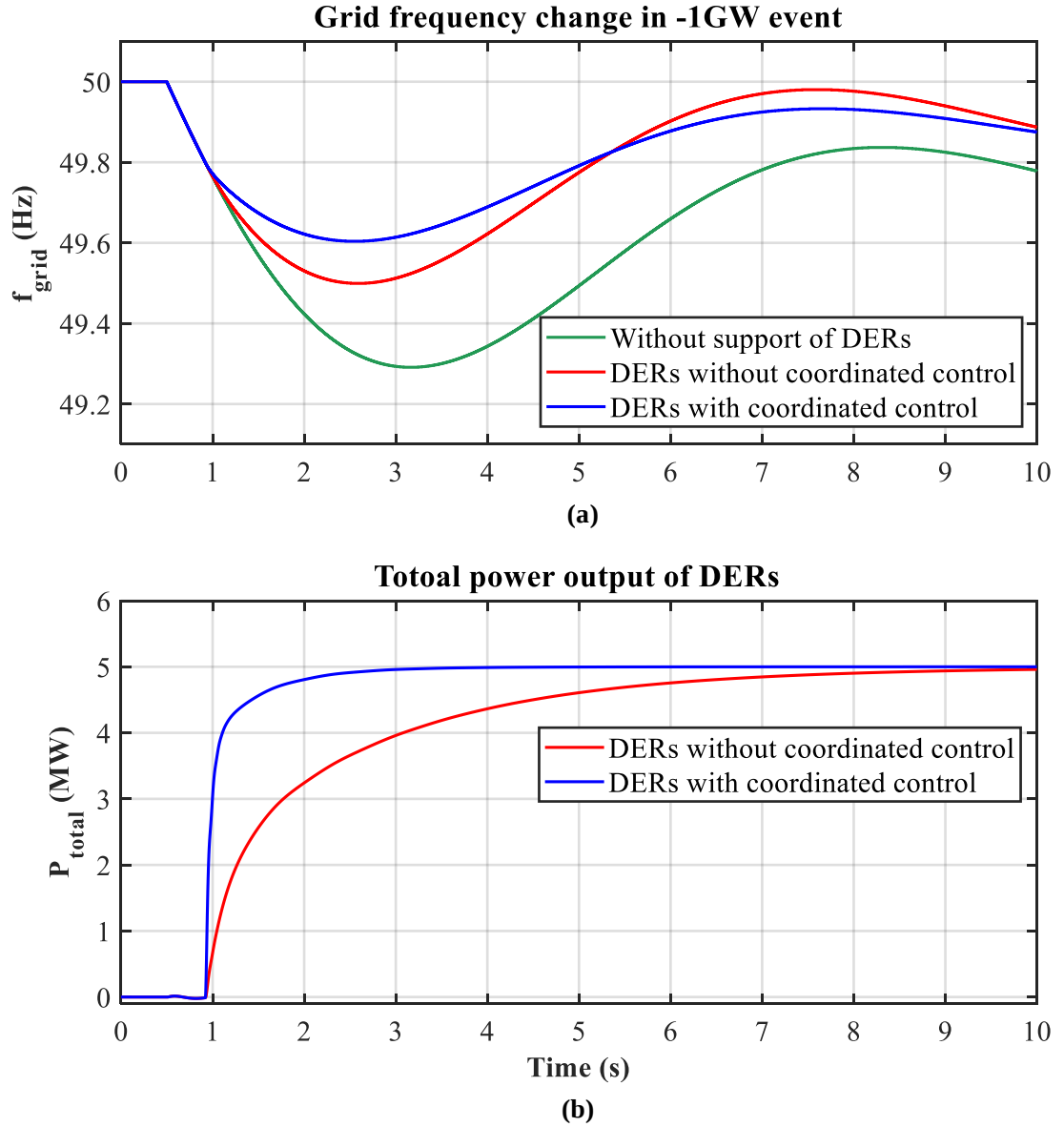


Figure 6.16: Performance of frequency regulation comparison with and without DT-based distributed coordinated control: (a) frequency profile; (b) total active power provided by DERs

