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Transmission and Distribution (T&D) Quasi-Static Co-Simulation: Analysis and Comparison of T&D Coupling Strength

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ABSTRACT The critical need to model and analyze transmission and distribution (T&D) systems together, given the increasing levels of distributed energy resource (DER) penetrations, has led to the development of several T&D co-simulation platforms, both commercial and open-source. The strength of coupling between the T&D system dictates the accuracy of the co-simulation studies; however, higher accuracy comes at the cost of the increased computational burden. The objective of this paper is to (1) systematically model the different coupling protocols, viz. decoupled (DC), loosely coupled (LC), and tightly coupled (TC), for quasi-static T&D co-simulation studies; and (2) thoroughly compare the three T&D coupling protocols for their accuracy and computational efficiency. The T&D coupling protocols are evaluated for varying system parameters such as DER variability, load unbalances, DER penetration, and size of T&D network. It is observed that the accuracy of both DC and LC models deteriorate with increasing the: (1) system unbalance, (2) DER penetration and variability, and (3) number of T&D coupling points. The results further highlight the need for a tightly coupled (TC) protocol as the T&D system gets more stressed due to the influx of DERs.

INDEX TERMS Co-simulation, integrated transmission-distribution analysis, co-simulation coupling strength, tightly-coupled model, distributed energy resources.

I. INTRODUCTION

The electric power delivery systems are facing abrupt changes to its operations with increasing interests in the decarbonization of the power generation industry [1]. This has led to an influx of high-levels of distributed energy resources (DERs) penetrations where the intermittent nature of wind power and solar photovoltaic (PVs) generations are increasing the stress on the integrated transmission and distribution (T&D) systems [2]–[7]. For instance, high-levels of distribution-level PV integration is known to cause overvoltage problems, voltage unbalances, reverse power flow conditions, and other power quality issues. This necessitates the utility companies and distribution system (DS) operators to perform DER interconnection studies before permitting a new DER/PV connection request. With growing penetrations of DERs, such DER impact assessment requires a comprehensive analysis not only to assess the impacts at the transmission and distribution levels but also to evaluate the interactions between T&D systems during high levels of DER penetrations [5], [8].

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A. INTEGRATED T&D PLATFORMS

Owing to the need for capturing T&D interactions, lately, increasing efforts have been put forward to develop simulation tools capable of combined T&D modeling and analysis. The existing frameworks can be broadly categorized as (1) standalone T&D system models [9]–[11], and (2) T&D co-simulation platforms [12]–[20].

A standalone T&D system model is where both transmission and distribution systems are together simulated in one platform. This standalone T&D model leads to an accurate integrated T&D simulation study, however, there exist computational challenges for large-scale integrated T&D system models. There are two significant concerns with regard to the standalone T&D models: (1) The cost of simulation is substantial since the detailed model of a typical distribution feeder includes 1000s of buses, and a transmission/subtransmission bus may be supplying 1000s of such distribution feeders. Due to the associated scalability issues, at present, there are very few commercial software tools that can simulate a detailed T&D system model on a single platform. (2) The standalone T&D system models do not take advantage of the existing legacy software tools that individually solve the transmission system (TS) or the distribution system (DS) models. Due to the structural and operational differences in TS and DS, a standalone model may pose convergence issues when solving a large integrated T&D system model.

Recently, this led to the development of multiple co-simulation platforms that separately model transmission and distribution systems in their respective software platforms and capture the T&D interactions by exchanging solutions at the T&D coupling or interconnection points. A T&D co-simulation platform interfaces the simulators of multiple interacting domains by enabling communication, data exchange, and time synchronization. Following are a few popular open source T&D co-simulation tools: Framework for Network Co-Simulation (FNCS) [13], Integrated Grid Modeling System (IGMS) [14], and Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) [15]. Given that a T&D co-simulation tool is an appropriate environment to perform DER impact assessments, this paper discusses various coupling methods used in the co-simulation platforms and their need in DER evaluation studies. Current literature has two models for T&D coupling within a co-simulation framework. The first model employs a non-iterative coupling protocol termed as the loosely coupled (LC) model [13]–[16]. The second model is an iteratively coupled method or tightly coupled (TC) model that provides an accurate analysis of the integrated T&D system models [16]–[18], [21], [22].

B. NEED FOR ANALYSIS OF T&D COUPLING METHODS

Despite diverse literature available on T&D co-simulation tools, there remain several modeling limitations that need addressing. First, assuming a balanced loading condition, the TS is largely modeled in the positive-sequence domain that is not suitable to evaluate the impacts of distribution-connected unbalanced loads and single-phase DERs on transmission systems (TS) [13]–[16]. The integration of largely single-phase roof-top PVs at the distribution-level necessitates the analysis of unbalanced loading conditions on the interconnected TS, thus, calling for a detailed three-phase TS modeling and power flow analysis [22]. Second, many of the co-simulation tools do not include a mathematical model for T&D interactions and they mostly couple T&D systems using a non-iterative/loosely coupled (LC) protocol where the boundary values at T&D coupling points are sequentially exchanged without allowing for convergence at each time-step [12]–[15]. The LC co-simulation methods are accurate only when the changes in the DS loading characteristics, both the load unbalances and demand variability, are slower than the simulation time-step at which the two systems are solved, and the solutions are exchanged; otherwise, they introduce simulation errors [22].

The aforementioned challenges have been addressed in a few recent articles that proposed an iteratively/tightly coupled (TC) protocol for T&D co-simulation study. For example, in [17] and [18], an unbalanced three-phase integrated T&D system model is developed where boundary variables were exchanged iteratively between TS and DS. However, in [18]–[20], the necessity of tightly coupled T&D co-simulation has been reported only for dynamic studies and the error analysis for the non-iterative approach in quasi-static power system model is missing. Furthermore, models in [17] and [18], do not test the approach for a large-scale integrated T&D system. In order to accurately model the T&D interactions, an iteratively coupled T&D co-simulation framework was developed in our previous work [21]–[23]. Here, the TS is solved using a three-sequence power flow model to accurately capture the impacts of load unbalance. The co-simulation framework in [21] and [22] was implemented using a parallel method for computation and variable exchange. The existing literature, including our prior work, does not provide a comparison of existing coupling models (loosely coupled, decoupled, and tightly coupled) for increasing levels of load unbalance and DERs. Furthermore, the benefit of simulating the transmission system in three-sequence representation instead of a per-phase balanced system is not evaluated in the existing body of related work. This calls for a comprehensive evaluation and validation of different coupling methods for T&D co-simulation, especially for the systems with high-levels of DER penetrations. This paper addresses the aforementioned gaps in the literature, where, using multiple simulation case studies we present a comprehensive comparison of the DC, LC, and TC protocols for the integrated T&D analysis and evaluate their performances in accurately representing the impacts of distributed PVs.

We believe, as the DER penetrations continue to grow, leading to growing challenges to the interconnected T&D grid, the outcome of this work is extremely valuable to the power systems community. Especially, the results and discussions will inform system planners on when it might be imminent to use a more accurate T&D coupling approach to perform the co-simulation study prior to permitting a new DER/PV connection request.

C. CONTRIBUTIONS

The objective of this paper is two-fold. First, we systematically model and describe the different coupling mechanisms, aka. DC, LC, and TC models, for T&D systems in co-simulation studies. Second, we thoroughly compare the TC (iteratively coupled) T&D co-simulation approach with the existing and more popular methods such as LC (non-iteratively coupled) T&D co-simulation models and the decoupled (DC) approach especially, with regard to their accuracy and computational efficiency. The specific contributions of this work are detailed below.

