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Digital Twin Aided Dynamic Analysis of Distribution Networks with Power Hardware-in-the-Loop Validation

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***Abstract*—The scope of this paper is to develop and evaluate reduced-order equivalent models for distribution networks (DNs), serving as digital representations for the physical assets connected to the network under various operational scenarios. Despite different equivalent models proposed in the literature, the majority has not been integrated and tested in network simulation models that replicate real-world conditions, resulting in inadequate evaluation of their effectiveness in analyzing the DN dynamic behavior. This study bridges this gap by conducting real-time simulations using a Power Hardware-in-the-Loop experimental setup.**

***Index Terms*—Digital twin, dynamic equivalent models, experimental validation, power hardware-in-the-loop, real-time simulation.**

I. Introduction

The accurate representation of the dynamic characteristics of loads and distributed generation (DG) units connected to the distribution network (DN) has been a thoroughly studied research topic. Recently, the secure operation of DNs has been put in peril, due to the increasing penetration of DG units connected to both the primary and secondary DNs. This has also altered the dynamic behavior of DNs and subsequently influenced the overall power system dynamics [1].

DN equivalent models that can effectively mirror the dynamic characteristics of the constituent components allow proper management of their operation, ensure reliable prediction of future operating scenarios, and provide sufficient information for control actions that need to be taken to avoid undesirable situations. The purpose of these models is to replace either the entire or part of the studied system with a simplified equivalent, which exhibits similar dynamic behavior compared to the original system. Distribution system operators can employ such simplified equivalent models of their networks and incorporate them into the transmission network model for the benefit of transmission system operators. In light of the above, there is a need to determine suitable equivalent models for more accurate analysis and simulation of the dynamic behavior of modern DNs [2].

Nowadays, the expanding prevalence of measuring infrastructure promotes the data-driven approach, directly identifying model parameters through measurements and thus addressing the challenges posed by the lack of detailed system knowledge [3]. In addition, the advancement of information and communications technology has led to the emergence of the digital twin (DT) concept as a prominent research topic in various industries, including power systems. By gathering and analyzing data from physical systems, a DT model acts as a digital replica, emulating the real-time state and behavior of the physical entity with high fidelity. This real-time synchronization capability of DT technology is the key distinction from traditional simulation software, facilitating informed decision-making for optimal outcomes [4].

In the literature, the majority of the data-driven equivalent models proposed for the dynamic equivalencing of DNs have not been integrated and tested in complex network simulation models. This limitation hinders the proper evaluation of their effectiveness in analyzing the dynamic behavior of DNs. This study bridges this gap by conducting physical assets based real-time simulations, in contrast to similar studies relying on artificially generated responses or offline simulation results. To achieve this, a Power Hardware-in-the-Loop (PHIL) setup is used, consisting of a high voltage (HV) grid, two medium voltage (MV) and one low voltage (LV) DNs. The HV and MV grids are simulated in a digital real-time simulator (DRTS),

Laboratory measurements were conducted in the frame of ERIGrid 2.0 Transnational Lab Access project “Developing Digitally Twin Distribution Network Equivalent Models” with Grant Agreement No. 870620.

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while an actual laboratory environment constitutes the LV DN. The primary objective of this paper is to develop and evaluate measurement-based equivalent models, serving as digital representations of the physical assets connected to the LV network under distinct operational scenarios; this involves reproducing the LV DN behavior in response to voltage variations, in terms of real and reactive power exchanges at the point of common coupling (PCC).

II. Proposed Approach

A DT is considered as a virtual duplicate capable of replicating the actual behaviors of physical objects or systems, either in real-time or in a pseudo-real-time manner [5], [6]. To implement a DT for DNs the modelling process should be less complex than modelling individual physical behaviors for all assets, while ensuring that resulting models maintain the ability to accurately replicate the behavior of components with satisfactory performance. Additionally, these models should incorporate capabilities for online performance validation and adaptation [7].

Within this context, the primary objective of this paper is to explore the feasibility of a measurement-based equivalent model that satisfies DT requirements, capable of accurately replicating the dynamic behavior of the examined DN under voltage disturbances. To achieve this, the methodology depicted in Fig. 1 is adopted which comprises four discrete steps, analyzed in the next subsections, respectively.

