Cloud-Edge Hosted Digital Twins for Coordinated Control of Distributed Energy Resources

Jiaxuan Han, Qiteng Hong, Mazheruddin H. Syed, Md Asif Uddin Khan, Guangya Yang, Graeme Burt, and Campbell Booth

Abstract—This paper presents a novel approach for realizing coordinated control of Distributed Energy Resources (DERs) based on cloud-hosted and edge-hosted digital twins (DTs) of DERs. DERs are playing an increasingly important role in supporting the frequency regulation of power systems with massive integration of renewable resources. However, due to the significant differences in DERs' capability and characteristics, individual and un-coordinated responses from DERs could lead to a less effective overall response with undesirable traits, e.g. slow response, severe overshoots, etc. Therefore, the coordination of DERs is critical to ensure the desirable aggregated overall response. A major shortcoming of conventional centralized or distributed approaches is their significant reliance on real-time communications. This paper addresses the challenges by the application of DTs that can be hosted in the cloud for the centralized control approach and the edge for the distributed approach to minimize the need for real-time communications, while being able to achieve the overall coordination among DERs. The proposed DT-based coordinated control is validated using a realistic real-time simulation test setup, and the results demonstrate that the DT-based coordinated control can significantly improve the aggregated DERs' response, thus offering effective support to the grid during contingency events.

Index Terms—Cloud computing, distributed energy resources, distributed networks, digital twin, real-time control.

1 Introduction

Power systems globally are undergoing unprecedented changes with decentralization and digitization trends reshaping the energy sector through integration of renewable resources to meet the ambitious decarbonization targets [1]–[3]. According to the Paris agreement on climate change, the Great Britain (GB) has committed to achieve "Net Zero" greenhouse gas emission by 2050 and many other countries also set ambitious decarbonization plans [4]. Furthermore, the 26^{th} UN Climate Change Conference of the Parties (COP26) held in 2021 passed the Glasgow Climate Pact, where the global community has reached to an agreement with increased ambition to achieve the target of controlling the global warming within 1.5ºC [5], meaning continued and more ambitious global efforts on decarbonization in the coming decades. As a result, massive renewable generation are being connected to the power systems, where significant amounts are Distributed Energy Resources (DERs) integrated in the distribution systems, e.g. PV cell, wind turbine, energy storage, biomass, etc. [6], [7]. This presents major challenges for power system operators, as the integration of renewable generation will result in the decrease of overall system inertia, thus leading to the system frequency deviating faster during power imbalance events (e.g. loss of generation). This could risk the statutory frequency limit, (which is typically 49.5 Hz – 50.5 Hz) failing to be met, and lead to significant increase of operational costs [8].

While the massive amount of renewable can bring significant challenges, the rapid integration of controllable DERs at the grid edge also opens opportunities for DERs to provide valuable services to support the future system operation [9], e.g. provision of voltage support [10], frequency response [11], improved power quality [12], reduction in power losses [13], release of additional transmission and distribution capacity [14], and improved reliability [15], etc. Presently, there are many different control concepts being proposed for DERs, which can be broadly categorized into three main control strategies: 1) real and reactive power (PQ) control; 2) voltage and frequency (V&f) control; and 3) droop control [16]. The V&f control aims to maintain the voltage and frequency of the grid at specified values by adjusting their outputs, while with the droop control, the frequency and voltage could deviate from the targeted values, but the DERs will change their active and reactive references based on the level of deviation and the configured droop setting to provide the support to the grid. The DERs controlled by these two types of strategies are generally used to support islanded operation of microgrids [17]. Presently, the most widely used control for DERs connected to the power grid is equipped with the PQ control strategy (thus the focus of this paper), where the active and reactive power outputs of the DERs are controlled based on the commanded power set points. One of the most typical ways for DERs to provide the ancillary service for the system operators to support frequency regulation is via commercial aggregators. During

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This work is jointly funded by EPSRC via the RESCUE project (EP/T021829/1) and the European Union's Horizon 2020 research and innovation programme under grant agreement No 870620 - ERIGrid 2.0 project.

frequency disturbances, DER aggregators will firstly evaluate the active power response required (e.g. via frequency control schemes as reported in [18]), and send requests to a set of contracted DERs with PQ control strategies to change their active power output (either increase or decrease power) and then the DERs will respond individually to the commands to change their power outputs [19].

Due to the significant differences in DERs' capability and characteristics, individual and un-coordinated responses from DERs could lead to a less effective overall response with undesirable traits, e.g. slow aggregated response, severe overshoots, etc. A coordinated approach where the individual response characteristics of the DERs is harnessed for enhanced dynamic cumulative response is desirable for frequency during frequency events, especially in a system with low inertia. However, one of the major drawbacks to enable the effective coordination of the DERs is the requirement of high bandwidth real-time communication, which is not cost-effective and the overall control performance is highly dependent on the performance of the communications employed. Therefore, this paper presents a new approach for realizing the effective coordinated control of the DERs based on Digital Twins (DTs), which can minimize the need for real-time communications, while being able to achieve the overall coordination among DERs.

DT is considered to play a critical role in Industry 4.0, and it is the core part of many emerging technologies, e.g. Internet of Things (IoT), Cyber-Physical Systems (CPSs), Big Data Analytics (BDA) [20]. One of the key features of Industry 4.0 is the techniques for measuring, collecting and processing high volume of real-time data (which is also known as big data) to enable extensive applications in different domains. The applications of big data typically rely on a well-constructed five-layers CPSs architecture as defined in [21] with the aid of cloud computing, which has a similar structure with general definitions of DT. The concept of DT was first introduced in [22], where it was defined as a virtual representation of a physical component/system. After years of research and development, the definition of DT has evolved to "an appropriately synchronized body of useful information (structure, function, and behaviour) of a physical entity in virtual space, with flows of information that enable convergence between the physical and virtual states" [23]. In the context of power systems, the DT is more specifically defined as "software-based abstractions of complex physical systems or objects which are connected via a communication link to the real object through a continuous data flow from the real world" based on [24]. Despite different definitions of the DT concepts, in general, a DT can be considered as a realistic digital model of a physical system that is being constantly updated by real-time data of the physical system. The implementation of a prototype of a physical component in DT can be achieved by using one of these three methods: physics-based modelling [25], data-driven modelling [26], [27] and big data cybernetics [28].

In recent years, the DT technology has been widely used in different sectors in the industry (e.g. aerospace [29], [30], smart manufacturing [31], transportation industries [32], healthcare system [33] etc.). The trends of decarbonization and digitization in energy sectors also promote the adoption of the DT technique to facilitate renewable energy management and increase energy efficiency, where comprehensive discussions on the potential benefits of DTs and the associated advanced digitalization techniques on the energy sector are presented in [34], covering a wide range of areas, e.g. nuclear power plant deployment, efficient energy distribution and transmission, etc. In [35], a machine-learning driven DT is applied in a nuclear power plant, which aims to understand the complex interconnections of the nuclear power plant and predict component failure. Based on [36], the application of DT technology can significantly improve the industrial productivity, efficiency, safety of the personnel, and variability in the products life cycles with reduction in the capital and operating costs, and health and environment risks. The DT concept is also gaining increasing interests for its application in the power industry, with the majority of current applications in power system mainly focusing on fault diagnosis and real-time online analysis of power grid. In [37], a DT-based fault analysis system is developed for PV systems to identify the fault types once they occur. Another application on fault diagnosis was proposed in [38], which aims to use the DTs as reference to monitor and assess the health conditions of a given system. In [39], a data-driven DT framework is presented for online analysis of the power grid. To the authors' best knowledge, there is very limited work that has been reported on the application of DTs for enhancing the control of DERs, which play a critical role in future smart grid with high penetration of renewable generation.

