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Comparison of Coupling Techniques on Transmission and Distribution Co-Simulation with Distributed Generation and Load Growth

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Abstract

The increased demand for electrical power causes challenges with new power system planning and operations. These challenges are deepened with the simultaneous integration of Distributed Energy Resources (DERs) and Load Growth (LG) in distribution networks. However, realistic and practical modelling and simulation of DER's interactions under load growth with the Transmission and Distribution (T&D) networks is critical to assess the effects and advantages of DERs. This study thus, compared the different coupling techniques on transmissions and distribution co-simulation with Distributed Generation (DG) at varying loads. The T&D co-simulation test network comprises the Western System Coordinating Council (WSCC) 9-bus transmission network and the IEEE 16 nodes as the distribution network. Three coupling techniques; Decoupled (DC), Loosely Coupled (LC), and Tightly Coupled (TC), are simulated in MATPOWER environment, under DG penetration and load growth. The results show that the DC model is considerably less precise when compared to the LC model. The average percentage error in boundary variables was consistently 20 to 40 times worse in the DC model compared to the similar LC and TC models. Additionally, in both DC and LC models, the size of the percentage error in the power demand variable is greater than the magnitude of the voltage at the T&D Point of Common Coupling (PCC). This study provides valuable information on developing robust co-simulation frameworks essential for modern power grids, supporting sustainable energy transitions and enhancing grid resilience.

Keywords: Coupling Techniques, Modelling, Point of Common Coupling (PCC), Transmission and Distribution Co-Simulation, Distributed Energy Resources (DERs), Distributed Generation.

Introduction

The integration of Distributed Generation (DG) or Distributed Energy Resources (DERs) into the current power system is causing changes in the production, distribution, and consumption of electrical energy. Researchers and industry professionals are facing new possibilities and difficulties as the energy system undergoes a paradigm change towards decentralization and sustainability. Nevertheless, there are notable challenges that need to be surmounted, including the substantial upfront expenses associated with establishing renewable energy systems and the societal and political impediments that hinder the implementation of change (Lv, 2023). Current and future large-scale deployment initiatives of DER may impact the operations of regional transmission grids. This can lead to an imbalance in the system and increased variability in demand on integrated Transmission and Distribution (T&D) systems, as indicated by various exploratory studies (Krishnamoorthy & Dubey, 2020). The co-simulation of transmission and distribution networks occurs when the high-voltage transmission network and the lower-voltage distribution networks are simulated simultaneously. Co-simulation provides a more precise and complete understanding of the whole power system by including the linkages between the transmission and distribution tiers, which are often overlooked when these systems are simulated independently. Simultaneously simulating transmission and distribution networks with DERs offers a comprehensive approach to understanding and improving the modern power grid. Krishnamoorthy and Dubey (2020) contend that due to the unique characteristics and modelling methods involved, solo modelling is inadequate for studying the co-simulation of T&D networks with DERs. It is necessary to precisely represent both transmission and distribution networks, including their structure, electrical characteristics, and operational constraints. To facilitate the exchange of data and synchronize control actions, co-simulation often requires a communication infrastructure (Bhattarai et al., 2022; Martínez Sanz et al., 2019; Mejia-Ruiz et al., 2023). Hardware-in-the-loop (HIL), also known as power-hardware-in-the-loop, and software-in-the-loop (SIL) co-simulation are often used techniques for assessing the practical performance of DERs and analysing grid behaviour. HIL co-simulation connects physical DER components, such as inverters and batteries, to real-time grid simulators. On the other hand, SIL co-simulation uses computer-based models to simulate system interactions and analyse grid behaviours (Gao et al., 2020; Jain et al., 2021; Mizuta et al., 2019).

Over time, the process of simultaneously modelling transmission and distribution networks with DERs would greatly enhance energy management and the robustness of the power grid. This information helps in predicting challenges in integrating DERs, maintaining grid stability, and managing voltage fluctuations. The Point of Common Coupling (PCC) is a vital component of the co-simulation integration process, serving as the convergence point for the transmission and distribution networks. The point at which energy produced by DER is connected to the grid before being delivered to customers is referred to as the grid connection point (Sadnan et al., 2020). To properly handle the challenges posed by the ever-changing nature of DER, such as solar panels, wind turbines, energy storage devices, and other decentralized energy assets, the PCC must use efficient and effective co-simulation approaches. To maintain the stability of the electrical grid, assure reliable power supply, and effectively integrate DERs, it is crucial to thoroughly understand and optimize the interactions at the PCC (Krishnamoorthy & Dubey, 2020; Sadnan et al., 2020).