- *Comparison of T&D coupling methods:* Different methods of T&D coupling, namely DC, LC, and TC, are compared for their accuracy in modeling the integrated T&D system for quasi-static simulation studies for different DER integration scenarios. We also elaborate the algorithmic differences in coupling protocols.
- *Tightly-coupled T&D protocol with Serial Method (SM) for Solution Exchange:* We introduce a tightly-coupled (TC) protocol that uses serial method (SM) for solution exchange between T&D systems. This approach is shown to be computationally efficient compared to the parallel method (PM) of exchanging T&D system solutions that was used in our previous work.
- *Accurate simulation during stressed system conditions and the significance of Three-sequence TS Analysis:* The three coupling models (DC, LC, and TC) are evaluated for their accuracy with different levels of PV variability, PV penetrations, load unbalances, and the number of T&D coupling points. Further, the co-simulation results with three-sequence TS model are compared against a balanced per-phase TS model. It is validated that the three-sequence TS analysis with a TC protocol accurately represents system unbalances and is more suited for co-simulation studies with high-levels of DER penetrations. The test cases highlight the need for more accurate simulation models moving forward to analyse the grid inundated with higher unbalance and variability.
- *Trade-off between co-simulation accuracy and time-cost:* The coupling methods are also compared for their time-cost. A comparison of co-simulation accuracy and time cost highlights the trade-off in selecting the co-simulation approach and provides a guidance on selecting co-simulation protocol based on system conditions.

The rest of the paper is organized as follows. Section II presents the TS and DS modeling and details DC, LC, and TC models for T&D co-simulation study. Section III describes the mathematical model for the series and parallel implementations of the TC protocol and derives update rules for fixed-point iteration (FPI) method to solve the coupled T&D systems. Section IV details the results using multiple test cases followed by discussions on results in Section V. Concluding remarks are drawn in Section VI.

II. INTEGRATED TRANSMISSION AND DISTRIBUTION (T&D) SYSTEM ANALYSIS

This section details the components of the T&D co-simulation framework namely TS, DS, and the co-simulation interface for different coupling methods. In a co-simulation study, TS and DS are modeled and solved in their respective simulation platforms. The boundary variables are exchanged via a co-simulation interface that couples the T&D models (see Fig. 1). Note that the increasing levels of DER penetrations necessitate an integrated T&D analysis. First, a high-level of DER penetration may lead to reverse power flow from DS to TS that may adversely affect the

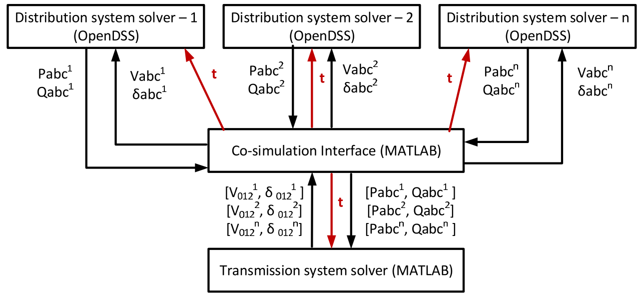

FIGURE 1. T&D Co-simulation framework.

transmission system operations resulting in frequency regulation problems due to power unbalance. In addition, the rapidly varying PV generation profiles and the increasing levels of system unbalance in the DS due to single-phase small-scale DERs may lead to high-levels of voltage unbalance and other power quality issues not only in DS but also in TS. This calls for the integrated T&D system analysis with due consideration to unbalanced system conditions.

A. TRANSMISSION SYSTEMS MODEL

In literature, the TS analysis is usually performed using a balanced single-phase AC power flow study. However, with increasing DER penetrations and with increasing system unbalance at the Point of Common Coupling (PCC), a single-phase TS modeling and analysis is no longer adequate [16]. A detailed three-phase modeling and power flow analysis for TS can help accurately capture the impacts of DERs. The T&D co-simulation framework used in this work adopts a three-sequence TS model and power-flow solver to appropriately represent the effects of load unbalances. The three-sequence transmission system power flow is modeled using [24].

B. DISTRIBUTION SYSTEMS MODEL

The distribution system (DS) is modeled and analyzed in full three-phase representation to accurately capture the unbalanced system conditions. The three-phase modeling and analysis of DS is conducted using the OpenDSS platform, an open-source distribution system simulator [25]. The distributed PV systems are connected at the load buses in the DS and modeled as a negative load in the OpenDSS platform. These PVs do not have a grid following capability and act similar to a load bus (PQ bus) having a negative power demand. Following the related literature on PV hosting analysis for the distribution feeders, a similar stochastic analysis framework is adopted to generate numerous PV deployment scenarios by varying PV size and locations [26]. Multiple scenarios are simulated to fully capture the randomness associated with the PV sizes and deployment locations for increasing customer penetration levels. Readers should refer to [26] for further details on PV deployment scenarios. Additional information on simulation cases for PV variability analysis in time-series simulations is detailed in Section IV.

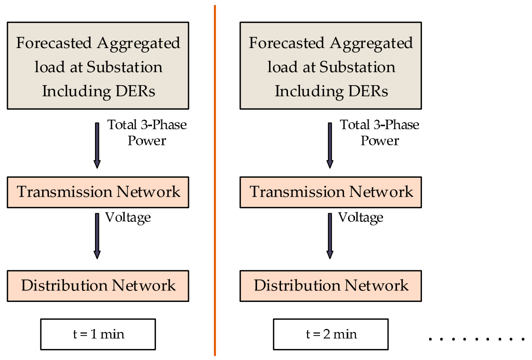

FIGURE 2. DC method for quasi-static time-series analysis.

C. METHODS FOR COUPLING IN T&D CO-SIMULATION PLATFORM

One of the key objectives of this study is to evaluate the impacts of T&D coupling strength in co-simulation models for DER interconnection studies. In this paper, we evaluate three models for T&D coupling. The first model includes zero degrees of T&D coupling, i.e., a decoupled (DC) T&D model. The second model employs a non-iterative coupling protocol termed as the loosely coupled (LC) model. Finally, we describe an iteratively-coupled method or tightly coupled (TC) model that provides the highest coupling strength for the T&D co-simulation analysis.

1) DECOUPLED (DC) T&D MODEL

In this model, for DS analysis, TS is modeled as a stiff voltage source behind a thevenin-equivalent impedance connected to the substation. Similarly, DS is modeled as a lumped load in the TS analysis. The equations describing DC T&D model at time instant t are detailed below.

$$V_T(t) = f_T(S_D^*(t), m_T(t), G_T(t)) \quad (1)$$
$$S_D(t) = f_D(V_T^*(t), m_D(t), PV_D(t)) \quad (2)$$

where, in (1) and (2), V_T and S_D represent transmission bus voltages (obtained using TS solver) and substation power flow (obtained using DS solver) at the point of common coupling (PCC), respectively; f_T, f_D, G_T and PV_D represent TS and DS simulator, generation of scheduled generators in TS, and known PV generation in DS, respectively; TS and DS network models with loads and line parameters are represented using m_T and m_D. Here, S_D^* is the forecasted aggregated load at the substation bus and V_T^* is the forecasted balanced voltage, represented as an ideal voltage source at the T&D PCC for DS analysis.

TS is solved first using the forecasted value of the aggregated DS load model (S_D^*), followed by DS using a balanced ideal voltage source (V_T^*). Thus, in this model, there is no coupling between the TS and DS. The impact of PV generation variability and DS load unbalances cannot be accurately captured by the DC model as it uses only forecasted values for T&D boundary (PCC) variables. The DC model and the workflow of its time-series analysis is shown in Fig.2.