In this paper, the concept of DT is adopted to enable the coordinated control of DERs to provide an optimal overall response to the power grid, with the minimized need and reliance on real-time communications. Two conventional design and implementation approaches of DERs coordinated control, i.e. centralized and distributed coordinated control, will be firstly presented. It will be illustrated that both approaches could present a relatively high reliance on real-time communications, and the performance of the communication system (e.g. latency) can have severe impact of the control performance. Corresponding to the two conventional coordinated control design, this paper presents two new approaches based on the DTs of DERs: for the centralized coordinated control, the proposed method uses the DTs of the DERs hosted in a cloud server to estimate the real-time outputs of the DERs (rather than gathering the information continuously via communications), which are used by the controller (also hosted in the cloud) to coordinate the DERs' response; for the distributed coordinated control design, the proposed method proposes to have the DTs of the DERs hosted in the grid edge at individual DERs' sites, along with the coordinated controller. Similarly, the DTs are used to estimate the real-time outputs of the DERs for the coordinated controller to minimize the need for real-time communication. It will be demonstrated that for both centralized and distributed approaches, the proposed DT-based coordinated control can largely mitigate the need and reliance on communications, while being capable of delivering effective support to the grid during contingency events.

Therefore, the key research motivation of the work is to provide a solution that is both technically and economically effective to enable the coordination of DERs in supporting the frequency control in future power systems. The paper addresses the research gap of the existing work on coordinated control of DERs, e.g. [40], [41], which has significant dependence and reliance on high-speed and high-bandwidth real-time communications between the central controller and the individual DERs are required, resulting in poor performance and high costs. The uniqueness of the solution provided by the paper can be summarised as follows: 1) through the use of the DTs of DERs, the proposed DT-based coordinated control enables effective coordination of DERs, which can deliver an optimal overall response to support the grid. This provides a promising solution for DERs to play a critical role in future frequency regulation in low-inertia power systems; and 2) two approaches to enable the DT-based coordinated control have been proposed and presented, i.e. the DT can either be hosted in the cloud or in the edge, where both approaches demonstrate highly effective performance with significantly reduced reliance on real-time communications.

The rest of the paper is organised as follows: Section 2 presents the fundamental principle of the coordinated control being used in this paper for optimizing the aggregated DERs' response; Section 3 presents the design and implementation of the coordinated control based on the DT of the DERs for both centralized and distributed schemes; In section 4, the test network and the process of creating the DTs of the DERs in the test network are presented; In Section 5, case studies are presented to validate the performance the DT-based coordinated control, with comparison of conventional implementations; In Section 6, the benefits of the proposed DT-based coordinated control for enterprise are discussed; and finally, Section 7 provides conclusions of the paper.

2 Coordinated Control 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., centralized and distributed approaches, which will serve as the reference for comparison of the DT-based design and implementation, which is presented in Section 3.

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 $i = 1, 2, ..., N$) as shown in Fig. 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:

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

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 5 that the overall aggregated DERs response can be undesirable due to the significant differences in DERs capabilities and characteristics.

2.1.1 *Improving local response*

A simple 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 is modified as

$$p'_{i_{sp}}(t) = p_{i_{sp}} + u_i^I(t) \tag{2}$$

where u_i^I is the modulation factor defined as

$$u_i^I(t) = m_i \times \hat{e}_{i_{pred}}(t). \tag{3}$$

where $\hat{e}_{i_{pred}}$ is the predicted active power output error from a linear error trajectory predictor used in this work. The error in power over prediction horizon T_{pred} is

$$\hat{e}_{i_{pred}}(t_0 + T_{pred}) = e_i(t_0) + r(t_0)T_{pred} \tag{4}$$

where $r(t_0)$ is the average rate of change of error calculated over past measurements based on least squares error and e_i is the measured error in active power output of DER i calculated as

$$e_i(t) = p_{i_{sp}} - p_{i_m} \tag{5}$$

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

2.1.2 *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 optimized dynamic response from all participating DERs at the PCC. The set point of the i^{th} DER is therefore modified as:

$$p''_{i_{sp}}(t) = p_{i_{sp}} + u_i^I(t) + u_i^{II}(t) \tag{6}$$

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

$$u_i^{II}(t) = m_i \sum_{j=1, j\neq i}^{M} \hat{e}_{j_{pred}}(t) \tag{7}$$

where $\hat{e}_{j_{pred}}(t)$ is the predicted output power error of j^{th} DER. Substituting (2) to (5), the DERs' set points become:

$$p''_{i_{sp}}(t) = p'_{i_{sp}}(t) + u_i^{II}(t) \tag{8}$$

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 paper. The main contribution of the paper is the new design and implementation approaches in realizing the coordianted control with the DTs of DERs hosted in the cloud and edge for minimizing the reliance on real-time communication with effective overall control performance.