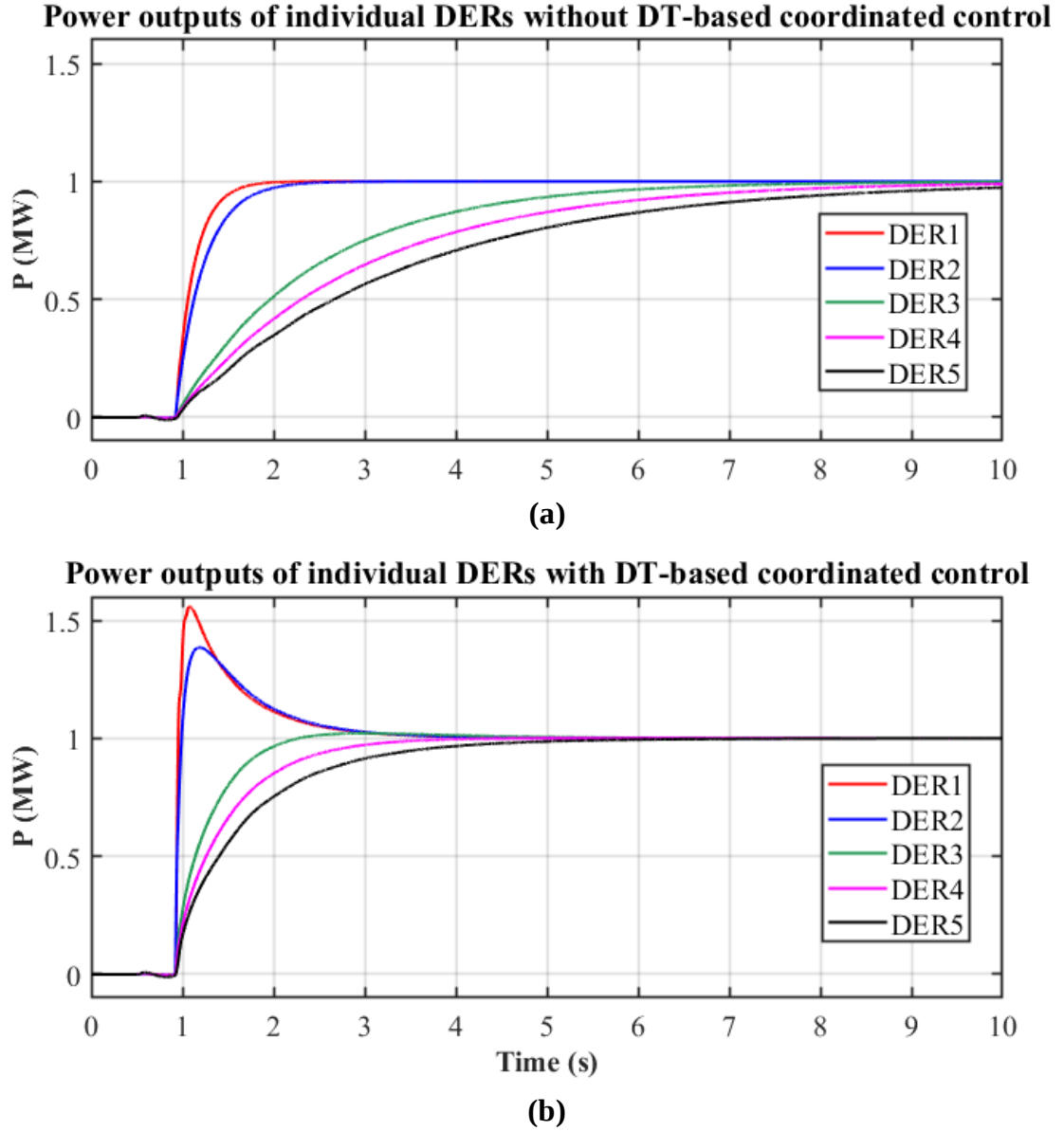


Figure 6.17: Active power outputs of individual DERs: (a) with DT-based distributed coordinated control; (b) without coordinated control

performance, where the frequency nadir has been raised from approximately 49.5 Hz to 49.6 Hz.