A. Equivalent Model Structure Selection

Generally, there is a wide range of model structures available to represent a DN downstream from its point of interconnection (POI) with the external grid [8]. The selection of DN equivalent model relies on both the composition of

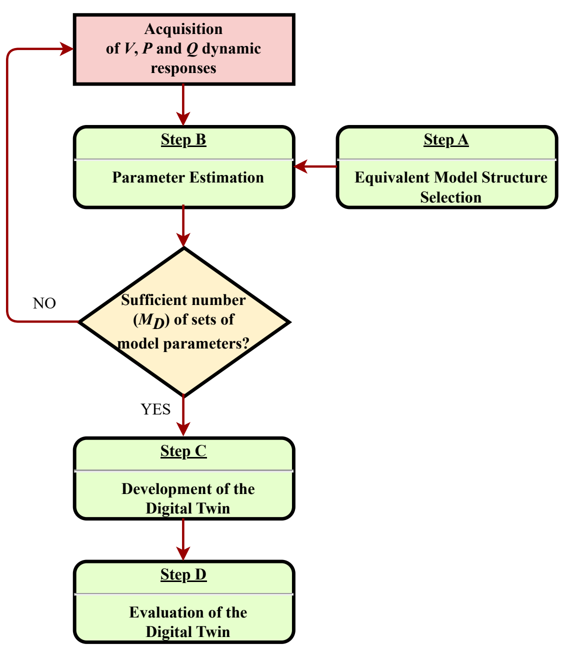

Fig. 1. Flowchart of the adopted methodology.

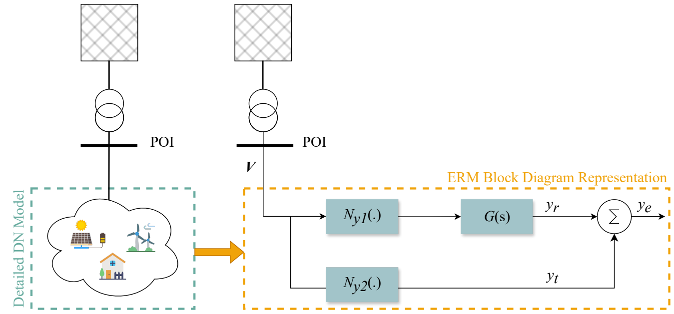

Fig. 2. Actual DN model (left) and its dynamic equivalent (right).

the system under study and the scope and type of power system analysis being conducted [9]. Fig. 2 illustrates the concept of DN dynamic equivalencing, along with the block diagram representation of the exponential recovery model (ERM), which is the model employed in this work. It is worth noting that ERM is chosen due to its computational efficiency and effectiveness in dynamic analysis of DNs across diverse network conditions [10]; its formulation is given by (1)–(4):

$$y_e(V) = y_r(V) + y_t(V) \tag{1}$$

$$N_{y_1}(V) = y_s(V) - y_t(V) \tag{2}$$

$$G(s) = \frac{1}{T_y s + 1} \tag{3}$$

$$\begin{aligned} y_t(V) &= N_{y_2}(V) = y_0 \left(\frac{V}{V_0}\right)^{N_t} \\ y_s(V) &= y_0 \left(\frac{V}{V_0}\right)^{N_s}. \end{aligned} \tag{4}$$

Here, $y_e(V)$ represents the estimated power (real and/or reactive), with V denoting the grid voltage. y_0 and V_0 represent the power demand and voltage magnitude before the disturbance. T_y denotes the recovery time constant, whereas N_s and N_t refer to the steady-state and transient voltage exponents, respectively. To replicate both real (P) and reactive (Q) power, the following parameter sets must be identified: $\boldsymbol{\theta_P}$ = [$N_{s,p}$, $N_{t,p}$, $T_{y,p}$] and $\boldsymbol{\theta_Q}$ = [$N_{s,q}$, $N_{t,q}$, $T_{y,q}$].

B. Parameter Estimation

The measurement set used in the parameter estimation procedure is composed of V, P, and Q dynamic responses at the POI. Vectors $\boldsymbol{\theta_P}$ and $\boldsymbol{\theta_Q}$ include the entire sets of parameters that have to be estimated by the identification procedure for real and reactive power modelling, and are estimated by minimizing the disparity between the model outputs and the actual dynamic responses. This is achieved by employing a least squares approach, involving successive iterations aimed at minimizing the objective function of (5).