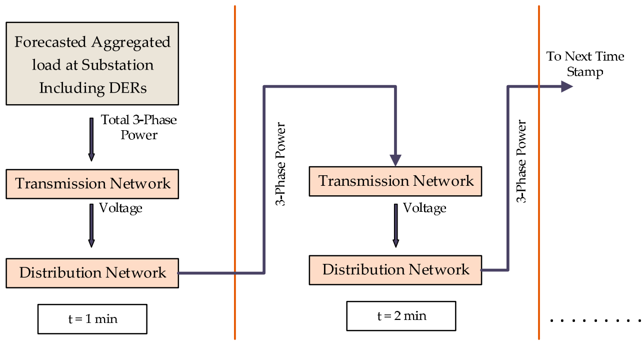

FIGURE 3. LC method for quasi-static time-series analysis.

2) LOOSELY COUPLED (LC) T&D SYSTEM

In LC co-simulation model, at the time-step t, the solutions from TS solver $V_T(t)$ are exchanged with the DS. The DS model is then solved using the updated value for the substation bus voltage ($V_T(t)$). The solutions from the DS solver, i.e., DS load demand ($S_D(t)$) are exchanged with TS solver and the time-step is advanced to $(t + 1)$ with no consideration to the convergence of the boundary variables. The TS solver then solves the system for $(t + 1)$ time-step using the load demand obtained from DS solver at t time step. This model assumes that the changes in the system states are slow compared to the solution time-steps such that the boundary variables for the LC T&D systems converge over multiple time stamps. Mathematical equations describing this method are shown in (3) and (4).

$$V_T(t) = f_T(S_D(t-1), m_T(t), G_T(t)) \quad (3)$$
$$S_D(t) = f_D(V_T(t), m_D(t), PV_D(t)) \quad (4)$$

where, the TS at time step t is solved using the aggregated substation load demand obtained at the previous time step ($S_D(t-1)$). Since the solvers do not use the current values of the PCC variables, we term this coupling as a loosely coupled (LC) protocol. Note that here, the coupling strength of T&D systems is weaker than the standalone T&D system models but stronger than the DC models. The workflow of LC model is shown in Fig. 3.

3) TIGHTLY COUPLED (TC) T&D SYSTEM

The TC model developed in this work provides a strong coupling between the T&D systems. In this case, for a given time-step, the boundary variables are exchanged multiple times until they converge with a pre-specified convergence criterion. The approach employs an iterative procedure that terminates when the boundary variables obtained by separately solving the TS and DS, are within a pre-specified tolerance limit. We denote the iterations within a time-step required for boundary variable convergence as co-iterations. This iterative coupling ensures that the model closely approximates the stand-alone T&D model simulation where T&D systems are modeled and solved together in a single platform. We have validated the accuracy of the TC iterative co-simulation model against an equivalent stand-alone T&D model. The mathematical equations describing the TC

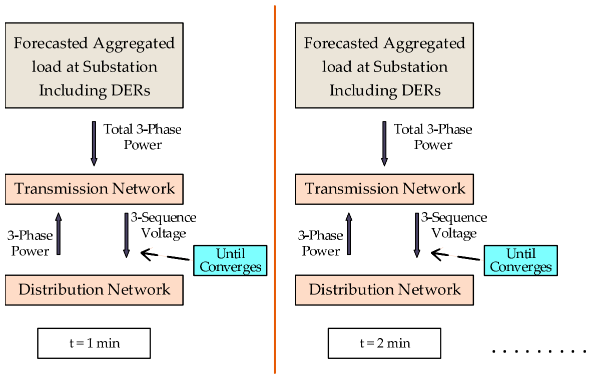

FIGURE 4. TC method for quasi-static time-series analysis.

co-simulation model are presented below.

$$V_T^{(n+1)}(t) = f_T(S_D^{(n)}(t), m_T(t), G_T(t)) \tag{5}$$
$$S_D^{(n+1)}(t) = f_D(V_T^{(n)}(t), m_D(t), PV_D(t)) \tag{6}$$

where, (5) and (6) describe the TC model at time t; n represents the co-iteration step at time-step t of co-simulation. Until the power flow variables obtained from solving TS and DS converge, the co-iteration steps continue and the time-step is not advanced. The converged solution in the TC model leads to the most accurate co-simulation result among all three T&D coupling methods discussed. The workflow of TC model's time-sequence analysis is presented in Fig. 4.

III. ANALYTICAL MODEL FOR TC T&D CO-SIMULATION FRAMEWORK

In this paper, we detail a tightly coupled co-simulation approach for the quasi-static analysis of T&D subsystems. Contrary to our prior work in [21], where a parallel method (PM) was used, here, a serial method (SM) for independent system solver and solution exchange is adopted owing to its faster convergence properties. In Serial Method (SM), the Transmission System (TS) is solved first. This is followed by solving all interconnected Distribution Systems (DSs) simulated. Note that all DSs are solved in parallel using the substation bus voltages obtained from TS analysis. The solutions from DS solver are then used to solve the TS system. The process continues until convergence. Since the TS and DSs are solved in a serial fashion, i.e. one after the other, this is referred to as a serial co-simulation method (SM). On the contrary, in PM method both TS and DSs are solved at the same iteration index followed by a solution exchange. It should be noted that compared to parallel method (PM), the serial approach for T&D coupling leads to a faster convergence of boundary variables. In fact, the number of iterations required for convergence in the SM framework is nearly half compared to the PM framework. The results are detailed in Section IV.

The boundary variables exchanged through the TC co-simulation platform are complex three-phase power demand (S_D) and three-phase voltages (V_T) at the respective PCCs. The subscript T and D denotes TS and DS, respectively. The mathematical model governing the coupled T&D system in the co-simulation framework is detailed in (7) - (10).

$$V_T = \mathcal{A}(f_T(S_T)) \tag{7}$$
$$V_D - \mathcal{A}(f_T(S_T)) = 0 \tag{8}$$
$$S_D = f_D(V_D) \tag{9}$$
$$f_D(V_D) - S_T = 0 \tag{10}$$

where, $f_T(x)$ and $f_D(x)$ are the nonlinear function for TS three-sequence power flow and DS three-phase power flow, respectively.

$$S_T = \begin{bmatrix} S^a \\ S^b \\ S^c \end{bmatrix}_T, \quad S_D = \begin{bmatrix} S^a \\ S^b \\ S^c \end{bmatrix}_D, V_D = \begin{bmatrix} V^a \\ V^b \\ V^c \end{bmatrix}_D$$
$$\text{and } V_T = \begin{bmatrix} V^a \\ V^b \\ V^c \end{bmatrix}_T = \mathcal{A} \begin{bmatrix} V^0 \\ V^1 \\ V^2 \end{bmatrix}_T, \mathcal{A} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}.$$

Note that (7) and (9) are solved using their own subsystem solvers. Equation (8) and (10) are the interface equations of the TC co-simulation platform. To achieve convergence, we define residual matrices.

$$\mathcal{A}(f_T(S_T)) - V_D = \mathcal{R_T} \tag{11}$$
$$f_D(V_D) - S_T = \mathcal{R_D} \tag{12}$$

A global interface residual vector, $\mathcal{R}$ is defined in (13) to evaluate the condition for the convergence of the co-simulation framework, where ϵ_1 and ϵ_2 are predefined tolerance parameters.

$$\mathcal{R} = \begin{bmatrix} \mathcal{R_T} \\ \mathcal{R_D} \end{bmatrix} \leq \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \end{bmatrix} = \begin{bmatrix} \epsilon \end{bmatrix} \tag{13}$$

The co-simulation interface shown in Fig. 1 calculates R_T and R_D as defined in (11) and (12) subject to (7) and (9). Then it is compared with the predefined tolerance ϵ.