6.4.5 Case Study 4: Robustness against DT synchronisation Errors

In the proposed DT-based coordinated control, synchronisation between the DERs and their DTs follows two main principles: 1) discrete event-triggered update, i.e., whenever there is a power set point change in one DER, the synchronisation between the DER and its DT needs to be conducted. This can happen at different time interval depending on the energy market conditions driven by the system needs, but typically the set point of DERs will only change when a settlement period finishes (i.e. every 30 mins); 2) periodic update, i.e., periodic synchronisation to check the DTs' status and the actual active power output at the DER is also conducted, typically every minute. This is selected based on the fact that when a frequency event occurs, typically it will last over 1 minute, so having 1-minute resolution will ensure the statuses of the DERs remain updated whenever a frequency event occurs. In practice, the periodic synchronisation can be relaxed to a longer period (e.g. 5 mins) if needed, as the proposed DT-based coordinated control has a high-level of tolerance even if there is inconsistency of the DT estimation and the actual power output occurring between two synchronization instances, which will be demonstrated in this case study.

In this test case, errors of 5% to 20% between the DERs' actual active power outputs and their DTs estimated values are applied to intentionally introduce the inconsistencies between DERs and DTs. As shown in Figure 6.18, for both of the grid and edge hosted approaches, the DT-coordinated control provides most desirable response when there is no error between the DTs and DERs. With the increase of errors up to 20%, although the control effectiveness can be slightly comprised as compared with the case without any error, the overall performance is still significantly more effective with faster response and settling time compared with the case without DT-based coordinated control.

It should be noted that, while the synchronisation between DERs and the DTs do not need to be conducted in real time, the active power outputs from the DTs are estimated in real time, which are used as the inputs to the DT-based coordinated controller to

enable the real time control of DERs to deliver effective frequency control support.

6.4.6 Discussions

The operation of future power systems with increasing renewable penetration and declining system inertia poses significant challenges for frequency stability. As noted earlier, the rapid growth of DERs means they will play an increasingly critical role in frequency regulation. However, their distributed nature, limited visibility, and diverse response capabilities create substantial barriers. Conventional approaches to coordinating DERs typically rely on high-bandwidth communication links, so reducing this dependency is essential to develop robust and scalable control methods that can ensure reliable system response under low-inertia conditions.

This chapter has demonstrated a step-change in both centralised and distributed control implementations through the application of DTs. The key findings are:

- DT-enabled centralised control eliminates the need for real-time feedback from DERs to the aggregator. This reduces the number of communication links from $2M$ to M for M DERs, while maintaining accurate estimation of DER dynamics in real time.
- DT-enabled distributed control removes the need for DER-to-DER communication by embedding DTs of peer DERs at the local level. This effectively transforms distributed control into a decentralised scheme, but one that preserves the benefits of coordination.

Overall, the DT-based coordinated control framework provides a cost-effective and technically robust solution for enhancing frequency response from DERs. By reducing reliance on real-time communications, it not only improves control resilience but also lowers infrastructure costs for utilities. Furthermore, it expands the commercial potential of DERs and aggregators by enabling more reliable provision of ancillary services. Although this chapter has focused on frequency control, the proposed DT-based approach is generic and can be adapted to other centralised or distributed control applications in future power systems.