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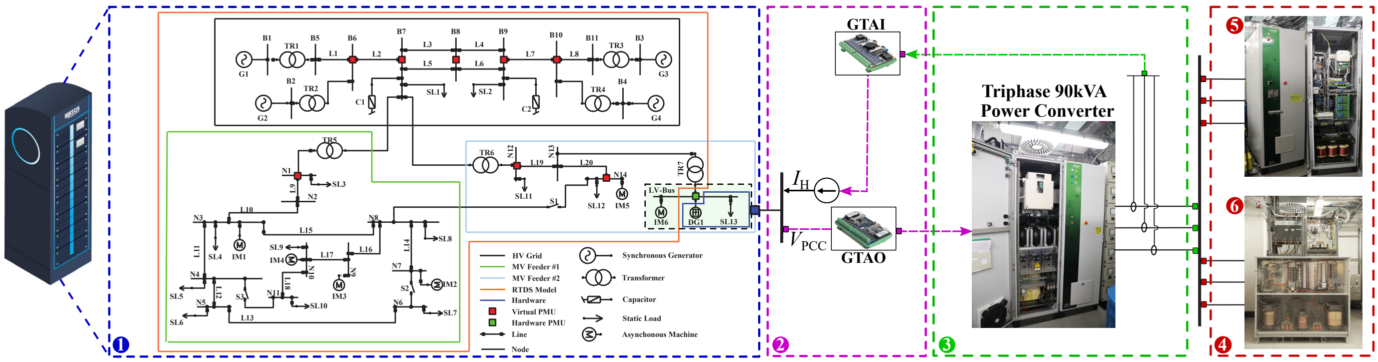

❶Digital Real-time Simulation ❷Power Interface ❸Power Amplifier ❹Hardware under Test ❺Triphase 15kVA Power Converter ❻256-step 40kW Load Bank

Fig. 3. PHIL setup. HV and MV buses are symbolized using capital letters B and N, respectively.

$$J = \sum_{k=1}^{K} \left(y[k] - \hat{y}_e[k]\right)^2 \tag{5}$$

Here, K is the total number of the response samples, while $y[k]$ and $\hat{y}_e[k]$ are the original and estimated real/reactive power response at the k-th sample, respectively.

C. Development of the Digital Twin

Initially, to incorporate the DT into the power system model instead of the actual LV DN, the detailed dynamic model (see Fig. 2) outlined in Section II-A is implemented within the DRTS. Then, to develop the DT, representative real and reactive power model parameters, for the selected measurement-based equivalent model, need to be computed. Note that representative model parameters are applicable for analyzing a wide range of loading, operational conditions, and disturbances. In the literature, several methods have been proposed for the derivation of typical model parameters [2]. In this work, the task of deriving representative model parameters is formulated as a statistical analysis problem. Specifically, since a sufficient number of M_D discrete disturbances under a specific operational scenario is analyzed, robust sets of real/reactive power model parameters are determined as the median values of all corresponding identified parameters. The resulting sets are provided as input into the detailed dynamic model, to develop the DT. In this way, the impact of the digital representation of the actual DN can be examined as if it were connected directly to the real system.

D. Evaluation of the Digital Twin

In the final stage, the efficacy of the developed DT is evaluated by comparing the actual real and reactive power responses with those obtained from the digital replica of the DN, derived using representative parameters. Specifically, the performance of the developed DT is assessed using the coefficient of determination (R^2) metric:

$$R^2 = \left(1 - \frac{\sum_{k=1}^{K} \left(y[k] - \hat{y}_e[k]\right)^2}{\sum_{k=1}^{K} \left(y[k] - \bar{y}\right)^2}\right) \cdot 100\% \tag{6}$$

Here, $\bar{y}$ represents the mean value of the original response. R^2 is employed to evaluate the accuracy of the established model in terms of the overall response; a R^2 value equal to 100% indicates a perfect match.

III. Power Hardware-in-the-Loop Setup

In order to test and validate reduced-order dynamic equivalent models, which act as digital representations for the physical assets interfaced with the test facility, PHIL simulations are performed. In this Section, the developed PHIL setup and the experimental scenarios employed for validation are detailed.