Accurate and efficient modelling and simulation of DERs interacting with T&D networks are necessary to evaluate the impacts and benefits of DERs (Fulgêncio et al., 2020; Panossian et al., 2021; Rezvani et al., 2020). Jain et al. (2021) and Kenyon et al. (2020) state that T&D systems are often simulated separately using different methods and assumptions. However, this strategy may fail to include the interconnection and reciprocal impacts between the two systems, especially in the presence of DERs. Therefore, to accurately depict the complex behaviours and interactions of DERs in both the transmission and distribution domains, a co-simulation framework for T&D systems is necessary.

However, the process of T&D co-simulation is still difficult since it requires the coordination and synchronization of different simulation tools, models, and data. Furthermore, the PCC, which acts as the intermediary between the distribution network and the transmission system, requires the selection and implementation of appropriate coupling strategies. Different coupling mechanisms may have different effects on the accuracy, stability, and efficiency of co-simulation. According to Sadnan et al. (2020), it is essential to study the impact of different coupling approaches on the performance and outcomes of co-simulation. Enhancing coupling methods is crucial for enhancing the precision of grid modelling and ensuring the successful integration of sustainable DERs in a dynamic power system. This study aims to assess and analyse current coupling approaches in T&D networks, specifically examining their performance under different load circumstances and degrees of DG integration.

T&D Co-simulation Framework and Coupling Techniques

The T&D co-simulation frameworks have become essential tools in power systems research, allowing researchers to analyse and assess complex connections among various components in electric grids. This methodology enables a comprehensive understanding of the dynamic behaviour of T&D networks by integrating many simulation models. T&D co-simulation frameworks are built upon a theoretical basis that combines power system engineering, control theory, and computer science. The essence of T&D co-simulation is rooted in comprehending power system dynamics (Hajebrahimi et al., 2020; Mohseni-Bonab, Hajebrahimi, Kamwa, et al., 2020). Numerical approaches and algorithms may be used to model the complicated behaviour of large-scale linked systems. These theories effectively capture the dynamic reactions to disturbances, as shown by Bahmanyar et al. (2021) and Khazaee et al. (2020). Furthermore, Ledesma et al. (2022) and Zhong et al. (2019) has shown that T&D co-simulation frameworks integrate control and communication systems to represent the intricate nature of smart grids, using control theory and cyber-physical systems. The integration of specialized tools in a unified co-simulation environment is facilitated by theoretical frameworks such as the Common Information Model (CIM) and the Functional Mock-up Interface (FMI). These frameworks establish the necessary foundation for interoperability (Gougeon et al., 2021; Mohseni-Bonab et al., 2020).

Coupling approaches facilitate the integration and coordination of simulations for transmission and distribution systems, enabling a comprehensive analysis of their interconnections (Sadnan et al., 2020; Velaga et al., 2019). These approaches or procedures facilitate the exchange of information across simulation tools that would otherwise be incompatible, which is crucial for understanding the dynamic behaviour of the whole power system. Different degrees of connection between the distribution and transmission model are represented by various strategies, including decoupled, lightly linked, and strongly or iteratively coupled. The T&D systems are simulated individually and independently using a decoupled technique (Sadnan et al., 2020). The results of the two simulations are sometimes communicated, even though they operate alone. While this approach decreases the computational burden, it may exclude crucial network connections. Loosely coupled techniques maintain a certain level of contact between simulations of the T&D networks (Sadnan et al., 2020; Velaga et al., 2019). There is a certain level of coordination between the two domains as the models interact at predefined intervals. This approach strikes a balance between recording essential interactions and achieving computational efficiency. The tightly coupled method enables continuous and synchronous interaction between T&D models. The exchange of information in real-time across the models leads to a more precise and authentic representation of the grid network, and this method offers a comprehensive understanding of the dynamic behaviour and interactions inside T&D networks, despite their high computing demands (Jain et al., 2021; Krishnamoorthy & Dubey, 2020; Sadnan et al., 2020). The choice of coupling technique for a T&D co-simulation depends on its unique aims, computing capabilities, and the required degree of detail, considering the intricate trade-off between accuracy and computational efficiency.