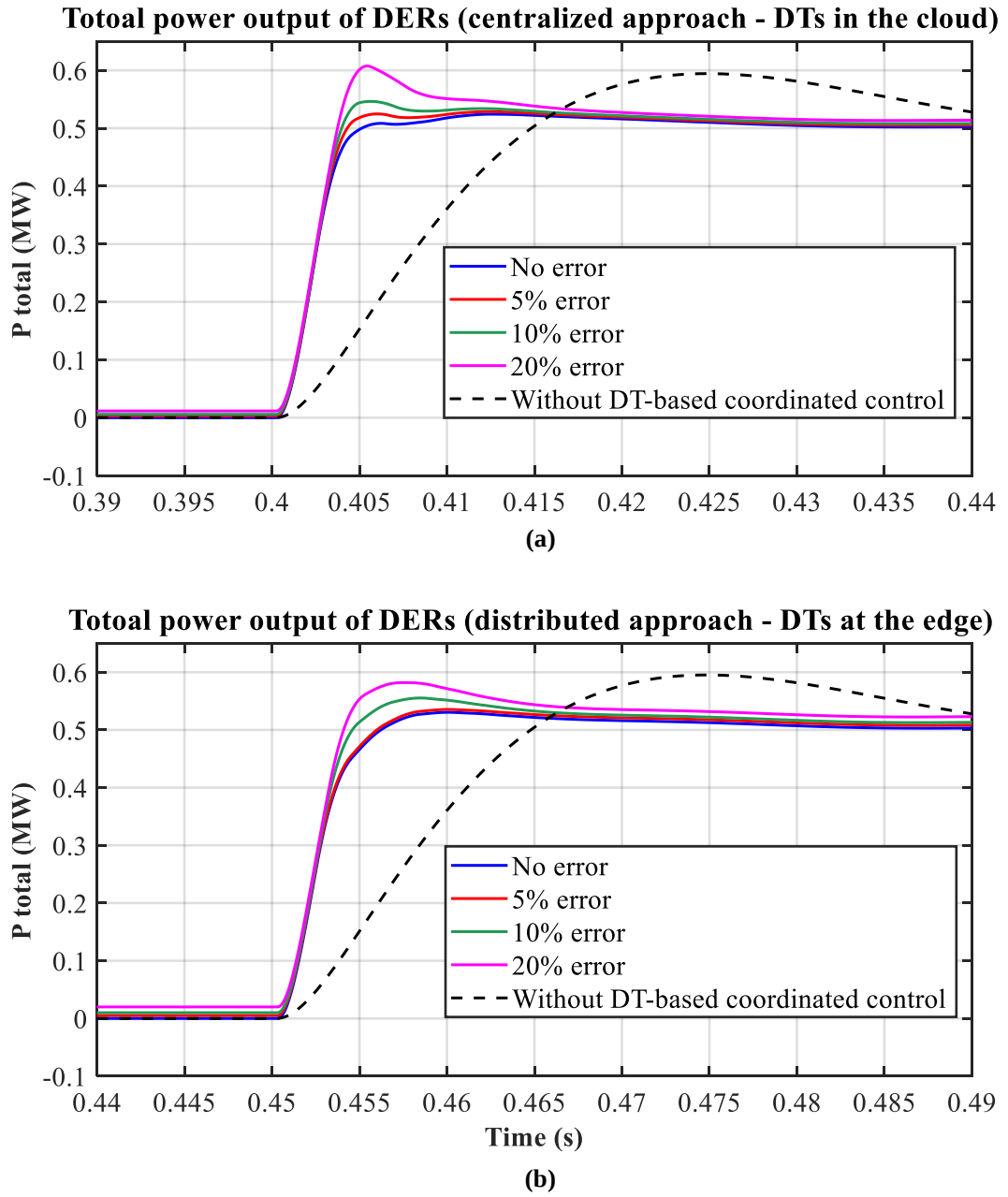


Figure 6.18: Perfomance of the DT-based coordinated control with different level of estimation errors: (a) cloud-hosted DTs: centralised approach (b) Edge-hosted DTs: distributed approach

6.4.7 Summary

This chapter has presented a novel method for realising coordinated control of DERs using on cloud- and edge-hosted DTs to optimise the overall aggregated dynamic response and enhance frequency regulation in power grids. Conventional centralised and distributed implementations were reviewed, where it was found that they have heavy reliance on real-time communication and are subject to adverse impact of latency on control performance. In contrast, the proposed DT-based coordinated control enables real-time estimation of DER states, which allows effective coordination without extensive communication overhead. In the chapter, two DT-based implementation approaches, i.e. cloud-hosted for centralised control and edge-hosted for distributed control, were presented for coordinating DERs, both of which were demonstrated to significantly reduce communication requirements while maintaining strong control performance. These findings show that DT-based coordinated control offers a promising and scalable solution for enabling effective active power response from DERs in future low-inertia power systems.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The rapid transformation of modern power systems, driven by the large-scale integration of converter-interfaced renewable generation, has created new operational challenges that conventional modelling and control systems were not designed to address. Among these challenges, the reduction of system inertia and the growing reliance on variable, converter-based resources have highlighted the need for faster and more effective solutions for frequency control. The rapid increase of DERs means they have the potential to play a more active and critical role in supporting the regulation of frequency in future low-inertia systems. However, their limited visibility within distribution networks and the diversity of their response capabilities often prevent many DERs, particularly when acting individually, from providing effective frequency support.