A. System under Study and Experimental Setup

To assess the applicability of the proposed approach, the power system depicted in cell 1 of Fig. 3 is implemented in a DRTS, comprising a HV transmission grid, two MV DNs, and a part of a LV DN. The HV transmission grid is based on the Kundur two-area power system [11], while the MV DNs are based on the benchmark European MV DN proposed by the CIGRE Task Force C6.04 [12]. To interconnect the original Kundur system (230 kV, 60 Hz) with the CIGRE benchmark MV system (20 kV, 50 Hz), control system reference values were modified for 50 Hz conditions. Details concerning the modelling of transformers, capacitors, lines, synchronous generators, and their associated control devices, as well as the adjustments applied to the MV benchmark model, along with comprehensive descriptions of all HV and MV network loads, are provided in [13]. Moreover, the LV DN is formed by an asynchronous machine (IM6) operating as a motor in conjunction with an inverter-interfaced DG unit and static load. The establishment of the latter is facilitated through the infrastructure offered by the Dynamic Power Systems Laboratory (DPSL) at the University of Strathclyde, utilizing the PHIL approach to incorporate them into the simulated network.

As shown in cells 3&4 of Fig. 3, the PHIL setup comprises a Triphase 90kVA (TP90kVA) power converter serving as a grid simulator to bridge the real-time simulated network hosted at RTDS and the hardware under test (HuT), which is encompassed by a 40 kW static load bank (SLB) and a 15 kVA inverter-interfaced DG unit (DG1) operating in either P-Q or

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P-V control mode. The PHIL setup is configured by using the ideal transformer model interface [14] aided by the interface compensation method presented in [15]. The PCC voltage (V_{PCC}) between the MV and LV networks is transmitted to the TP90kVA converter via the Giga-Transceiver Analogue Output (GTAO) card as its command signal, to be replicated and applied to the HuT. Moreover, the HuT current response (I_{H}) is injected into the LV bus through the Giga-Transceiver Analogue Input (GTAI) card and controlled current source, thereby closing the PHIL setup.

B. Experimental Test Cases

Using the hardware infrastructure of the LV power network within the DPSL, different DN configurations were established, considering distinct load compositions, DG penetration levels, and types of DG controls. The examined test cases (TCs) are summarized in Table I.

Dynamic responses resulting from on-load-tap-change (OLTC) actions are favored for parameter estimation in measurement-based equivalent models [13], [16]. Thus, for each one of the examined cases for the LV DN, $M_D = 10$ voltage disturbances are induced, comprising 5 step-up and 5 step-down variations by adjusting the tap position of TR7 (refer to Fig. 3), and ranging between ± 0.2 p.u. Then, to determine model parameters for the ERM, we record the voltage, real power, and reactive power responses at the secondary side of TR7 per disturbance, using a sampling rate of 100 samples per second.

As described in Section II-C, the median values of the model parameters, derived from the dynamic responses of each TC, are employed within the detailed dynamic model to develop the DT of the LV DN. It is important to note that in order to test and validate the performance of the DT for each TC, the exact same disturbances were applied. However, in these cases, the LV grid is not connected to the PHIL setup. Conversely, it is replaced with the corresponding DT, i.e., detailed ERM using representative parameters. The new resulting dynamic responses of voltage, real, and reactive power are then recorded at the secondary side of TR7. These responses, practically defined by the developed DT, are used to assess its performance against the actual responses of the LV DN, as discussed in Section II-D.

TABLE I
EXPERIMENTAL TEST CONFIGURATIONS*. REAL (P) AND REACTIVE (Q) POWER IN KW AND KVAR, RESPECTIVELY.

TC	SLB		IM6		DG1	
	P	Q	P	Q	P	Q
TC1.1	15	7.2648	—	—	5	2.4216
TC1.2	10	4.8432	—	—	5	2.4216
TC1.3	7.5	3.6324	7.5	3.6324	5	2.4216
TC1.4	5	2.4216	5	2.4216	5	2.4216
TC1.5	2.5	1.2108	2.5	1.2108	5	2.4216
TC1.6	1.875	0.9081	1.875	0.9081	5	2.4216
TC1.7	1.25	0.6054	1.25	0.6054	5	2.4216
TC2.1	7.5	3.6324	7.5	3.6324	5	2.4216
TC2.2	5	2.4216	5	2.4216	5	2.4216
TC2.3	2.5	1.2108	2.5	1.2108	5	2.4216
TC2.4	1.875	0.9081	1.875	0.9081	5	2.4216
TC2.5	1.25	0.6054	1.25	0.6054	5	2.4216

* In TC1.1-TC1.7, DG1 operates in P-Q while in TC2.1-TC2.5 in P-V control mode.