In PM co-simulation framework, used in our prior work, (7) and (9) were solved in parallel and the boundary parameters were exchanged through interface equation (8) and (10). On the contrary, in SM co-simulation framework, the subsystem equation (7) is solved first and the solution of that equation is used to calculate DS substation parameters using (9). The boundary variables are exchanged at the PCC and solved iteratively to converge at every time step with a predefined tolerance ϵ. The objective is to iteratively solve interface equations defined in (8) and (10) for convergence until the residual evaluated using (13) is within permissible error tolerance. The interface equations in (8) and (10), at each iteration step, are solved using (14) and (15). Here, in the proposed co-simulation method, $\alpha = -1$. The algorithm for solving coupled T&D system via proposed tightly-coupled serial-method is detailed in Algorithm 1.

$$V_D^{(n+1)} = V_D^{(n)} + \alpha(V_D^{(n)} - V_T^{(n)}) \tag{14}$$
$$S_T^{(n+1)} = S_T^{(n)} + \alpha(S_T^{(n)} - S_D^{(n)}) \tag{15}$$

Algorithm 1: Solving Coupled T&D System - SM framework

Initialize time index for the time-series simulation, $t = t_1$

for $t = t_1 : \Delta t : t_f$ **do**

- Initialize Input Variables: $S_T^{(0)}(t)$, $V_D^{(0)}(t)$
- Set $\alpha = -1$
- Initialize iteration count, n = 1
- Solve subsystems in series manner -
- At first solve TS with initialized $S_T^{(0)}(t)$
- $V_T^{(1)}(t) = \mathcal{A}(f_T(S_T^{(0)}(t)))$
- Update the boundary variable of DS
- $V_D^{(1)}(t) - \mathcal{A}(f_T(S_T^{(0)}(t))) = 0$
- Solve DS with updated parameter
- $S_D^{(1)}(t) = f_D(V_D^{(1)}(t))$
- Update the boundary variable of TS
- $f_D(V_D^{(1)}(t)) - S_T^{(1)}(t) = 0$
- Check residual at the interface

$$\mathcal{R}^{(1)}(t) = \begin{bmatrix} S_T^{(0)}(t) & - S_D^{(1)}(t) \\ V_D^{(0)}(t) & - V_T^{(1)}(t) \end{bmatrix}$$

— Iteration loop —

while $|\mathcal{R}^{(n)}(t)| \geq \epsilon$ **do**

- Solve TS with $S_T^{(n)}(t)$
- $V_T^{(n+1)}(t) = \mathcal{A}(f_T(S_T^{(n)}(t)))$
- Update the boundary variable of DS
- $V_D^{(n+1)}(t) = [V_D^{(n)}(t)] + \alpha[V_D^{(n)}(t) - V_T^{(n+1)}(t)]$
- Solve DS with updated parameter
- $S_D^{(n+1)}(t) = f_D(V_D^{(n+1)}(t))$
- Update the boundary variable of TS
- $S_T^{(n+1)}(t) = [S_T^{(n)}(t)] + \alpha[S_T^{(n)}(t) - S_D^{(n+1)}(t)]$
- Check residual at the interface

$$\mathcal{R}^{(n+1)}(t) = \begin{bmatrix} S_T^{(n)}(t) & - S_D^{(n+1)}(t) \\ V_D^{(n)}(t) & - V_T^{(n+1)}(t) \end{bmatrix}$$

- Increment iteration count
- n = n+1

end

end

IV. SIMULATION RESULTS

The results of co-simulation studies are detailed using IEEE standard T&D test systems for DER integration analysis. The different T&D coupling methods (decoupled, loosely coupled, and tightly coupled models) are compared for their accuracy and computational efficiency with the increasing levels of DER penetrations, generation variability, and load unbalances. The results highlight (1) the need for a tightly coupled T&D co-simulation models for the future T&D systems that is expected to observe stressed system conditions. The tightly coupled co-simulation, however, comes at an additional computational cost; (2) the limitations of single-phase loosely coupled T&D models, prevalent in the existing commercial co-simulation platforms, with regard to their applicability for T&D systems observing demand profiles with faster variations (due to DERs) and higher-levels of system unbalance that is expected to be a growing concern.

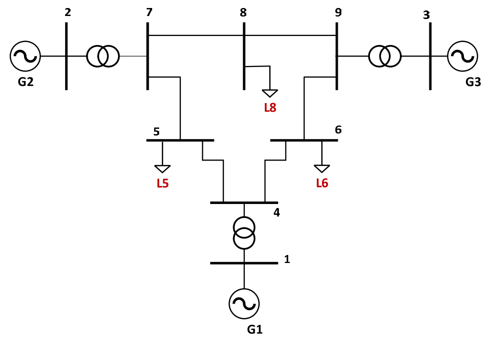

FIGURE 5. Test System-1.

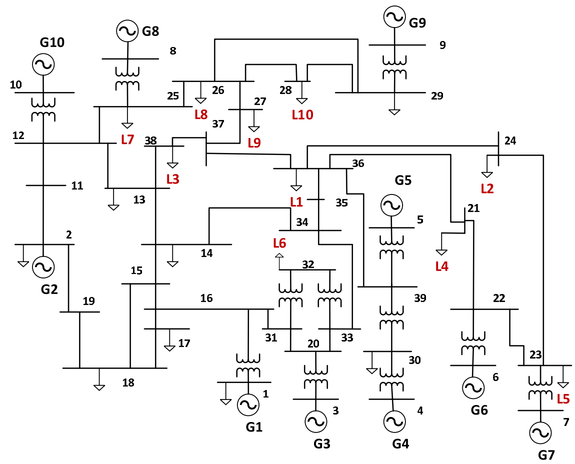

FIGURE 6. Test System-2.

A. SIMULATION SETUP

For a detailed analysis of the previously discussed T&D coupling models, two integrated T&D test systems are developed: TSm-1 and TSm-2. TSm-1 simulates a small IEEE 9-bus TS model with one interconnected DS model (Fig. 5). TSm-2 simulates a large integrated T&D system model; TS is modeled using IEEE 39-bus system that includes 18 load buses and 10 generators (see Fig. 6) where multiple load buses are replaced by EPRI Ckt-24 (DS system model). EPRI Ckt-24 is a large unbalanced 6000-bus distribution test system that models a real-world distribution feeder with 3885 customers and 87% residential load [25].

The small-scale test system is used to evaluate the trend in simulation errors as the DER/PV penetrations, load unbalance, and PV variability are increased for the interconnected DSs. Despite the simulation errors being less, the test case demonstrates the variations in T&D simulation errors for different coupling methods. The simulation errors are observed to be more pronounced for the larger T&D system model. The development of the two test systems is detailed next.

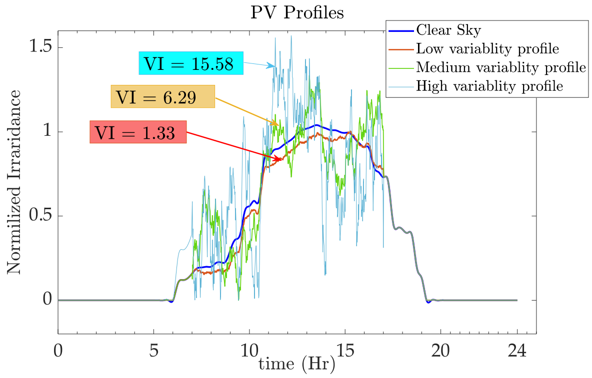

FIGURE 7. PV profile for different irradiance variability.