Problem Formulation and Description

To represent the T&D co-simulation network, it is necessary to have a clear understanding of its constituent parts, namely the Transmission System (TS) and Distribution System (DS), as well as the co-simulation interface and the coupling techniques used. The DS and TS are both modelled and solved within their simulation systems. To accurately assess the impacts of DERs, the TS is simulated using an enhanced three-phase power-flow analysis that incorporates sequence components (Fernandes et al., 2019). The effects of load imbalances may be accurately depicted by using a power-flow solver and a three-sequence TS model inside the T&D co-simulation framework. Equation (1) is solved iteratively to yield the three-phase power flow solution for all sequence networks.

$$J^{\alpha}[v^{\alpha}]^{(h+1)} = [Z^{\alpha}]^{(h)} \tag{1}$$

To accurately describe the imbalanced circumstances of the system, the DS is modelled and presented in a comprehensive three-phase format. The MATPOWER platform, a freely available DS simulator, is used for the three-phase modelling and analysis of DS (Jain et al., 2021). The T&D co-simulation framework is shown in Figure 1, which depicts the DS solvers, the co-simulation interface, the TS solvers, and the corresponding boundary variables.

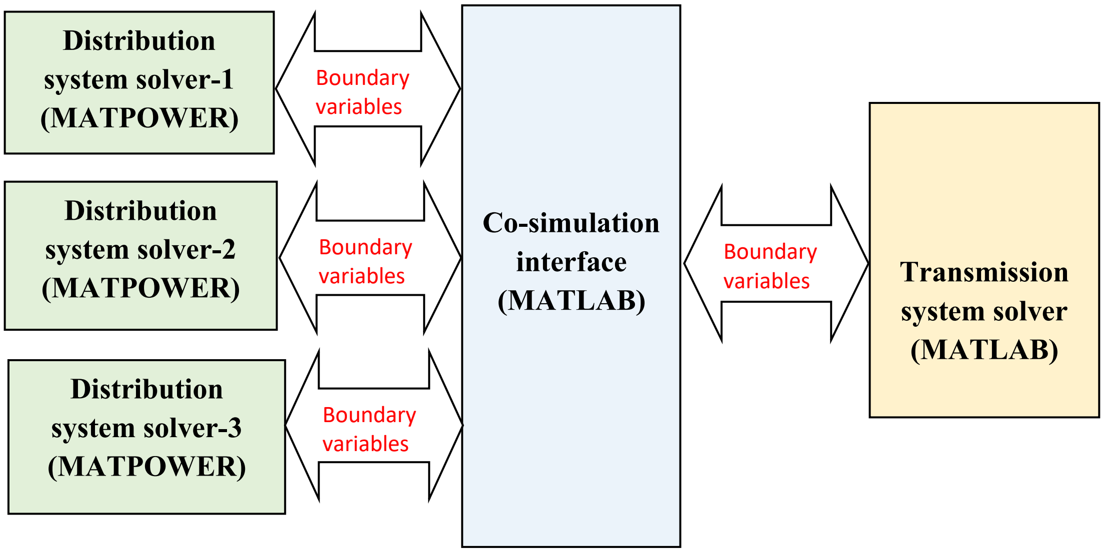

Figure 1: T&D Co-simulation Framework

Decoupled (DC) Co-simulation Technique

The decoupled technique is used to solve transmission and distribution co-simulations, where the TS and DS are separated at the interface buses. In this method, the TS is modelled as a rigid voltage source for the study of the DS. The TS is concealed behind an impedance equal to a Thevenin circuit, which is linked to the substation. Equations (2) and (3) describe the DC T&D model at time t.

$$V_T(t) = f_T\left(S_D{}^*(t), m_T(t), G_T(t)\right) \tag{2}$$

$$S_D(t) = f_D(V_T{}^*(t), m_D(t), PV_D(t)) \tag{3}$$

The substation power flow obtained using the DS solver, and the transmission bus voltages obtained using the TS solver, at the PCC are represented by V_T and S_D respectively, m_T and m_D are used to represent TS and DS network models with loads and line parameters. The TS and DS simulator, scheduled generator generation in TS, and known PV generation in DS is represented by f_T, f_D, G_T, and PV_D respectively. In this case, the predicted balanced voltage, V_T*, is represented as an ideal voltage source at the T&D PCC for DS analysis, and the predicted aggregated load, S_D*, is at the substation bus.