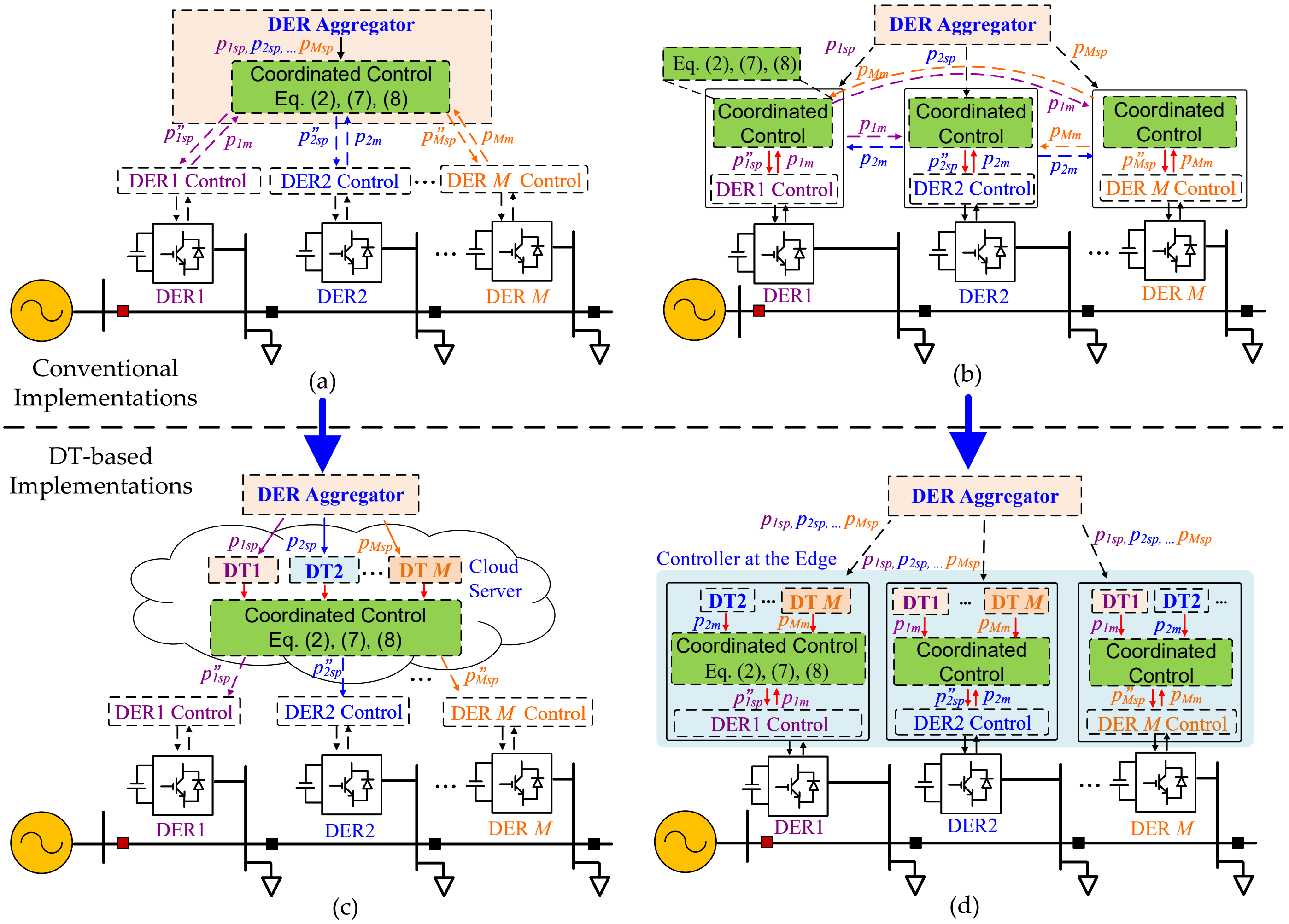

Fig. 1: Conventional and proposed DT-based coordinated control of DERs: (a) conventional implementation: centralized; (b) conventional implementation: distributed; (c) DT-based implementation: centralized; (d) DT-based implementation: distributed.

2.2 Conventional Implementation: Centralized Coordinated Control

The coordinated control presented in Section 2.1 can be realized via a centralized approach with a conventional implementation as illustrated in Fig. 1.(a). In the conventional centralized approach, it is assumed that the coordinated control is implemented within the aggregator. The coordinated controller, as evident from Eq (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 5 that the communication delay could lead to highly unstable response from the DERs.

2.3 Conventional Implementation: Distributed Coordinated Control

An alternative to the centralized implementation of the coordinated control is to implement the controller in a distributed manner. Fig 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. 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 centralized approach presented in Section 2.2). In this approach, individual DERs will still need to receive the power set points ($p_{i_{sp}}$) 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 ($p''_{i_{sp}}$) 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 centralized approach, with the distributed implementation, it will be demonstrated in Section 5 that the communication delay could significantly compromise the overall aggregated response from the DERs.

3 Proposed Digital Twin Based Implementation of Coordinated Control

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

3.1 DT-based Implementation: Centralized Coordinated Control

The proposed design and implementation of coordinated control with the centralized scheme using DTs of the DERs is illustrated in Fig. 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 centralized implementation). However, contrary to the conventional centralized approach that requires bi-directional real-time communication between the central coordinated controller and individual DERs for exchange of measured power output p_{i_m} and modified power set point ($p''_{i_{sp}}$), in this approach, dynamic behaviour of DERs can be estimated by their DTs at the cloud based 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 4.2 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 utilized 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.

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 Fig. 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 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 Fig. 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 decentralized 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.

4 Test Network and Development of DTs for DERs

4.1 Test Network

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 [42], [43] and is illustrated in both Fig. 4 and Fig. 9. 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 battery energy storage 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 centralized 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.

4.2 Development of DTs for the DERs

As discussed in Section 1, the creation of the models for DTs can generally be realized via physics-based and data-driven modelling. For the physics-based approach, good knowledge and understanding of the DER system and its inherent controller is required. In practice, this could be difficult as the information might not be readily available for the DER aggregator or owners of other DERs. Therefore, in this paper, the data-driven approach is utilized to capture the dynamics of the DERs in response to power reference commands, thus generating the model in the format of transfer functions. The detailed process is illustrated in Fig. 2.

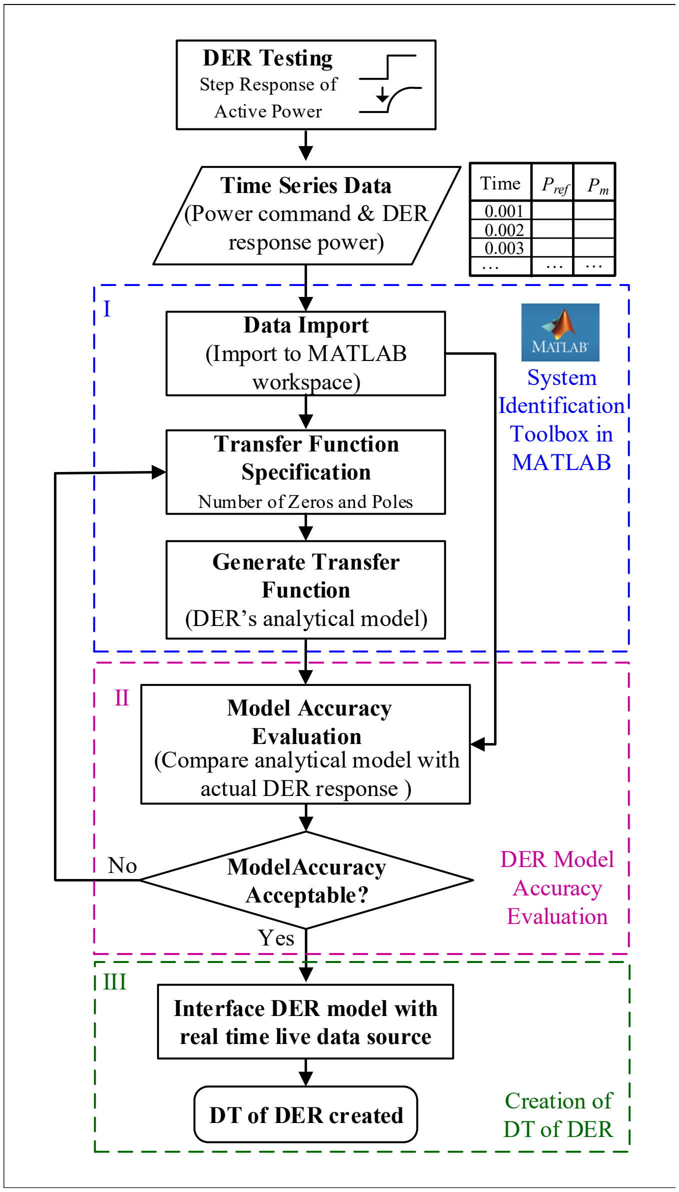

Fig. 2: The process of implementing DTs for the DERs

The process starts with applying a step command to the active power reference signal of the targeted DER. This can be done with the physical DER or a detailed DER model, which could be in a black-box format without the need to share internal details with aggregator and other DER owners. The reference power signal and the response active power will be monitored and recorded in the format of the time series data, which can be subsequently imported to system identification tools. In this work, the system identification toolbox available in MATLAB is used as illustrated in Stage I in Fig. 2. To perform the system identification, the anticipated system characteristics should be specified via defining the number of zeros and poles of the transfer function. The generated transfer function can be simulated with the same input power reference step change signal and the response can be compared with the actual DER's behaviour as shown in Stage II in Fig. 2. The process of stage I and II can be automated via scripts until the model accuracy meets the pre-defined criteria.