1) TEST SYSTEM-1

In test system-1 (TSm-1), TS is modeled using IEEE 9-bus system where the load buses are replaced by EPRI Ckt-24 distribution system model as shown in Fig. 5. The following scenarios are simulated on TSm-1. (i) *PV Variability*: PV variability cases are simulated for three different scenarios with low, medium, and high variations in PV generation profiles having variability indices (VI) of 1.33, 6.29, and 15.58, respectively [27] (see Fig. 7). (ii) *Load Unbalance:* The load unbalance is varied from 10% to 50% in the steps of 10% by varying the customer load distribution in each of the phases of the DS. Here, the PV deployment cases are also unintentionally unbalanced as the PV systems are randomly deployed on the different phases. (iii) *PV Penetrations:* Test cases with ten different PV penetration levels are simulated by varying customer penetrations levels from 10% to 100%. PV deployment scenarios are simulated using Monte-Carlo simulations with random sizes and locations of PVs as discussed in Section II.B. In this paper, % PV penetration refers to the percentage of DS customers with PV. For quasi-static time-series analysis, a specific 1-hour (12.00-1.00pm) window of the day is selected with specified PV penetration level and variability profile. The DS loads are assumed to be constant for the 1-hour simulation duration.

2) TEST SYSTEM-2

Test system-2 (TSm-2) simulates a larger integrated T&D system for co-simulation studies. We employ IEEE 39-bus test system as the TS model (see Fig. 6) and EPRI Ckt-24, connected at multiple load points, as the DS model. IEEE 39-bus test system includes 18 load buses that can serve as potential connection points for the DS. For a comprehensive analysis, we simulate three different integrated T&D test systems by varying the number of T&D coupling points. The following integrated T&D models are simulated: (1) a total of two load points - L1 and L7 in IEEE 39-bus TS are replaced with EPRI Ckt-24; (2) a total of five load points - L1, L6, L7, L8, and L10 in IEEE 39-bus TS are replaced with EPRI Ckt-24; and (3) a total of ten load buses L1-L10 in IEEE 39-bus TS are replaced with EPRI Ckt-24.

B. T&D CO-SIMULATION - COMPARISON OF DC, LC AND TC COUPLING METHODS

This section presents a comprehensive comparison of the DC, LC, and TC models using multiple test cases. We perform quasi-static time-series simulations of the two test systems for different simulation parameters. First, we validate the results obtained from the TC co-simulation platform against the corresponding standalone T&D model; TSm-1 is employed for the validation study. It is demonstrated that the TC model is as accurate as the standalone simulation of the integrated T&D system. Next, the trends of co-simulation error for loosely coupled (LC) and decoupled (DC) co-simulation models are evaluated for different PV integration scenarios; TSm-1 is employed for this analysis. Note that the errors are measured with respect to the simulation results obtained from the corresponding TC model. Since the TC model is validated to be as accurate the standalone integrated T&D model, the comparison against the TC model for the accuracy of other coupling methods is justified. We also compare the accuracy of 3-phase vs. 1-phase TS models in the co-simulation study.

Next, we employ TSm-2 to demonstrate the utility of the tightly coupled (TC) T&D model in accurately representing co-simulation studies on larger T&D systems. The three-phase DC (TPDC) and three-phase LC (TPLC) models are compared with the three-phase TC (TPTC) model using TSm-2 to show how the co-simulation errors are magnified for larger integrated T&D test systems. It is to be noted that the LC co-simulation models in the current literature use a single-phase power flow model for the TS. However, for a fair comparison, we have used three-phase models for both TC and LC co-simulation models. Finally, we compare the time-cost of simulating TPDC and TPLC co-simulation models against TPTC approach for different simulation scenarios.

1) STANDALONE T&D MODEL VALIDATION

The objective of this section is to validate the TC co-simulation model results with an equivalent standalone T&D system model. The analysis is done using TSm-1 where EPRI Ckt-24 distribution feeders are included at all three load points of the IEEE 9-bus TS. A standalone T&D model is developed for TSm-1 and solved using OpenDSS. The standalone model is simulated with varying PV deployment scenarios on all ckt-24 feeders connected to the TS. The results obtained at the PCC using the standalone model are analyzed and compared with those obtained using TC co-simulation model.

In this paper, the co-simulation framework is referred to as Model-1, and the standalone T&D model is referred to as Model-2. The voltages at PCC are compared in Table 1 for varying PV penetration levels. As can be observed from this table, the voltages at the three PCC points obtained by solving Model-2 (standalone) and Model-1 (co-simulation) closely match. The maximum difference in the voltages for the two models is less than 0.0001 pu. This study validates that the

TABLE 1. Comparison of positive-sequence voltages at T&D PCC using TC co-simulation and standalone T&D model.

	Model-1 Voltages (p.u.)			Model-2 Voltages (p.u.)		
% PV	Bus 5	Bus 6	Bus 8	Bus 5	Bus 6	Bus 8
10%	1.0444	1.0511	1.0558	1.0444	1.051	1.0557
20%	1.0447	1.0516	1.0576	1.0446	1.0514	1.0574
30%	1.0449	1.0519	1.0588	1.0449	1.0518	1.0585
40%	1.0449	1.0521	1.0598	1.0449	1.0521	1.0595
50%	1.0448	1.0523	1.0608	1.0448	1.0522	1.0606
60%	1.0446	1.0522	1.0617	1.0446	1.0522	1.0616
70%	1.0442	1.0521	1.0625	1.0441	1.052	1.0627
80%	1.0438	1.0518	1.0633	1.0437	1.0517	1.0635
90%	1.0433	1.0514	1.0639	1.043	1.0513	1.0640
100%	1.0426	1.0509	1.0644	1.0424	1.0508	1.0646

TABLE 2. Impact of PV generation variability on 3-Phase LC (TPLC) and 3-Phase DC (TPDC) Model (TSm-1).

Mean % error of TPLC						
	Voltage			Load		
Cases	Low var	Med var	High var	Low var	Med var	High var
L10P20	0.0496	0.0532	0.0536	0.0914	0.0958	0.0900
L50P10	0.2255	0.2348	0.2311	0.1881	0.2282	0.1922
L10P100	0.0294	0.0679	0.1044	0.1069	0.1443	0.2030
L50P40	0.2007	0.2038	0.2124	0.5054	0.5130	0.5400
Mean % error of TPDC						
L10P20	1.8202	1.9134	1.9799	2.8528	2.9717	3.6602
L50P10	8.7808	8.7979	8.8337	19.8825	19.9526	20.2183
L10P100	7.9033	8.3504	8.4257	22.2903	21.2053	24.6334
L50P40	8.5821	8.8098	8.8743	20.5772	20.8161	21.7992

TC co-simulation approach accurately models the integrated T&D system model.

2) COMPARISON OF T&D COUPLING METHODS FOR TSm-1

The DC, LC, and TC co-simulation models are compared for various DER integration scenarios. We detail the impacts of different levels of PV variability, load unbalance, PV penetration on the trend of co-simulation errors for the three coupling models. A 1-hour simulation study is done for scenarios with three different variabilities in PV irradiance, five different levels of load unbalance, and ten different levels of PV penetrations.

i. Impacts of PV Variability - Three different days with low, medium, and high PV variability cases shown in Fig. 7 are simulated using the quasi-static time-series analysis. The impacts of PV variability in terms of mean % errors in DC and LC co-simulation models at the PCC are shown in Table 2. Specifically, the mean error percentages incurred in TPLC and TPDC models with respect to the TPTC model for substation voltage magnitude and power demand are compared. Here, L** represents load unbalance and P** represents PV penetrations i.e., Case L50P80 means load unbalance is 50% and customer PV penetration is 80%.