Loosely Coupled (LC) Co-simulation Technique

When independently functioning sub-simulators that are not tightly connected are simulated together, their interactions are synchronized at certain communication points. This approach is sometimes referred to as a loosely connected co-simulation technique. The LC co-simulation technique involves exchanging the DS model and the solutions obtained by the TS solver $V_T(t)$ at time-step t. Subsequently, the DS model is solved by using the updated substation bus voltage value ($V_T(t)$). This approach is shown using the mathematical formulae presented in equations (4) and (5).

$$V_T(t) = f_T(S_D(t-1), m_T(t), G_T(t)) \tag{4}$$

$$S_D(t) = f_D(V_T(t), m_D(t), PV_D(t)) \tag{5}$$

Where the combined substation load demand from the previous time-step ($S_D(t\text{-}1)$) is used to solve the TS at time step t.

Tightly Coupled (TC) Co-simulation Technique

When stand-alone sub-simulators that are closely linked are simulated together, their interactions are synchronized at certain sites of continuous communication. In this process, the boundary variables are iteratively exchanged for a certain time interval until they reach a defined convergence threshold. By solving the TS and DS problems separately, the approach produces boundary variables that are within a pre-set tolerance limit. This procedure is iterative. The mathematical description of the TC co-simulation approach is expressed in equations (6) and (7).

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

$$S_D^{(n+1)}(t) = f_D(V_T^{(n)}(t), m_D(t), PV_D(t)) \tag{7}$$

Here, the co-iteration step at time-step t of the co-simulation is represented by n, and equations (6) and (7) define the TC model at that point.

Load Growth Using Continuation Power Flow

To capture the effect of load growth, the necessary parameterisation for evaluating different loading levels is obtained through the Continuation Power Flow (CPF) routine. Given the set of the general load flow equation as represented by equation (8), parameterising the load flow equation with the loading parameter λ and an additional equation, the variation in λ will enable the tracing of the state variable x.

$$g(x) = 0, x \in \mathbb{R}^n \tag{8}$$

Diagrammatically, the continuation method is depicted by the equation (9), where (x^j, λ^j) is the current solution point with a step j, $(x_p^{j+1}, \lambda_p^{j+1})$ is the predicted solution, and (x^{j+1}, λ^{j+1}) is the next solution on the curve (Zimmermann and Murillo-Sánches, 2016).

$$(x^j, \lambda^j) \xrightarrow{\text{Predictor}} (x_p^{j+1}, \lambda_p^{j+1}) \xrightarrow{\text{Corector}} (x^{j+1}, \lambda^{j+1}) \tag{9}$$

Using CPF, the steady-state stability limit is determined from the nose curve, and for a given power supply and demand bid direction, the nose represents the maximum power transfer the system can handle.

Co-simulation Scenarios and Loading Levels

The simulation was done under two (2) scenarios to represent various combinations of load growth and DER presence, offering a thorough review of their effects on network performance. For this simulation, a static load was used with loading levels of 1.05 and 1.25 (5% and 25%) respectively. The scenarios used are:

Scenario 1: Baseline with DG, without load growth.

Scenario 2: Without DG, with load growth (CPF).

T&D Co-Simulation Test Network

The power system test network is carefully selected to model a T&D Co-simulation network. The high voltage transmission section is the Western System Coordinating Council (WSCC) network at a nominal of 230 kV while the IEEE 16 nodes form the distribution section at a nominal of 23 kV. The WSCC is a 9-bus network, consisting of 3-PQ loads, 3 transformers and 6- transmission lines. Aggregate active and reactive loads of the WSCC are 315 MW and 115 MVAr respectively. The IEEE 16 nodes is a 3-feeder network comprising 13-PQ nodes with an aggregate loading of 28.7 MW and 17.3 MVAr. Part of the aggregate load at each load bus of the transmission network (WSCC 9-bus) is modelled as an IEEE 16 nodes distribution network, hence the complete integrated power grid model with transmission and distribution section is obtained. Figures 2 and 3 show the one-line diagrams of WSCC 9-buses, and IEEE 16-nodes, respectively (Sadiq et al., 2019)