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. Fig. 3 presents the responses from the DTs created based on the process illustrated in Fig. 2. In comparison of the actual behaviour of the DERs, Fig. 3 shows that the DTs can accurately reflect the DERs' dynamics with the supplied set point signals.

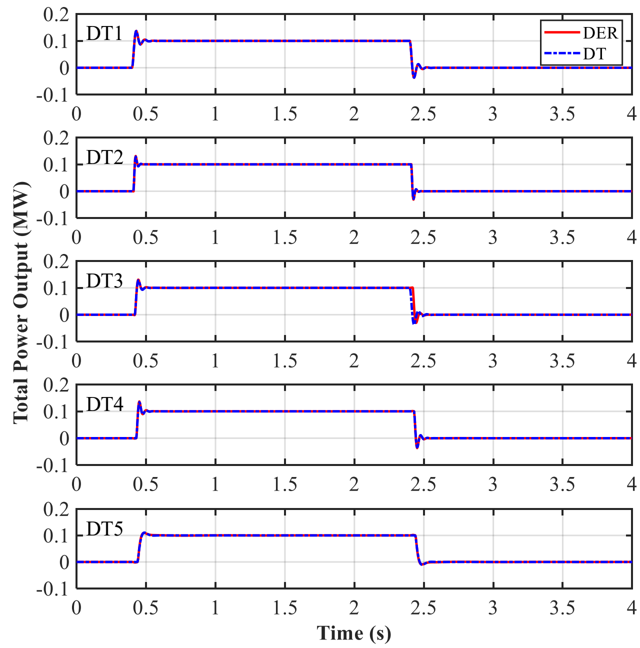

Fig. 3: Comparison of the responses from DTs and DERs

5 Case Study

5.1 Case Study 1: Testing of DT-based implementation: centralized coordinated control

5.1.1 Laboratory Implementation

As illustrated in Fig. 1.(c), in the case of the DT-based implementation for the centralized coordinated control, the DTs of the DERs and the coordinated controller are hosted in the cloud server. Fig. 4 presents a realistic Hardware-in-the-Loop (HIL) setup, which includes a Real-Time Digital Simulator (RTDS) for simulating the network with five DERs as discussed in Section 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 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 optimizing the overall response as discussed in Section 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 aggreator and the DERs on the proposed DT-based centralized 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 realized with low-cost communications based on the work reported in [44].

5.1.2 *Case 1.1: Simultaneous change in set point 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 (received by the DERs at 0.45 s due to the 50 ms communication delay). Therefore, the overall aggregated increase of active power from the five DERs is expected to be 500 kW. Fig. 5 and Fig. 6 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 Fig. 5 that different DERs have 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 6, 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

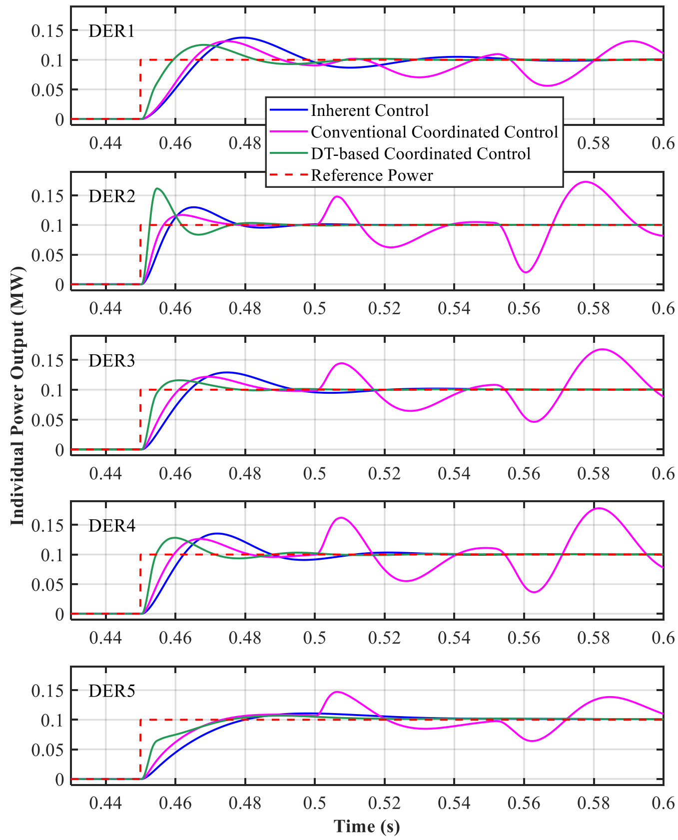

Fig. 5: Individual responses of DERs with simultaneous set point change - same amount of power requested from all DERs

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 the overall system frequency regulation.

In the case of DT-based coordinated control, since the coordinated controller receives data from the corresponding

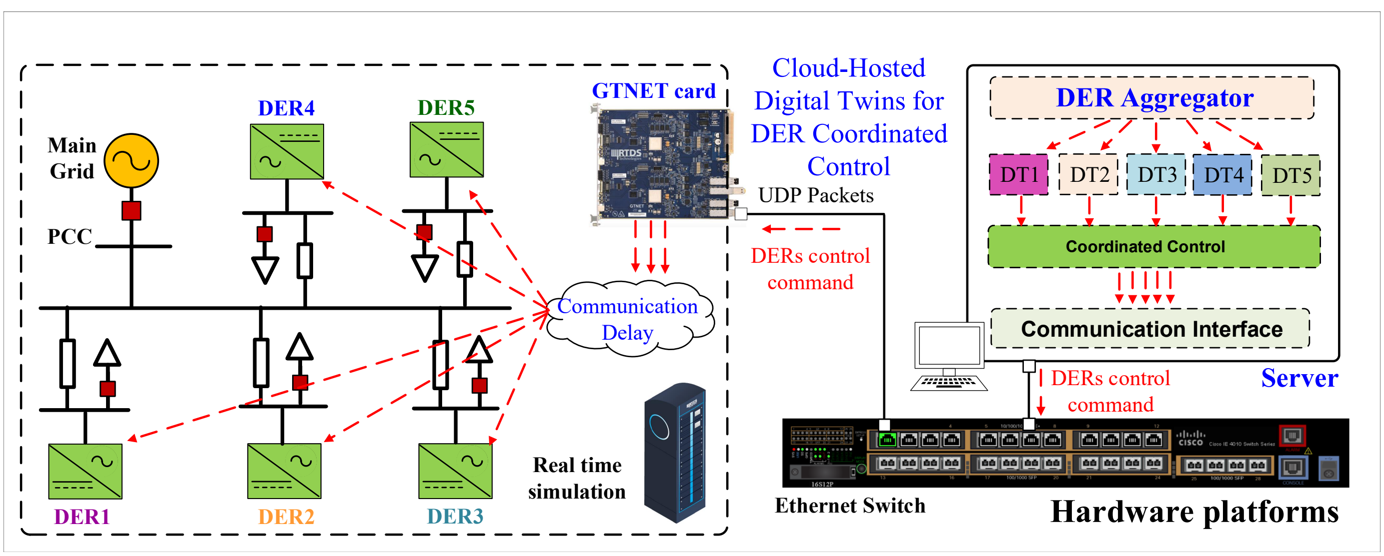

Fig. 4: Test setup for DT-based implementation: centralized coordinated control of DERs