DTs have emerged as a promising solution to the challenges of enabling DERs to contribute effectively to frequency control. They provide the capability to replicate, monitor, and predict the dynamic behaviour of physical systems in real time. However, despite growing interests in applying DTs within the energy sector, existing research and development activities have left critical gaps, particularly in model fidelity and efficiency, resilience to communication constraints, and supporting frameworks designed for supporting DERs in providing frequency control.

This thesis set out to address these gaps by developing methods for creating, im-

plementing, and validating DTs tailored for DER applications, along with DT-based frameworks for DER scheduling and coordinated control to enable fast frequency response. The research began by reviewing the state of the art in frequency control mechanisms, which highlights the challenges of integrating DERs into frequency regulation. This was followed by an investigation of DT technology, its existing applications, and its potential for unlocking DERs' role in frequency control. The research also identified key gaps, including the absence of suitable DT modelling approaches for frequency control, insufficient handling of real-world communication challenges, the lack of robust testing platforms for assessing DT performance, and the absence of DT-based dispatch and coordination schemes for DERs.

Against this background, the thesis made several contributions, which are summarised below in detail.

The thesis presents three modelling strategies for DTs of DERs (Chapter 4), tailored for real-time frequency control, i.e. physics-based, system identification-based and data-driven approaches. Physics-based DTs were constructed where detailed knowledge of system parameters and dynamics was available, allowing transparent representation of system behaviour. System identification-based models were applied in scenarios with only partial information about the DER system but with test data available to derive equivalent models of DER dynamics. Data-driven DTs can be developed in cases where only operational data were available, which can be achieved by employing machine learning methods, e.g. CNNs, trained on frequency input signals and corresponding DER output responses. Validation across all three approaches demonstrated that accurate DT dynamics could be achieved, with each method offering distinct strengths. Physics-based models provide interpretability and confidence under well-characterised conditions, while system identification and data-driven approaches offer flexibility when empirical data are the primary source of knowledge. Pure data-driven models have the strength of being light weighted, which makes them suitable for performing large number of live what-if simulations. The findings from developing these modelling approaches highlight the fundamental link between model fidelity and DT performance, showing that no single method is universally sufficient. Instead, the choice of modelling approach

should be guided by the specific requirements and context of the intended application.

Relating to the modelling and operation of DTs, another significant outcome of this research was the development of a methodology to determine the minimum reporting rate of input signals needed to achieve adequate DT accuracy. In practice, communication infrastructure limits reporting frequency, and excessively high rates can create bandwidth inefficiencies and increase costs. The proposed methodology enables the understanding of the minimum reporting rate required and also showed that DTs can preserve accurate dynamic responses as long as it is above the minimum reporting rate is met, thereby achieving an effective balance between fidelity and efficiency. This contribution is particularly relevant for practical deployment, where trade-offs between data quality, communication bandwidth, and computational load must be carefully managed.

The thesis also addressed the challenges of communication latency and jitter for DTs. A handling strategy based on sample reordering and linear reconstruction using timestamped signals was developed, which enables DTs to adapt effectively to unstable or delayed data streams. This ensured robust monitoring and control under adverse communication conditions, which addresses the gap in existing research where idealised communication assumptions often masked such issues. An HiL testing platform was established for evaluating DTs and their applications. This platform provided a controlled environment to validate DT performance against real-time DER dynamics in scenarios such as monitoring, what-if simulations, and active power control. HiL validation proved essential in bridging the gap between simulation-based studies and field trials, offering a practical step toward real-world deployment. By demonstrating feasibility under realistic operating conditions, this work advanced the adoption of DT-based solutions in future power systems

Chapter 5 builds on the established modelling frameworks and introduces a new DER scheduling and dispatch framework to address the challenge of over- or under-estimating DER capabilities in frequency control. The platform enables real-time execution of what-if scenarios using the live status of DERs, explicitly considering their limitations, e.g. response speed and available headroom, when projecting system frequency trajectories during power imbalance events. This provides system operators with

a more accurate assessment of the frequency control performance that procured DER services can deliver. The capability is particularly valuable in low-inertia systems, where disturbances can escalate rapidly and leave little time for corrective action. By allowing operators to test hypothetical interventions before implementation, the DT-based dispatch framework supports more informed and reliable decision-making, reducing the risk of both over- and under-procurement of DER services.