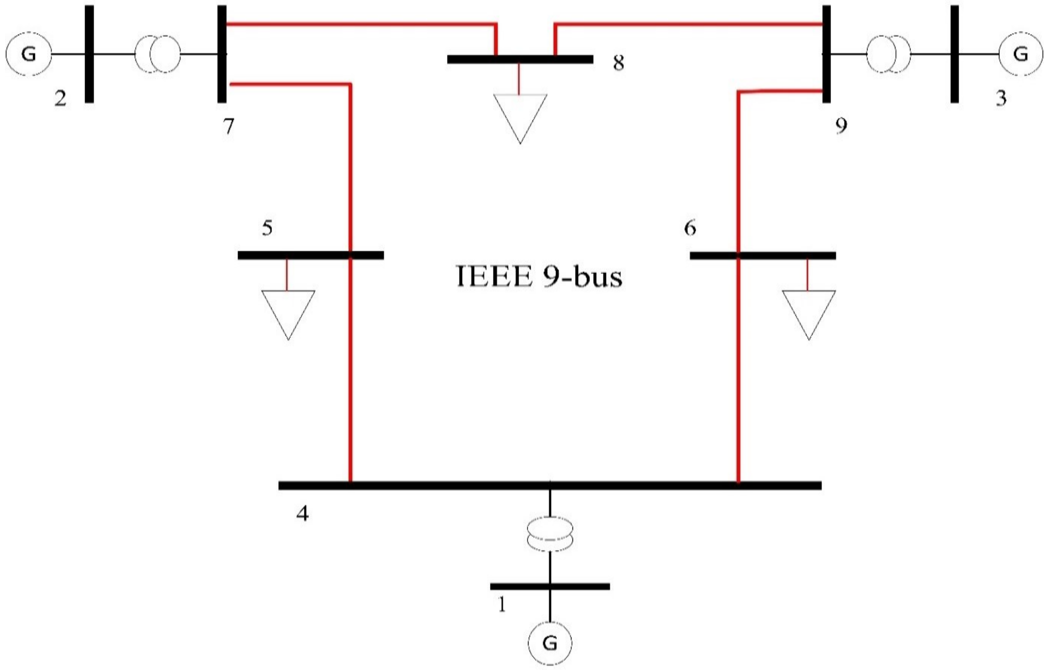

Figure 2: ***Western System Coordinating Council Network (WSCC 9 bus)***

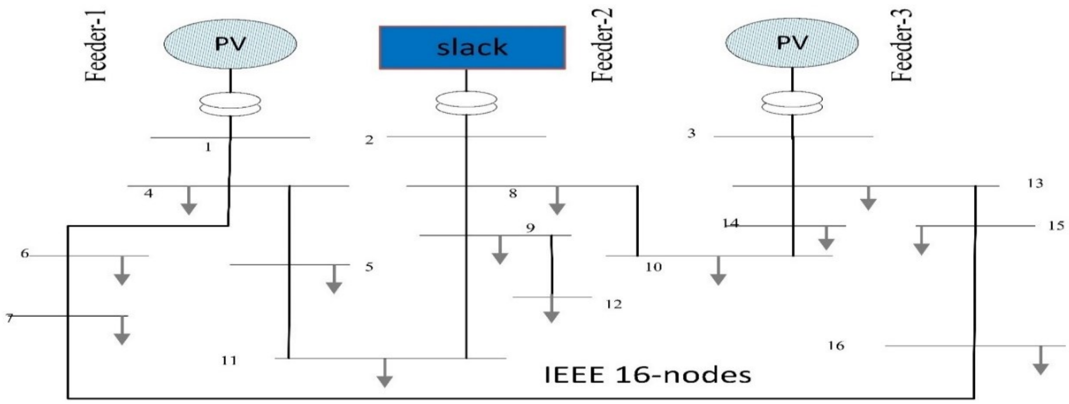

Figure 3: ***IEEE 16 nodes Distribution Network***

Results and Discussion

Scenario 1: Co-simulations for DC, LC, and TC

1. ***Baseline with DG, without Load Growth for DC co-simulation***

   In this scenario, there are a total of 16 buses, consisting of 4 generator buses, and a total of 13 load buses. For bus data, the generators have an actual generation of active and reactive power of 33.71MW and 24.03MVAr respectively. The load buses have a total load of 28.70MW and 17.30MW respectively. For branch data, the buses experience a total loss of 5.015MW and 6.73MVAr respectively. Figure 4 shows the graphical data for the voltage profile and power losses for DC co-simulation under scenario 1.