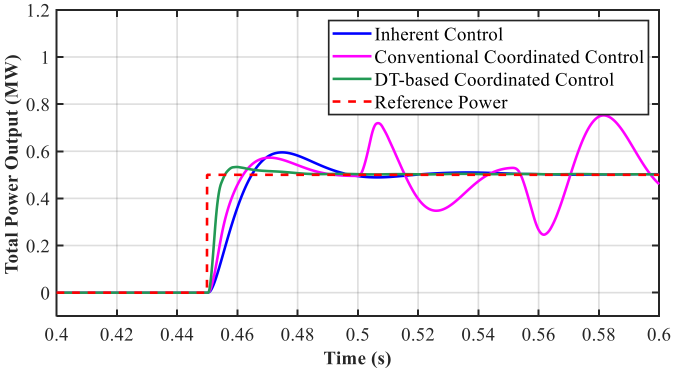

Fig. 6: Aggregated responses of DERs with simultaneous set point change - same amount of power requested from all DERs

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 Fig.6. Examining the individual DER responses as shown Fig.6, 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.

Similar observations as described above with the case presented in Fig 7, 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 Fig. 6, thus not being shown again in Fig. 7.

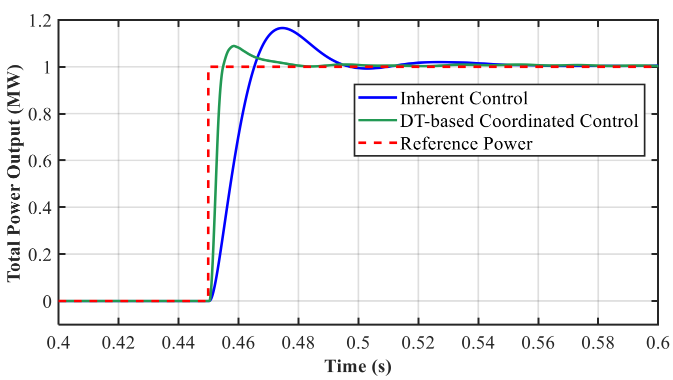

Fig. 7: Aggregated responses of DERs with simultaneous set point change - different amounts of power requested from all DERs

5.1.3 Case 1.2: Staggered change in set points of DERs

Similar to the previous case as explained in Section 5.1.2, the aggregator detects a frequency event and 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 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 Fig. 8.

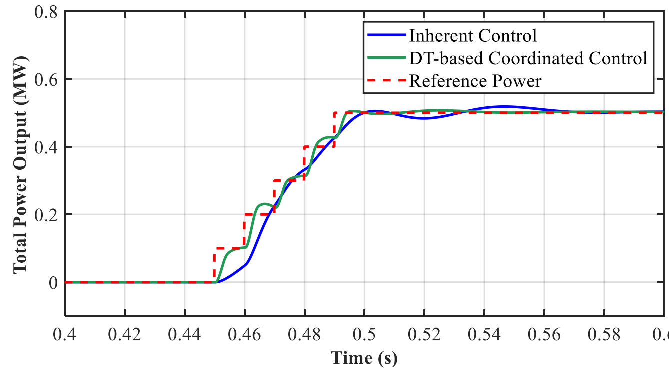

Fig. 8: DERs' Power output with applying staggered power reference inputs

In the inherent control of the DERs, as shown in 8, 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 effetive in tracking the reference power compared with the inherent control of the DERs.

5.2 Case Study 2: Testing of DT-based implementation: distributed coordinated control

5.2.1 Laboratory Implementation

The DT-based distributed coordinated control is illustrated in Fig. 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 9, 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 centralized 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 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 invovlves the use of the set points communicated from the aggregator without the need for communciation with other DERs, the performance of

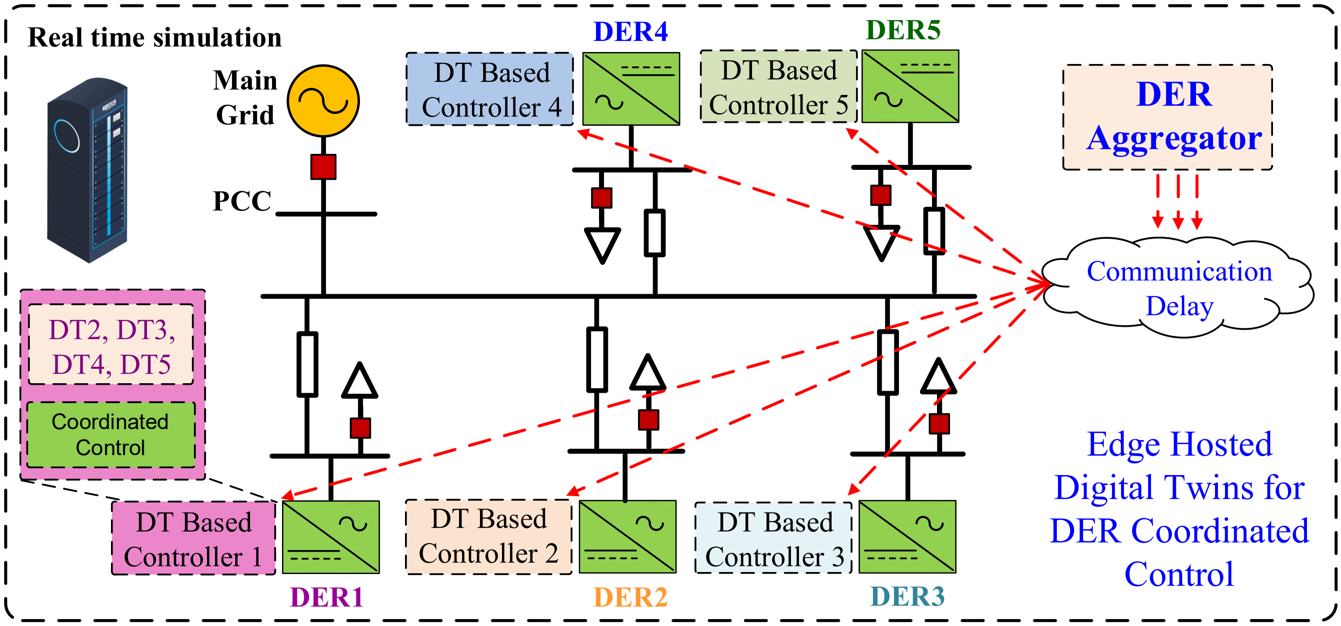

Fig. 9: Test setup for DT-based implementation: distributed coordinated control of DERs

the proposed DT-based coordinated control scheme can largely mitigate the reliance on the communications, which is demonstrated in the following sections.