To directly enable DERs to collectively provide frequency control, Chapter 6 developed a coordinated control strategy that exploited the advanced capabilities of DTs. Two DT-based hosting architectures were introduced: one with DTs strategically hosted in the cloud and the other with DTs distributed across edge environments. Both approaches were demonstrated to significantly reduce communication requirements while maintaining strong control performance. These findings demonstrate that DT-based coordinated control offers a promising and scalable solution for enabling effective active power response from DERs in future low-inertia power systems.

These contributions of this thesis provide valuable new knowledge and establish a coherent framework for the creation, deployment, and validation of DTs in enabling DERs for frequency control under low-inertia conditions. The work demonstrates that DTs are a highly effective tool for supporting the monitoring, operation, and control of DERs. By systematically addressing gaps in modelling, monitoring, communication, validation and control, the thesis provides a comprehensive foundation for advancing DT applications in the energy sector.

It should also be noted that this research was subject to limitations in hardware, software, and supporting tools. From a hardware perspective, edge devices such as Raspberry Pi put restrictions on the type of DT models that could be executed. In particular, data-driven CNN models could not be deployed efficiently on these devices due to their limited processing capability, which meant such models were only practical in cloud-hosted environments under current condition. On the software side, the DT executables were generated using Visual Studio, which introduced dependencies on specific libraries and imposed requirements for correct configuration of the runtime environment. In terms of testing platforms, the communication between RTDS and

DTs was limited by the set of supported protocols, restricting flexibility in choosing alternative communication schemes that may be more representative of real-world deployments. These constraints reflect practical challenges when moving from conceptual DT frameworks to implementation and validation.

In conclusion, this research demonstrates the transformative potential of DTs in shaping the future of frequency regulation. By enhancing the visibility of DERs while reducing reliance on real-time communications, DTs provide a pathway to unlock their full potential in supporting future decarbonised power systems. The methodologies and frameworks developed not only address key challenges in frequency control, but also establish a foundation for extending DT applications to a wider range of grid services, thereby contributing to the reliable and secure operation of future decarbonised power systems.

7.2 Future Work

While this thesis has made significant progress in applying DTs to enable DERs to support frequency control in low-inertia power systems, several important avenues remain open for exploration. These areas reflect both the limitations of the present work and the broader research challenges associated with scaling DT technology from laboratory prototypes to real-world deployments. The following directions outline the most promising opportunities for extending and enhancing the impact of this research.

7.2.1 Scalability of DER DTs and Integration with Wider Power System DTs

The scope of this thesis was centred on relatively small and regional systems with representative DER units, which provides a controlled environment to showcase DT creation and their potential in supporting real time control strategies. However, as modern power systems integrate increasing numbers of DERs, future research must focus on scalability. A key challenge lies in coordinating hundreds or even thousands of DTs across different regions, and potentially across both distribution and transmission levels, without

overwhelming communication and computational resources. Hierarchical DT frameworks may offer a solution, where local DTs interact with regional and system-level DTs through structured data exchange. Complementary techniques, including model reduction and multi-rate simulation, can also be critical to ensure that large-scale DT implementations remain computationally viable. Further research in this area could pave the way for a comprehensive digital replica of entire energy systems, enabling coordinated planning, monitoring, and real-time operation across multiple network layers.

7.2.2 Advanced Data-Driven Modelling and Adaptive DTs

While this thesis employed data-driven methods, including CNNs, there are further opportunities to advance DT modelling. For example, through physics-informed neural networks, it can potentially enhance both interpretability and accuracy. Moreover, DTs of DERs must remain adaptive as the physical system characteristics change over time due to ageing, maintenance, or environmental conditions. Continual learning, transfer learning, and online adaptation techniques could be explored to offer promising avenues for keeping DTs accurate without requiring complete re-training. Exploring these approaches could significantly enhance the robustness of DTs and enable long-term deployment without degradation in performance.