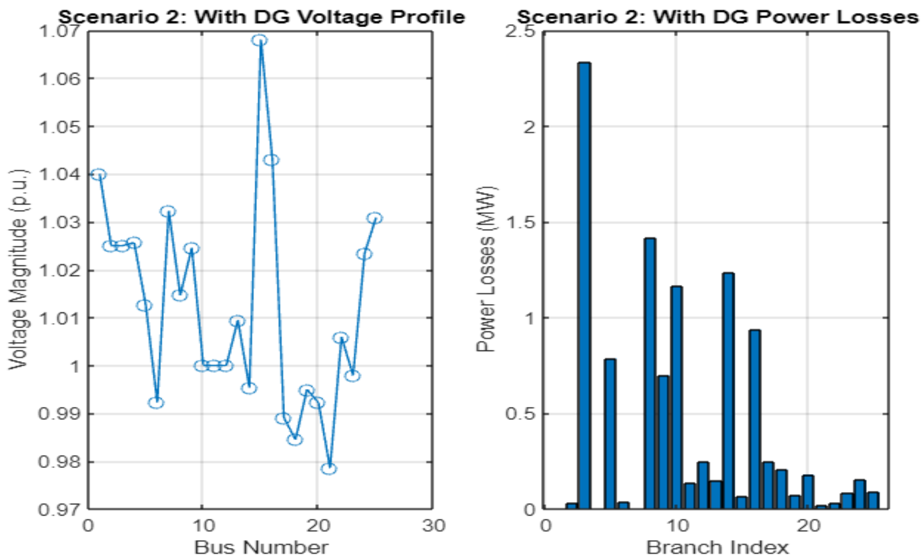

Figure 4: DC baseline voltage profile and power losses for Scenario 1

2. ***With DG, without Load Growth for LC co-simulation***

For this scenario, there are a total of 16 buses consisting of 4 generator buses, and 13 load buses, just as obtainable with the DC co-simulation. The generator buses have a total committed generation of 33.78MW and 24.12MVAr respectively. The load buses have a total load of 28.70MW and 17.30MVAr respectively. As for the branch data, the buses have a total loss of 5.082MW and 6.82MVAr respectively. The data for voltage profile and power losses for LC co-simulation under scenario 1 is provided in Figure 5.

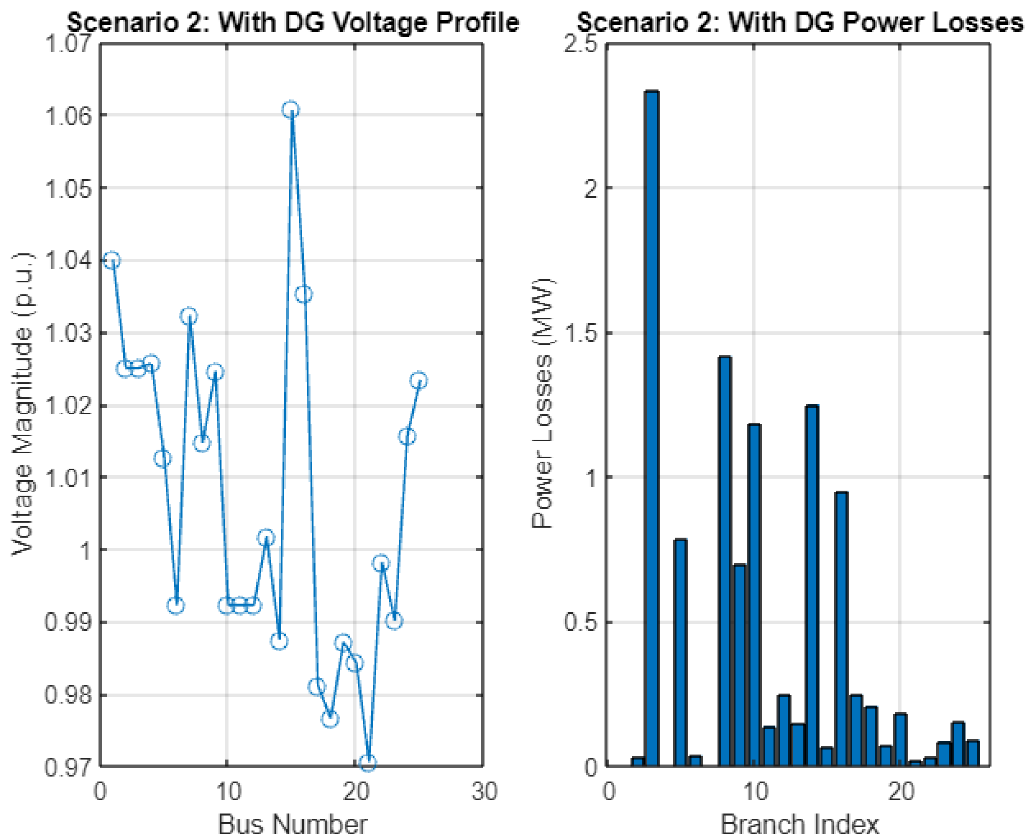

Figure 5: LC voltage profile and power losses for Scenario 1

3. ***With DG, without Load Growth for TC co-simulation***

For TC co-simulation under scenario 2, there are a total of 25 buses, consisting of 4 generator buses, and 16 load buses. The generator buses are 1, 2, 3, and 15 with a total committed generation of 321.72MW and 19.98MVAr. The load buses are bus 5, 6, 8, 13 to 25 with a total load of 315MW and 115MVAr. For branch data, the branch buses have a total loss of 6.723MW and 46.39MVAr. The voltage profile and power losses for TC co-simulation under scenario 1, is graphically illustrated in Figure 6.