IV. Experimental Results

This Section is dedicated to validating the DT modelling approach introduced in Section II. Initially, we assess the results of parameter identification using the ERM for the M_D disturbances per TC. Then, we detail the procedure for deriving representative model parameters for each TC, which are utilized in developing the digital replica of the laboratory LV DN. Finally, we evaluate the performance of the developed DTs in terms of replicating the actual behavior of the LV DN.

A. Identification of Representative Parameters per Test Case

In Fig. 4, the parameter estimation results (real and reactive power) for each of the examined TCs outlined in Table I are evaluated by means of box plots. Specifically, Fig. 4 depicts the R^2 values computed offline by comparing the corresponding M_D dynamic responses of the actual DN for each TC with those obtained from the ERM. As evident, the median R^2 is higher than 90% for all TCs, indicating that the ERM is able to represent LV DN dynamics with a significant level of

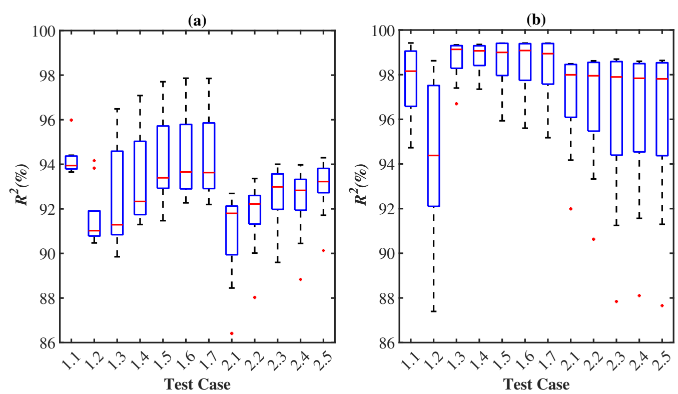

Fig. 4. Real and reactive power modelling. R^2 results across all 12 TCs.

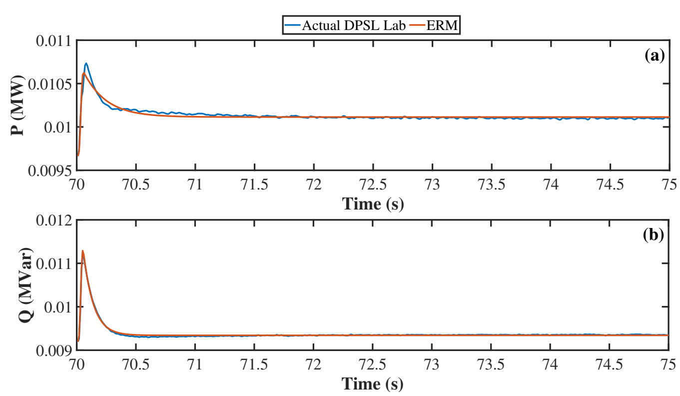

Fig. 5. TC1.4: Illustrative modelling of (a) real and (b) reactive power responses to step-up voltage disturbance.

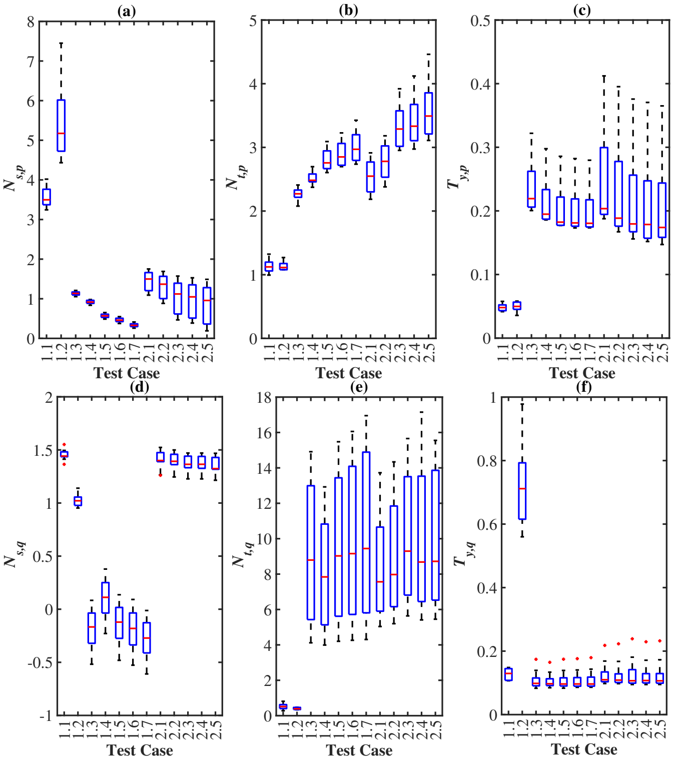

Fig. 6. Estimated model parameters across all 12 TCs. (a)-(c): Real power. (d)-(f): Reactive power.