As seen from Table 2, with the increase in PV variability, the error in voltage magnitude and power demand for the TPLC model and TPDC model increases for all the test cases simulated in this study. Further, the errors in TPDC model is higher than that of the TPLC model reflecting that the T&D coupling strength plays a vital role in T&D co-simulation error. The same trend in error is seen when evaluating the mean error in power flow at the T&D PCC for TPDC and TPLC models. The stronger the coupling of the T&D system, the less error it incurs in estimating the boundary variable for the T&D co-simulation (i.e., load flow and voltage magnitudes at the T&D PCC). It is also observed that the % mean error in power flow is higher than the % mean error in the voltage magnitude indicating that the load estimates are affected more compared to the voltage magnitude at the PCC due to PV variability.

TABLE 3. Impact of Load Unbalance on 3-Phase LC (TPLC) and 3-Phase DC (TPDC) Model (TSm-1).

		Mean % error (Voltage)			
	Cases	TPLC		TPDC	
PV %	Load Unb%	Med var	High var	Med var	High var
20%	10%	0.0532	0.0536	1.9134	1.9799
	20%	0.1223	0.1305	5.3513	5.3950
	40%	0.3076	0.3087	10.5985	10.6586
40%	10%	0.0568	0.0694	1.8822	1.9603
	20%	0.1294	0.1459	5.2604	5.3325
	40%	0.3035	0.3157	10.6254	10.7200
80%	10%	0.0620	0.0882	1.7571	1.8486
	20%	0.1410	0.1697	4.9877	5.0668
	40%	0.2296	0.3188	10.5479	10.6539

ii. Impacts of Load Unbalance - In this section, the impact of load unbalance on the DC and LC co-simulation models are evaluated. Several test scenarios are simulated by varying the levels of load unbalance in the distribution feeder for multiple PV penetration scenarios (10%, 20%, and 40%) with medium and high PV variability cases. The mean percentage errors in voltage magnitude at the PCC, i.e., T&D boundary variables are compared for TPLC and TPDC models with respect to the TPTC model. The results are shown in Table 3. Here, load unbalance refers to measured unbalance in three-phase load demand. The ANSI C84.1 limits the maximum voltage unbalance to up to 3%, however, no such standard is defined for load/current unbalance [28]. In the simulated scenarios, the voltage unbalance is less than 1.5% even for the worst case scenario with 50% load unbalance. Readers are referred to our previous work [22] for analysis on voltage unbalance scenarios.

As seen from Table 3, the percentage error for both TPLC and TPDC models increases on increasing the load unbalance for the same PV penetration and PV variability scenario. Furthermore, as expected, for all cases, TPDC model result in higher % errors in PCC voltages compared to the TPLC model. In the quasi-static time-series simulation of the TPLC model, this error is passed to the next time step. For the TPDC model under given simulation conditions, the error can go as high as 10%. Hence, for highly unbalanced DS systems, the DC and LC co-simulation platforms are less accurate and start to deviate more and more from the actual state of the system especially under stressed system conditions.

iii. Impacts of PV Penetration - The impact of increasing PV penetrations on the accuracy of T&D co-simulation for different T&D coupling methods is evaluated in this section. For the same load unbalance and PV variability condition, the PV penetration level is increased in steps and the simulation results obtained using TPTC, TPLC and TPDC

TABLE 4. Impacts of PV penetration on 3-Phase LC (TPLC) and 3-Phase DC (TPDC) Model (TSm-1).

	Cases	Mean % error (Voltage)			
		TPLC		TPDC	
Load Unb%	PV %	Med var	High var	Med var	High var
10%	20%	0.0532	0.0536	1.9134	1.9799
	60%	0.0601	0.0781	1.7997	1.8933
	100%	0.0679	0.1044	1.6693	1.7324
20%	20%	0.1223	0.1305	5.3513	5.3950
	60%	0.1358	0.1595	5.1005	5.1817
	100%	0.1453	0.1794	4.8441	4.9041
50%	20%	0.1918	0.1957	8.8628	8.9230
	60%	0.2208	0.2491	8.6019	8.6752
	100%	0.2425	0.2843	8.3504	8.4257

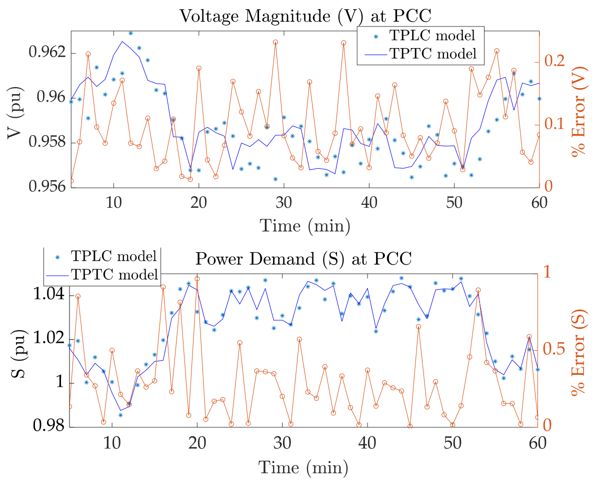

FIGURE 8. Voltage magnitude and power demand at PCC for 50% Load unbalance and 80% PV penetration (High variability) - TPLC and TPTC model (TSm-1).

co-simulation models are compared. The mean error percentage in substation voltage magnitude is compared for TPLC and TPDC models relative to the TPTC model. Three different levels of PV penetration scenarios (20, 60, and 100%) with 10, 20 and 50% load unbalance scenarios are compared. The results are shown in Table 4. It can be observed that upon increasing PV penetration levels in the DS, the errors in voltage magnitude increases for the TPLC model. However, unlike the TPLC co-simulation model, for TPDC model, the errors on boundary variable (PCC voltage magnitude) decreases for higher levels of PV penetration. This is because, an increase in PV penetration indirectly reduces the voltage unbalance at the PCC. The errors are, however, significantly large. For example, a 9% error is observed in voltage magnitude at the T&D PCC in the TPDC model for the scenario with 50% load unbalance, 20% PV penetration, and high PV variability.

iv. Time-series Comparison of TPTC & TPLC - The voltage magnitude and power demand at PCC for 1-hour time-series simulation of TPTC and TPLC models are compared and presented in Fig. 8. Here, the PV penetration and load unbalance in DS are 80% and 50%, respectively. The voltage magnitude for the TPLC model is lagging one time-step form TPTC model as TPLC model uses the load demand evaluated in the previous time-step. This lagging

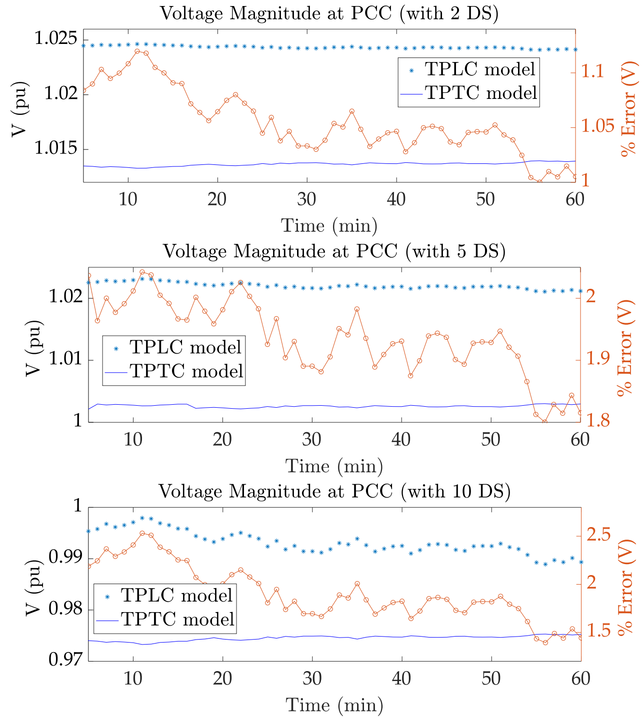

FIGURE 9. Voltage magnitude at PCC - TPLC and TPTC model (TSm-2) for medium variability.

profile of voltage magnitude causes a large error with high variability. The trend of error in voltage magnitude and power demand at PCC for TPLC model is summarized and presented in Fig. 12. As seen from the figure, the voltage magnitude error is not as high as that of the power demand for the LC model. It is expected that for a larger system integrated with multiple DS, the error in voltage magnitude will be magnified.