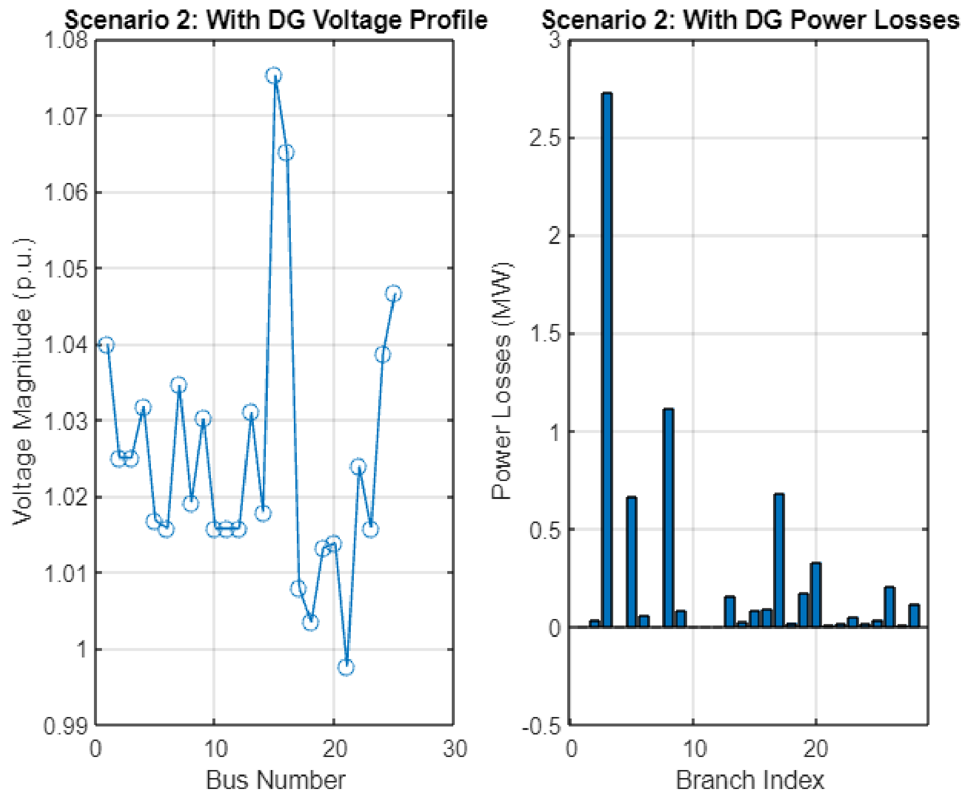

Figure 6: TC voltage profile and power losses for Scenario 1

Scenario 2: DC, LC, TC co-simulation without DG, with load growth (CPF)
For scenario 2, the CPF is implemented to only increase the load without increasing the generator. The essence of this scenario is to understand how the network behaves under systematic load increments without an additional increase in the generator. It is observed that buses 18 and 21 of the distribution section of the network act as the reference buses forming the nose curve, this is because the voltage limitations happen at these buses.

1. ***At 5% load growth***

   For the DC co-simulation technique, CPF terminated after reaching a steady state loading limit in 680 continuation steps, and at 134.8λ for buses 18 and 21. For the LC co-simulation technique, CPF terminated after reaching a steady state loading limit in 527 continuation steps, and at 104.2λ for buses 18 and 21. For the TC co-simulation technique, CPF terminated after reaching a branch flow limit of 150MVA in 79 continuation steps at 15.4λ for bus 18 and 21. Figure 7 is the nose curve comparing the lambda values of DC, LC, and TC at a loading factor of 1.05.