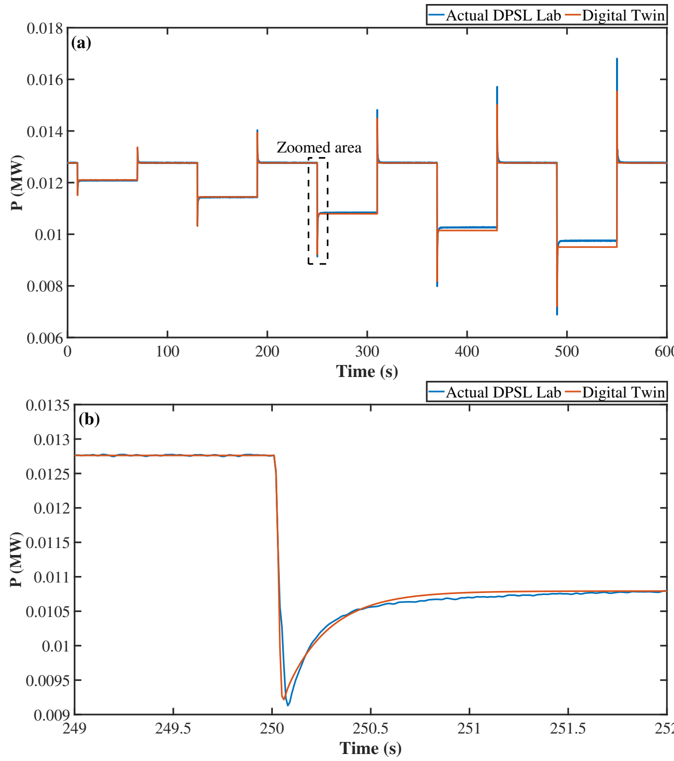

Fig. 7. TC1.3. (a) Comparison between the results obtained using the DT and the actual DPSL real power responses. (b) Close-up of 5^{th} disturbance.

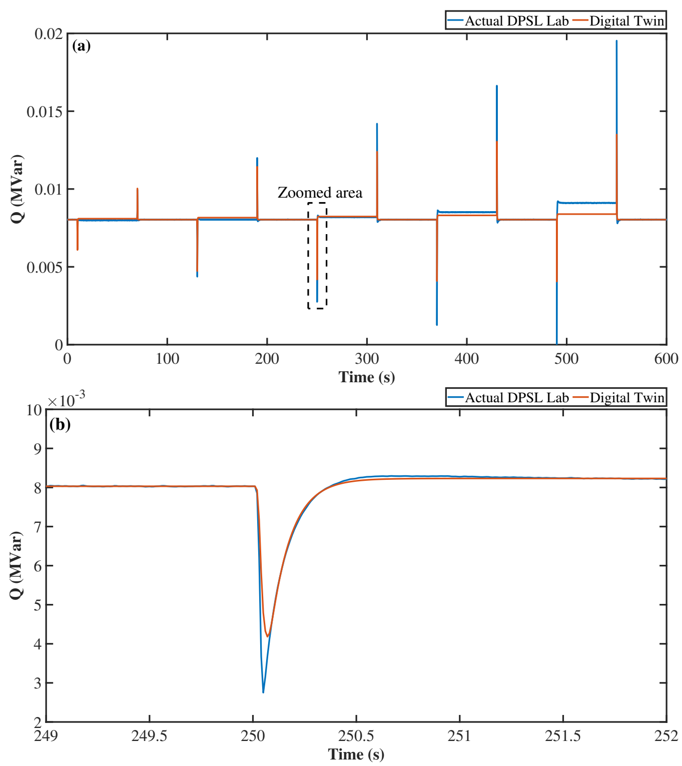

Fig. 8. TC1.3. (a) Comparison between the results obtained using the DT and the actual DPSL reactive power responses. (b) Close-up of 5^{th} disturbance.

accuracy. Illustrative examples of laboratory real and reactive power responses corresponding to TC1.4 are juxtaposed with the estimated responses derived from the ERM in Fig. 5. In both instances, it is evident that the ERM accurately captures the power overshoot, recovery phase and new steady-state. Notably, the calculated R^2 values for real and reactive power are 91.29% and 99.19%, respectively.