7.2.3 Integration with Market Mechanisms and Regulatory Frameworks

The DT-based DER dispatch and coordinated control developed in this thesis were primarily evaluated from a technical standpoint, with emphasis on dynamic performance. However, practical deployment requires alignment with economic and regulatory environments. Future research should therefore investigate how DTs can be embedded into ancillary service markets, particularly for the provision of fast frequency response, dynamic containment, and flexibility services. This can include investigation of how DTs could be used to support cost-benefit allocation and incentive design. Regulatory frameworks will also need to evolve to consider the potential roles of DTs in the process of compliance monitoring and operational decision-making. Exploring these intersec-

tions between technology, economics, and governance will be essential for accelerating DT adoption and ensuring that their value is realised in practice.

7.2.4 Cross-Domain DT Integration and Standardisation

Energy systems do not operate in isolation, and they are tightly coupled with other infrastructures such as transportation, heating, and communications. Future energy systems are expected to be integrated with resources from different vectors, and it is critical such changes are considered for creating future DTs for DERs so that they can be interoperability for integration with wider network components. Therefore, future DT research could investigate cross-domain integration of DTs, where power systems interact with electric vehicles, district heating networks, and communication infrastructure. Such integration would allow the holistic assessment of interdependencies and cascading effects, supporting resilience planning under extreme conditions, e.g. cyber-attacks, natural disasters, or energy crises.

Furthermore, DT implementations in the energy domain are fragmented, with each project developing its own data models, interfaces, and simulation techniques. Future research should contribute to the creation of standardised frameworks for DTs in power systems, considering lessons learned from initiatives in manufacturing and aerospace sectors. Developing interoperable DT architectures would enable plug-and-play integration of new assets, reduce engineering costs, and facilitate cross-vendor compatibility. This line of work will be essential for scaling DTs from bespoke research projects to mainstream industrial adoption.

In summary, the future of DT research for DERs lies in scaling from technically validated prototypes to large-scale, adaptive, cost-effective, and interoperable systems. Addressing challenges will be pivotal for realising the full potential of DTs. By pursuing these directions, DTs can evolve into a cornerstone technology for enabling resilient, flexible, and sustainable energy systems of the future.

Appendix A

Distribution Network Model

The 11kV distribution network connects with main grid through grid connection point as shown in Figure A.1. It is configured to be able to operate in islanding mode.

The hydro generator has a rated power of 1 MVA and a rated voltage of 0.4 kV. It is modelled as a synchronous machine with an inertia constant of 2 s. The unit is governed by the standard HyGov hydro turbine model, with a permanent droop of 5%, a governor time constant of 6 s, and a damping factor of 0.2.

The combined heat and power unit has a rated power of 1 MVA and a rated voltage of 0.4 kV. It is also modelled as a synchronous generator, with an inertia constant of 2 s. The prime mover is represented by the GAST gas turbine governor model, configured with a droop of 5%, a time constant of 0.8 s, and a fuel system gain of 2.

The wind generator is an inverter-based unit with a rated power of 1 MVA and a rated voltage of 0.4 kV. It is implemented as a controllable current source under PQ control. The controller operates with an active power reference of 0.2 pu and a reactive power reference of 0 pu, with a current limit of 1.2 pu.

The photovoltaic unit is an inverter-based source with a rated power of 1 MVA and a rated voltage of 0.4 kV. It is operated under maximum power point tracking combined with PQ control. The model uses an active power reference of 0.6 pu and a reactive power reference of 0 pu, with a response time constant of 1 ms to reflect the inverter dynamics.

The BESS is rated at 1 MVA and 0.4 kV. It is controlled using a PQ strategy with

Appendix A. Distribution Network Model

a low-pass filter to emulate different response speeds. The control includes a droop coefficient of 5%, a filter time constant of 1 ms.

The VSM-based GFC is an inverter-based unit configured to emulate the behaviour of a synchronous generator. It has a rated power of 1 MVA and a rated voltage of 0.4 kV. The model incorporates a virtual inertia constant of 2 s and a virtual damping factor of 50. Its control parameters include a current limit of 1.2 pu and a response time constant of 1ms.