3) COMPARISON OF T&D COUPLING METHODS ON INCREASING NUMBER OF T&D COUPLING POINTS (TSm-2)

The objective of this section is to understand the impacts of increasing the number of T&D coupling points on co-simulation errors for TPLC models. For this evaluation we employ the larger T&D test system, TSm-2, and simulate the following three test cases: (1) TS coupled with DS at two load buses, (2) TS coupled with DS at 5 load buses, (3) and TS coupled with DS at 10 load buses. All three test cases are simulated for 40% load unbalance, and 80% PV penetration with medium PV variability. Both TPTC and TPLC co-simulation methods are employed for all three test cases. The co-simulation errors are compared using load bus L7 in IEEE 39-bus test system. The % errors in voltage magnitude and power demand at the PCC (load bus L7) are shown in Figs. 9 and 10 respectively. Note that this is 1 hour time-series simulation between 12 noon and 1pm.

Two important observations are made from this simulation study. First, the co-simulation errors in TPLC models are higher for the larger test system (TSm-2) compared to the smaller test system (TSm-1). Second, with the increase in

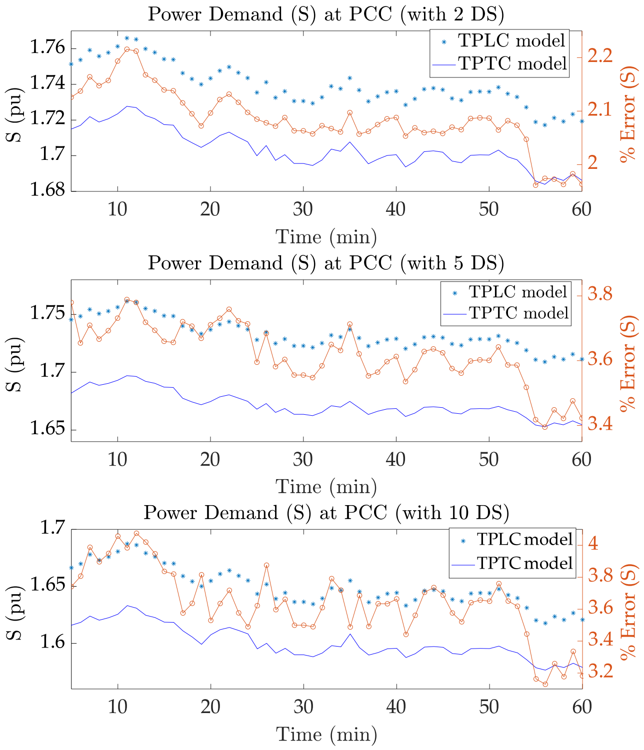

FIGURE 10. Power demand at PCC - TPLC and TPTC model (TSm-2) for medium variability.

T&D coupling points, the errors in the TPLC T&D model increases. For cases 1 to 3, where the number of connected DS is increased from 2 to 10, the error in TPLC model increases from 1.05% to 2.5% for voltage magnitude and from 2.1% to 4.0% for power demand at the load bus L7. This is because, every loosely coupled T&D point in the larger T&D system contributes to co-simulation error, thus increasing the cumulative error for entire system. Hence, the accuracy of TPLC co-simulation model degrades both upon increasing the size of the T&D system and the number of T&D coupling points.

4) POSITIVE SEQUENCE VS. THREE SEQUENCE TRANSMISSION SYSTEMS MODEL

This section compares the implications of using a balanced positive sequence TS model vs. a three-sequence TS model in T&D co-simulation study. In what follows, the voltage magnitude at PCC is compared for the two cases: (1) Tightly-coupled (TC) co-simulation model using single-phase TS model termed as single-phase tightly-coupled co-simulation (SPTC), and (2) Tightly-coupled (TC) co-simulation model using three-phase TS model termed as three-phase tightly-coupled co-simulation (TPTC). For TPTC, we pick one of the phase voltages for comparison, here, Φ_C of PCC.

The respective voltages obtained using SPTC and TPTC models are compared in Table 5 for different cases of load unbalance simulated with 20% PV penetration and low PV variability. The errors in SPTC depends on the level of unbalance in the distribution system and the substation

TABLE 5. Three-phase TS tightly coupled (TPTC) vs. positive-sequence TS tightly-coupled (SPTC) models.

	Voltage Magnitude Comparison (pu)					
	$\Delta-\Delta$		$\Delta-Y$		Y - Y	
Case	**TPTC**	**SPTC**	**TPTC**	**SPTC**	**TPTC**	**SPTC**
L10P20	1.0340	1.0329	1.0117	1.0144	1.0119	1.0114
L20P20	1.0074	1.0017	0.9913	0.9851	0.9950	0.9852
L30P20	0.9962	0.9992	0.9738	0.9632	0.9735	0.9633
L40P20	1.0022	1.0082	0.9320	0.9451	0.9174	0.9476

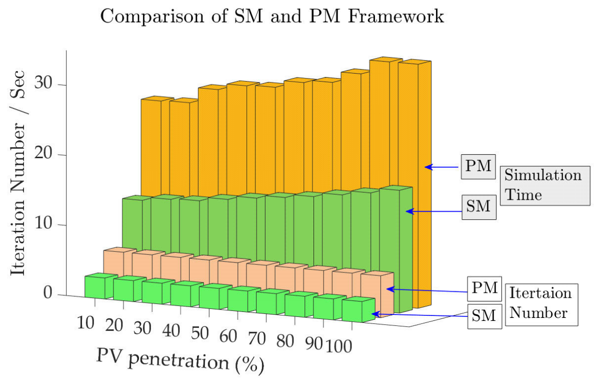

FIGURE 11. Comparison of TPTC SM & TPTC PM Co-simulation framework (TSm-2).

transformer configuration. It is observed that on increasing the load unbalance, the errors in SPTC model increases. In addition, transformer's configuration affects the SPTC model's accuracy. While the difference in voltage magnitude is 0.0060 pu for $\Delta-\Delta$ transformer, it can go high as 0.0131 for $\Delta-Y$ transformer configuration and 0.0302 for $Y-Y$ transformer configuration. Note that generally, a $\Delta-Y$ configuration is employed at T&D coupling point. From Table 5, even with 20% load unbalance at distribution level, the error in SPTC for $\Delta-Y$ configuration is significantly high (about 0.7%). This simulation test case highlights the rationale for using a three-phase TS analysis.

C. COMPARISON OF SERIAL METHOD (SM) AND PARALLEL METHOD (PM) CO-SIMULATION

This section compares the computational advantages of the proposed serial method (SM) for co-simulation and information exchanges against the parallel method (PM) used in our previous work [21]. It is observed that on simulating TS and DSs serially (one after other), the TC co-simulation requires half the number of iterations for convergence compared to when both TS and DS are simulated in parallel. Note that in SM, while TS and DS solvers are executed sequentially, all DS are solved in parallel at the same time.