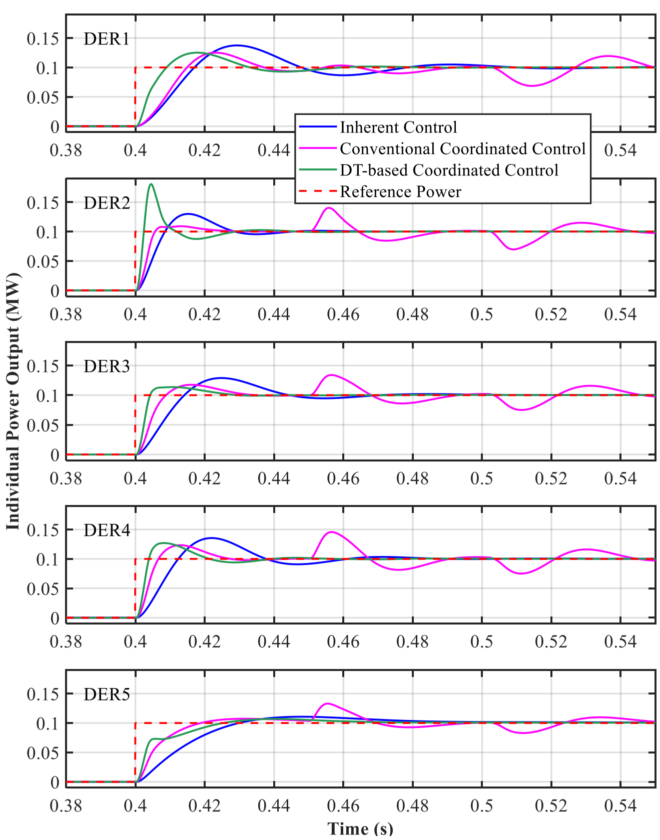

Fig. 10: Individual responses of DERs with simultaneous set point change - different amounts of power requested from all DERs

5.2.2 *Case 2.1: Simultaneous change in set point of DERs*

In this test case, the aggregrator 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 Fig. 10 and Fig. 11 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.

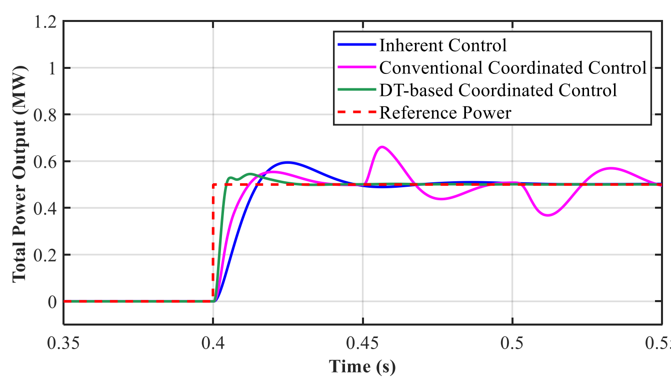

Fig. 11: Aggregated responses of DERs with simultaneous set point change - same amount of power requested from all DERs

As it can be seen form Fig. 10 and 11 that, in the case of inherent 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 Fig. 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.

Fig. 12 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 12. Similar observation as motioned above for Fig. 11 can be made for both DT-based coordinated control and the inherent DER control, where DT-based coordinated control shows significantly improved response.

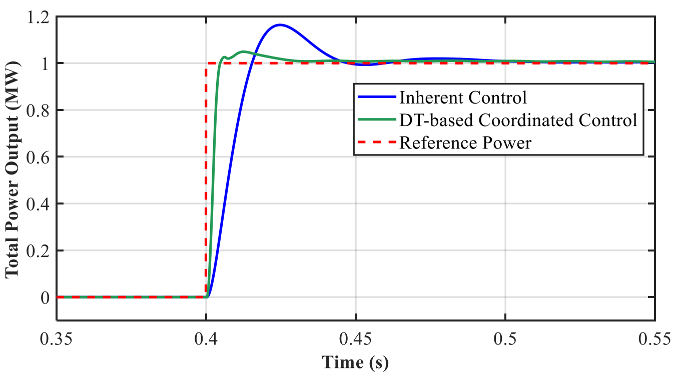

Fig. 12: Aggregated responses of DERs with simultaneous set point change - different amounts of power requested from all DERs

5.2.3 *Case 2.2: Staggered change in set points of DERs*

In this case, the aggregrator sends power set points to all of the five DERs to request a same amount of increase in active

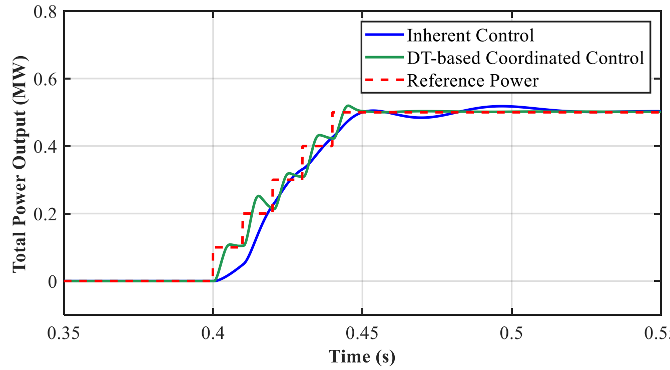

Fig. 13: Power output with coordinate control by applying staggered inputs

power output (i.e. 100 kW) but at different time rather than sending signal simultaneously. The results for this case are shown in Fig. 13. 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.

5.3 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 (centralized) or at the edge (distributed) as demonstrated in Section 5.1 and 5.2 is to support the control of grid frequency, which can deviate from its nominal value during load-generation imbalance events. Based on the current National Electricity Transmission System Security and Quality of Supply Standard [8], the statuary 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.