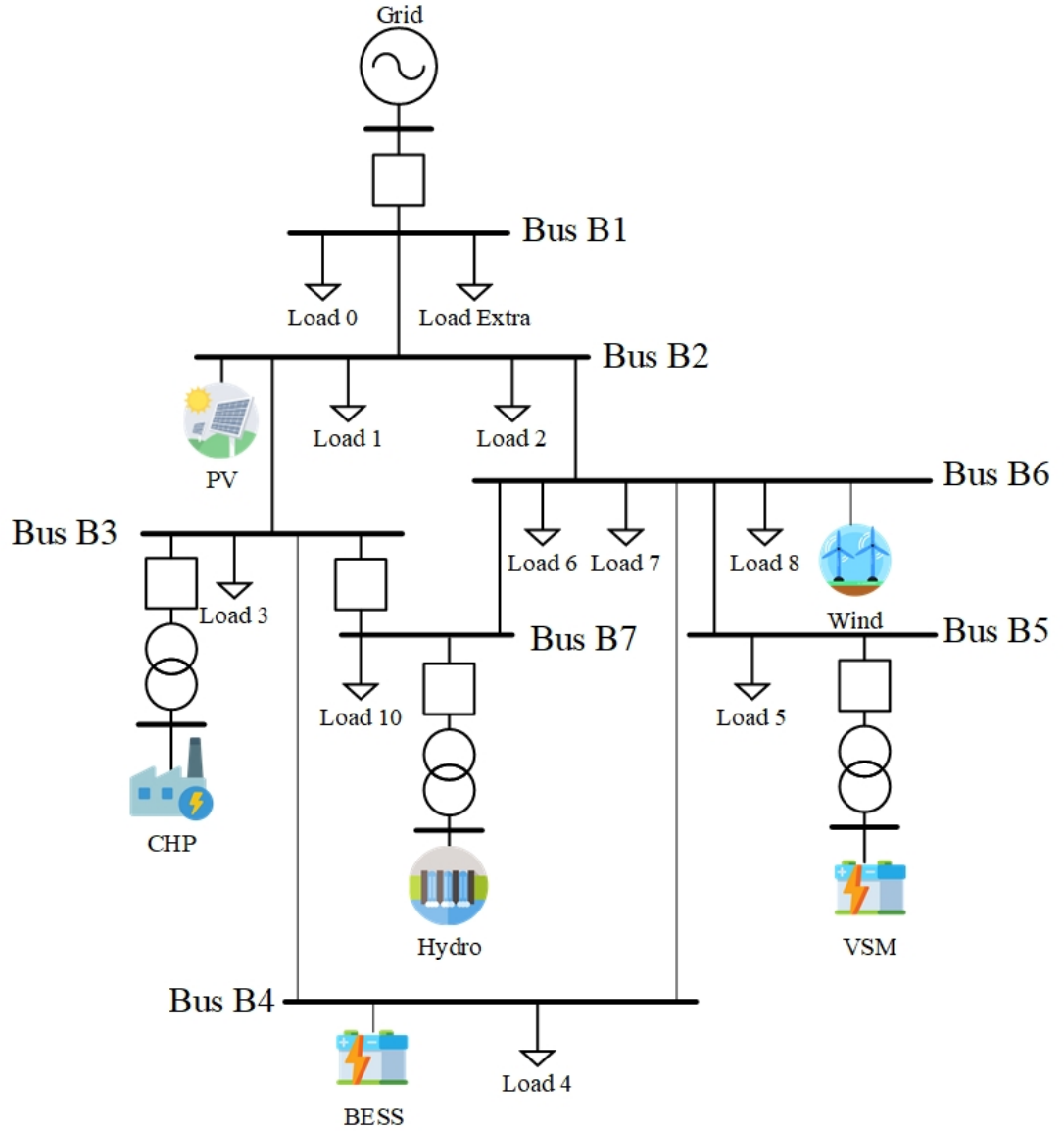


Figure A.1: The distribution network model of modified IEEE 9bus benchmark

Appendix A. Distribution Network Model

Pi model are adopted for transmission line, and their parameters are listed in Table A.1

Table A.1: π -Section Line Parameters

Parameters	Sequence Series Resistance [Ω]	Sequence Series Inductive React [Ω]
$L12$	0.0865	0.21585
$L23$	0.1038	0.25902
$L26$	0.2249	0.56121
$L34$	0.3979	0.99291
$L46$	0.2249	0.56121
$L56$	0.2941	0.733389
$L67$	0.0865	0.21585

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