As discussed in Section II-C, to develop a DT, appropriate real and reactive power model parameters need to be determined. The box plots of Fig. 6 illustrate the identified real and reactive power model parameters across all 12 TCs. Note that within each box plot, the central mark (in red) indicates the median parameter value, which is employed to develop the digital replica of the DN. Results reveal that model parameters vary considerably among the examined TCs. This indicates the need to update the DT real and reactive power representative model parameters under different operational conditions.

B. Assessment of the Developed Digital Twin

Figs. 7 and 8 showcase illustrative DT modelling outcomes for real and reactive power, respectively. In particular, they provide comparisons between the actual real and reactive power responses obtained from the actual LV DN hardware configuration for TC1.3 and the corresponding responses reproduced from its digital replica. As evident from the graphs, the responses of the DT exhibit a good overall agreement with the laboratory responses, indicating its capability to represent the DN dynamics with high fidelity, even in cases with more substantial voltage disturbances.

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TABLE II
MEDIAN R^2 (%) BETWEEN THE RESULTS OBTAINED USING THE DT AND THE ACTUAL DPSL RESPONSES.

TC	Real Power	Reactive Power
TC1.1	88.8533	89.5283
TC1.2	87.8533	88.9976
TC1.3	84.5174	87.7181
TC1.4	85.5559	88.8389
TC1.5	87.5825	88.1895
TC1.6	88.2883	88.2042
TC1.7	88.0285	89.5898
TC2.1	78.8222	86.4249
TC2.2	77.9058	84.3343
TC2.3	81.4903	86.6682
TC2.4	80.0609	87.5162
TC2.5	70.3740	83.0830

To quantify the efficacy of the developed DTs in mirroring LV DN dynamics, Table II summarizes the median R^2 values for both real and reactive power across all voltage disturbances within each TC. The calculated R^2 values can be considered sufficiently high, indicating that the DT models are able to reproduce the LV DN active and reactive power responses with good accuracy. It is worth noting that lower R^2 values are generally obtained in TCs where DG1 operates under $P-V$ control mode, and in cases with reduced static load participation; this is more pronounced for the real power responses.

It is important to acknowledge that a mathematical representation, such as the one employed (see Eqs. (1)–(4)), inherently involves simplifications, which may result in differences between the DT's response and real-world phenomena [1]. Also, it is worth noting that employing a representative set of model parameters derived from a larger number of voltage disturbances (M_D) could enhance the precision of the developed DT. Furthermore, to achieve a more accurate simulation and analysis of the intricate dynamics observed in complex cases, where real and reactive power responses exhibit a more oscillatory behavior, a higher-order model should be exploited. The relatively poor performance of the DT in mirroring real power dynamics in TC2.5 is a potential example of this phenomenon.

V. CONCLUSIONS

In this work, reduced-order dynamic equivalent models, serving as digital representations for the physical assets connected within the LV DN under study (actual laboratory environment), are developed and tested across 12 different operational scenarios. To conduct the experiments, a hybrid setup was implemented, leveraging the synergy between the real-time simulation platform offered by a DRTS unit and the physical hardware assets accessible at the DPSL, all operating together within a PHIL configuration.

The evaluation of the examined equivalents is performed by applying a two-phase procedure. During the first phase, the measurement-based approach is used to compute representative model parameters for different operational conditions. During the second phase, the derived sets of model parameters are provided as input into the detailed dynamic model implemented within the DRTS, replacing the actual system for each scenario, to develop the corresponding DT of the LV DN. The accuracy of the developed DTs is quantified by means of the R^2 metric.

The results demonstrate that the developed digital replicas are able to reproduce the dynamic real and reactive power responses of the LV DN to voltage disturbances with commendable accuracy. Notably, the implemented DT can be adapted without difficulties to different configurations by varying the adopted model's parameter values.

Further analysis and comparisons of different equivalent model structures, as well as investigating the efficiency of DTs in accurately reflecting the DN dynamics under large disturbances in the transmission network will certainly contribute to a better understanding of DT aided dynamic analysis of DNs.

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