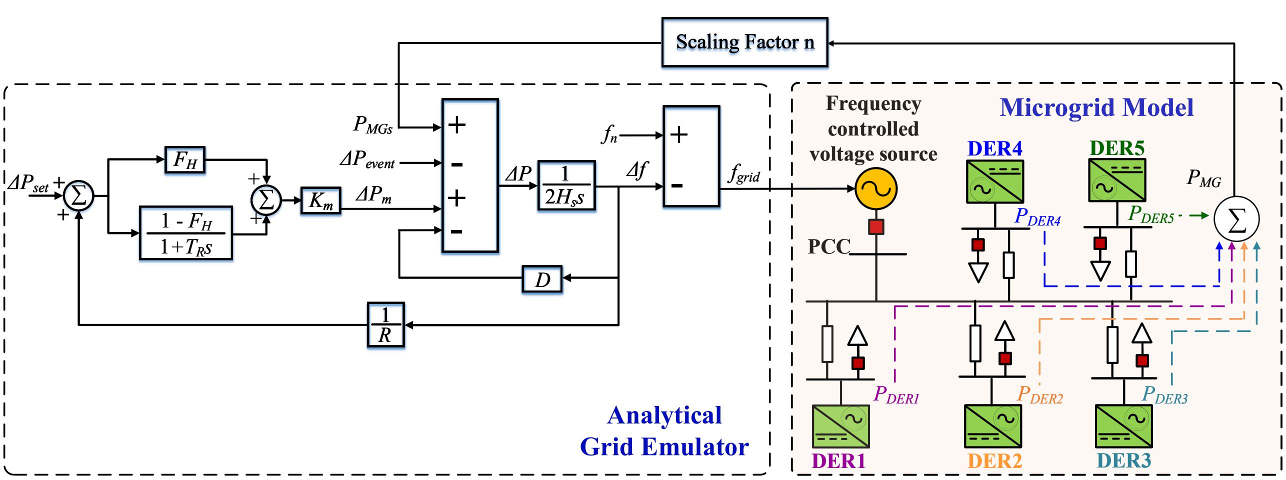

Fig. 14: Test setup for evaluating DT-based coordinated control in supporting grid frequency regulation

TABLE 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}	Normalized grid frequency	Variable

As shown in Fig. 14, 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 [45]. 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 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 n is introduced to control the level of scaling of the frequency response from DERs being controlled. Descriptions of the parameters as presented in Fig. 14 are provided in Table 1.

5.3.1 *Case 3.1: Grid frequency regulation with DT-based centralized 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 Synchronous Generators (SGs) with relatively slow response and one representing converter-based source (e.g. Battery Energy Storage System) 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 Fig. 15 and Fig. 16. 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

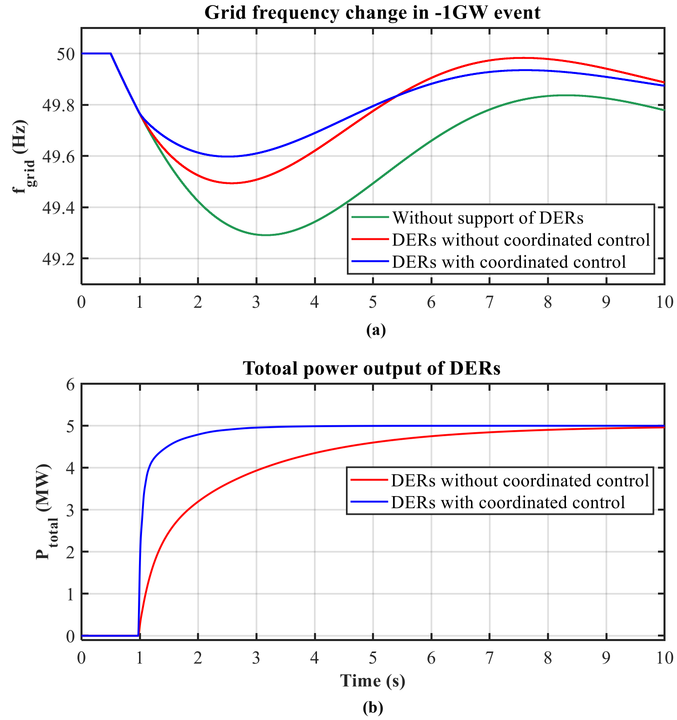

Fig. 15: Performance of frequency regulation comparison with and without DT-based centralized coordinated control (cloud-hosted): (a) frequency profile; (b) total active power provided by DERs

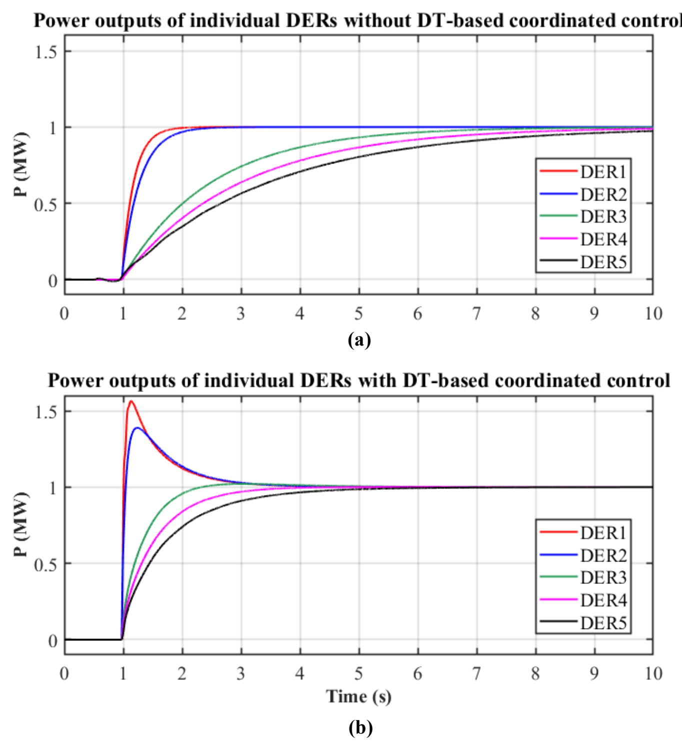

Fig. 16: Active power outputs of individual DERs: (a) with DT-based centralized coordinated control; (b) without coordinated control

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 Fig. 16.

5.3.2 *Case 3.2: 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 Fig. 17 and Fig. 18.

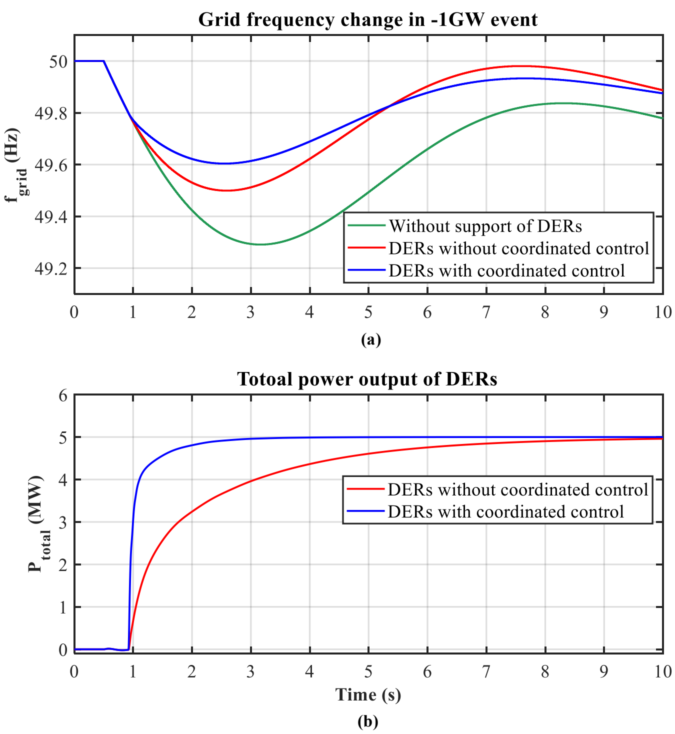

Fig. 17: Performance of frequency regulation comparison with and without DT-based distributed coordinated control: (a) frequency profile; (b) total active power provided by DERs