The total one hour simulation time for SM and PM co-simulation are compared for several test cases and the results are presented in Fig. 11. The simulations are done using large test system (TSm-2) with 10 load points connected with EPRI Ckt-24 distribution feeder. For selected test system, we simulate test case with 40% load unbalance with medium PV variability for 10 penetration scenarios (10-100% at 10% step). It can be seen from the figure that with the SM framework, the number of iterations and thus the total time taken for the simulation is half compared to the PM framework.

V. DISCUSSIONS

The major observations based on different simulation scenarios are detailed below.

- DC model is significantly more inaccurate compared to the LC model. Typically, the mean % error in boundary variables were found to be 20 to 40 times higher in DC model compared to the equivalent LC model. Further, for both DC and LC models, the absolute value of percentage error observed in power demand variable is higher than the voltage magnitude at the T&D PCC.
- The errors in LC model are higher during stressed system conditions such as high PV variability, high levels of load unbalance, high percentages of PV penetrations; the LC model leads to higher error when PVs incur a higher generation variability. A quantitative comparison indicates that the levels of load unbalance significantly affects the accuracy of the LC co-simulation. For same levels of PV penetration, the error increases by two-fold upon doubling the load unbalance (see Fig. 12).
- The errors in the LC model increase as the number of coupled T&D points in the integrated T&D system are increased. That is, for the larger T&D test systems, LC model will lead to significantly higher errors. For example, upon increasing the connected DS from 2 to 10, the maximum error in LC model increases from 1.2% to 2.5%.
- A serial coupling method for TC co-simulation requires half the number of iterations to converge compared to when both TS and DS are simulated in parallel. This leads to a significant reduction in the co-simulation time providing a remarkable computational advantage.

To further elaborate, the trend of errors in voltage magnitude and power demand at PCC for TPLC model (TSm-1) is summarized and presented in Fig. 12. In addition to unity power factor, 0.98 power factor PVs are simulated as well. As seen from the figure, the voltage magnitude error is not as high as that of the power demand for the LC model. It is expected that for a larger system integrated with multiple DS, the error in voltage magnitude will be magnified. In addition, the power factor of PVs (with the Q generation capabilities for PVs with lower pf) also increases % error at the PCC in LC models.

Finally, the time it takes for TPTC, TPLC, and TPDC in co-simulation study ($Y - Y$ transformer at the substations for TSm-1) are compared in Fig. 13. We compute and plot the average simulation time in 1-min interval, required by the TPTC, TPLC, and TPDC model for T&D co-simulation study with different levels of PV penetration and load unbalance cases. It can be seen that the simulation time for TPDC and TPLC for 1-min simulation scenario are in the same order - as they simulate the scenario only once before they move onto the next timestamp, but slightly increases with the stress in the system. The Time-cost, i.e., the additional time taken

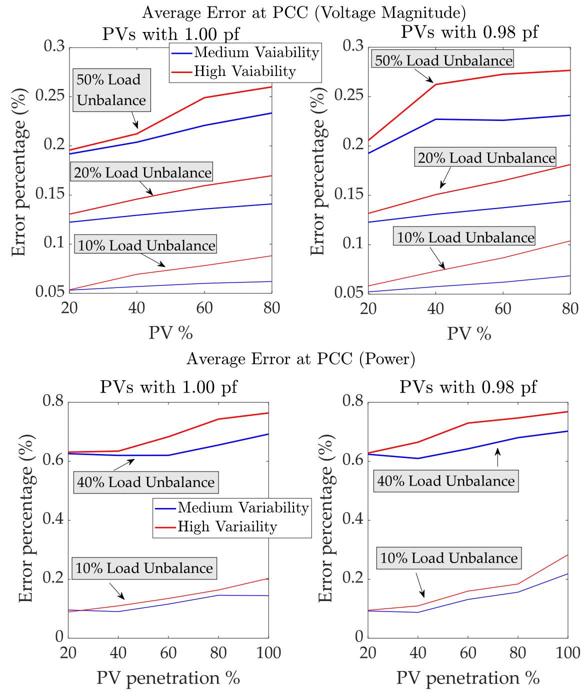

FIGURE 12. Impact of different variables on % error in Three-phase Loosely-coupled (TPLC) Co-simulation (TSm-1).

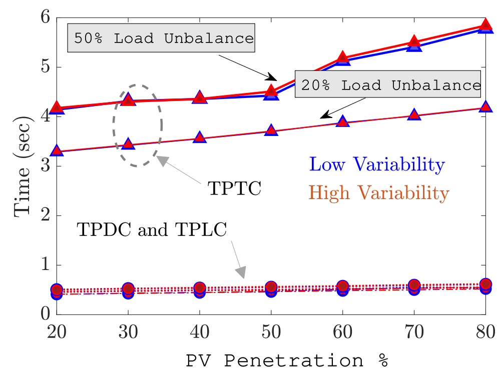

FIGURE 13. Time Comparison of TPLC & TPDC w.r.t. TPTC (TSm-1) for 1-hour Simulation.

by TPTC is dictated by the number of iterations it takes to converge and increases with the stress in the system. The relative time-cost for TPTC co-simulation increases with the increase in load unbalance and percentage PV penetrations. Please note that the PV variability has a small impact on the simulation time. Better algorithms such as second-order method proposed in our prior work can help in reducing the time cost [22].

The trade-off in selecting coupling protocols for T&D co-simulation studies lies with 'co-simulation accuracy' and 'co-simulation Time Cost'. For example, for low PV penetration levels, low levels of PV variability, and small load unbalances in the DS, a loosely coupled (LC) model is reasonably accurate. Therefore, a LC co-simulation model should be preferred under less stressed system conditions due to the associated computational advantages leading to a smaller time-cost. However, the TC model should be prioritized when the co-simulation accuracy is relatively more important than the Time-Cost. For example, the TC co-simulation approach is more suitable during stressed system conditions since the LC model results in poor accuracy.

VI. CONCLUSION

This paper presents a comprehensive assessment of T&D coupling protocols on the accuracy of T&D co-simulation study. The following coupling protocols are compared for quasi-static time-series simulation studies: decoupled (DC), loosely coupled (LC), and tightly coupled (TC). Several cases with varying levels of PV variability, DER penetrations, and load unbalances are simulated, and T&D co-simulation models are solved for DC, LC, and TC protocols. It is shown that both DC and LC T&D co-simulation models incur errors when modeling integrated T&D systems. The errors are more pronounced for stressed system conditions, i.e., upon increasing load unbalance, including higher levels of PV penetrations, and cases with high-levels of variability in PV generation profiles. As expected DC model leads to significantly larger errors compared to the LC and TC models and is not suitable for DER impact analysis on integrated T&D systems. Furthermore, with the increase in system size, a higher error is incurred by the LC model, indicating that the LC model may be insufficient in conducting DER impact analysis on the integrated T&D systems. Same as before, the errors are more pronounced during stressed system conditions. It is also concluded that the single-phase transmission model is unable to represent actual system conditions and is inadequate for the integrated T&D system analysis when DS introduces significant levels of load unbalance. Thus, the currently used LC co-simulation methods that employ a single-phase TS model is not accurate for DER impact studies, especially, when DS introduces unbalanced system conditions due to single-phase loads and DERs. The simulated test cases clearly demonstrate the advantages of the TC co-simulation model over LC and DC methods especially during stressed system conditions.

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