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

5.4 Case Study 4: Robustness against DT synchronization errors

In the proposed DT-based coordinated control, synchronization between the DERs and their DTs follows two main principles: 1) discrete event-triggered update, i.e., whenever there is a power setpoint change in one DER, the synchronization between the DER and its DT needs to be conducted. This can happen at different time interval depending on

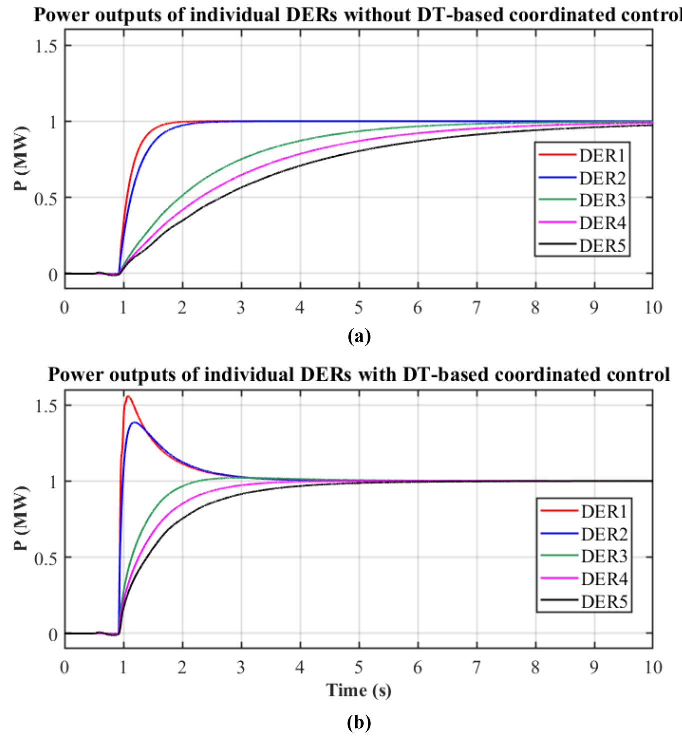

Fig. 18: Active power outputs of individual DERs: (a) with DT-based distributed coordinated control; (b) without coordinated control

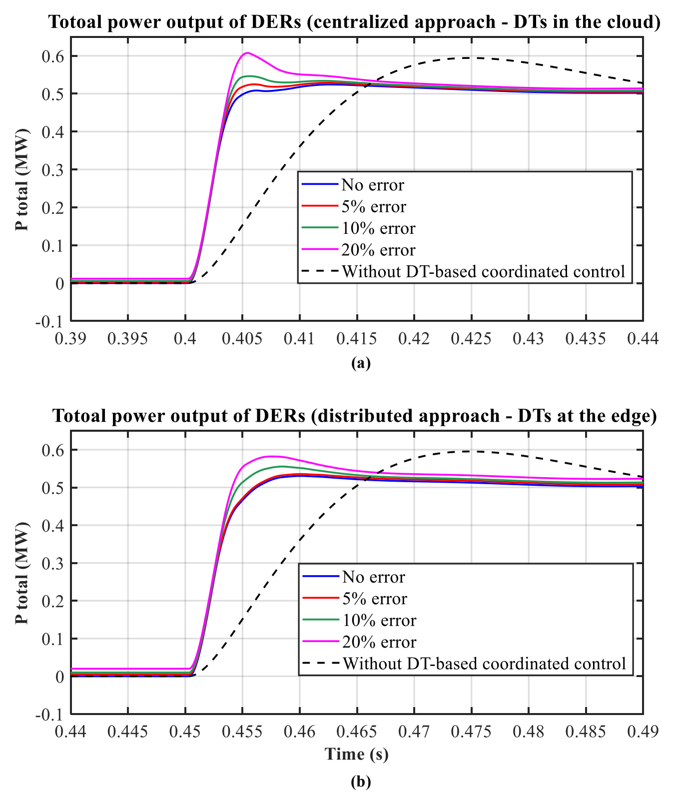

Fig. 19: Perfromance of the DT-based coordinated control with different level of estimation errors: (a) cloud-hosted DTs: centralized approach (b) Edge-hosted DTs: distributed approach

the energy market conditions driven by the system needs, but typically the setpoint of DERs will only change when a settlement period finishes (i.e. every 30 mins); 2) periodic update, i.e., periodic synchronization 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 pratice, the periodic synchronization 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 Fig. 19, 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 synchronization 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 Discussions

The operation of the future power network with increased renewable generation and reduced inertia is an imminent challenge the power industry faces. With the expected proliferation of DERs expected within the network in coming years, it is increasingly important to reduce the reliance on communications to realize robust controls that will improve the resilience of a renewable rich low inertia power system.

Power system controls can be architecturally categorized as: centralized; decentralized (no communications needed); and (iii) distributed / hybrid (might still require communications), which are also discussed within Section 1. In the paper, the radical change in implementation of centralized and distributed control solutions through the use of DTs has been proposed and its effectiveness demonstrated.

- The use of DTs for implementation of a centralized control approach effectively eliminates the need for real-time feedback to be communicated from DERs, thereby reducing the number of real time communication links from $2M$ to M, given there are M DERs being controlled.
- The use of DTs for the implementation of a distributed control eliminates the need for communications between the DERs, effectively transforming a distributed control approach to a decentralized control approach.
- The use of DTs for decentralized control has not been explored as they typically do not involve any communications. However, the use of DTs to further optimize the performance of decentralized control approaches can be explored, but remains out of scope of this paper.

In this paper, the proposed DT-based coordinated control enables effective coordination of DERs to realise improved frequency response with significant reduced reliance on real-time communications, thus providing a promising cost-effective solution for supporting future frequency regulation. It should be noted that although a frequency control approach has been demonstrated, the proposed approach serves as a template for realization of other future centralized or distributed control approach.

For utility companies, this brings significant technical benefits as it will enhance system stability, and also economic benefits through the reduced investment required for communication infrastructure. By enabling more effective control for DERs, it also provides greater potential for DERs in providing ancillary services to the grid, which presents major commercial benefits for DER owners and also DERs aggregators.

7 Conclusions

This paper has presented a novel method for realizing coordinated control of DERs based on cloud and edge-hosted DTs to optimize the overall aggregated dynamic response for effectively support frequency regulation in power grids. The coordinated control of DERs with conventional implementations for both of the centralized and distributed approaches have been presented and discussed. It was found that both of the conventional centralized and distributed approaches present significant reliance on the real-time communications and the latency of the communication can severely comprise the overall coordinated control performance. Through the use of the DTs of DERs, the real-time status of the DERs can be estimated and used for supporting coordinated control actions. In the paper, two DT-based design and implementation approaches for realizing the coordinated control (corresponding to the two conventional implementations) have been presented. It has been demonstrated that the use of DTs of DERs, hosted in the cloud for the centralized coordinated control, and hosted in the DERs edge for the distributed coordinated control, can significantly mitigate the reliance on real-time communications, while still providing satisfactory control performance. Therefore, the proposed DT-based coordinated control approaches represent a promising solution for enabling effective active power response from DERs to support the future power grid operation.

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