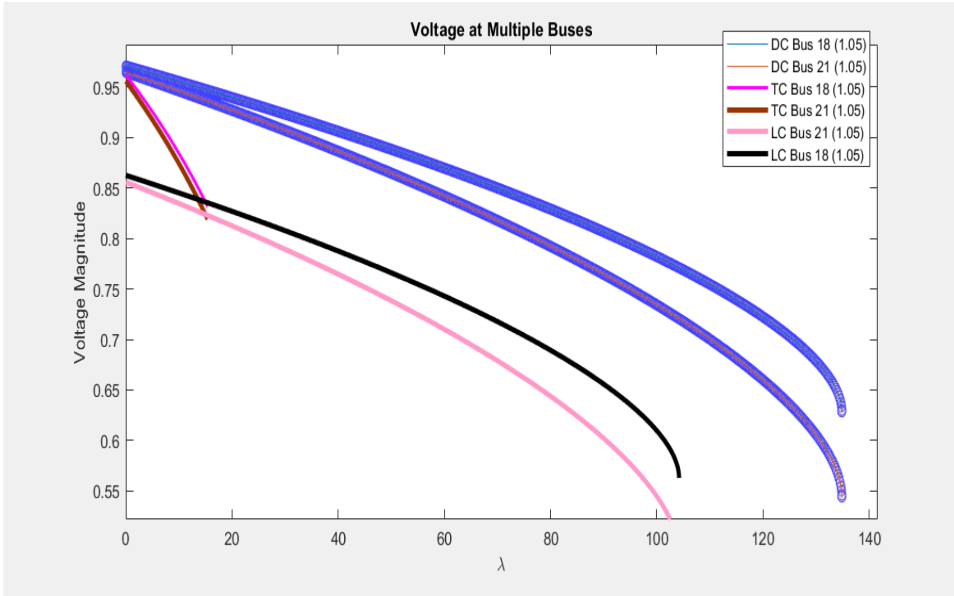

Figure 7: DC, LC, TC nose curves at 5% load growth

Also, the CPF results for load growth DC, LC, and TC co-simulation techniques at 1.05 is illustrated in Figure 8.

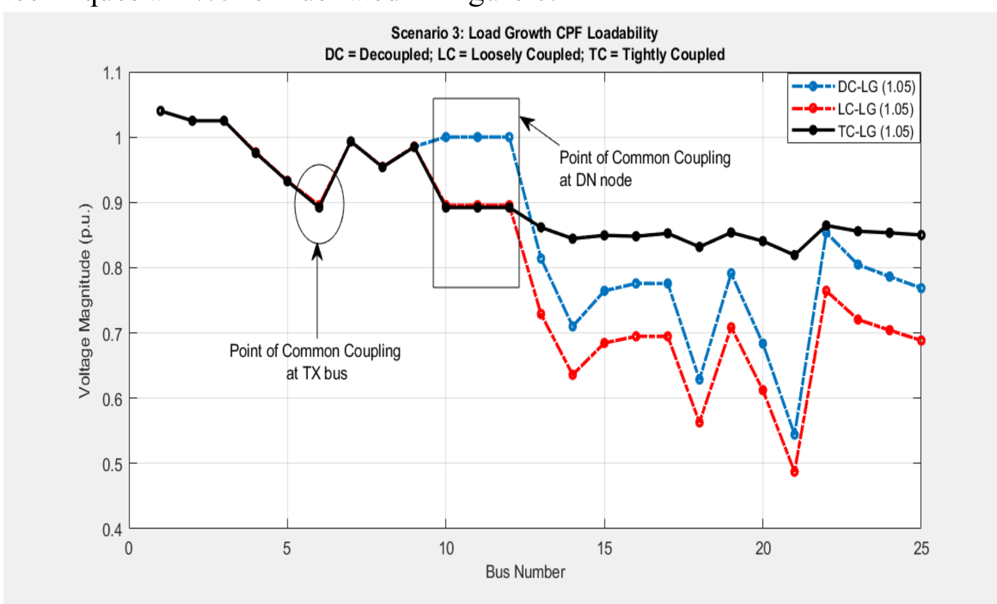

Figure 8: DC, LC, and TC voltage magnitude at 5% load growth

2. ***At 25% load growth***

For the DC co-simulation technique, CPF terminated after reaching a steady state loading limit in 147 continuation steps, and at 26.97λ for buses 18 and 21. For the LC co-simulation technique, CPF terminated after reaching a steady state loading limit in 117 continuation steps, and at 20.84λ for buses 18 and 21. For the TC co-simulation technique, CPF terminated after reaching a branch flow limit of 150MVA in 18 continuation steps at 3.081λ for buses 18 and 21. The nose curve comparing the lambda values of DC, LC, and TC at bus 18 and 21 and at a loading factor of 1.25 is shown in Figure 9.

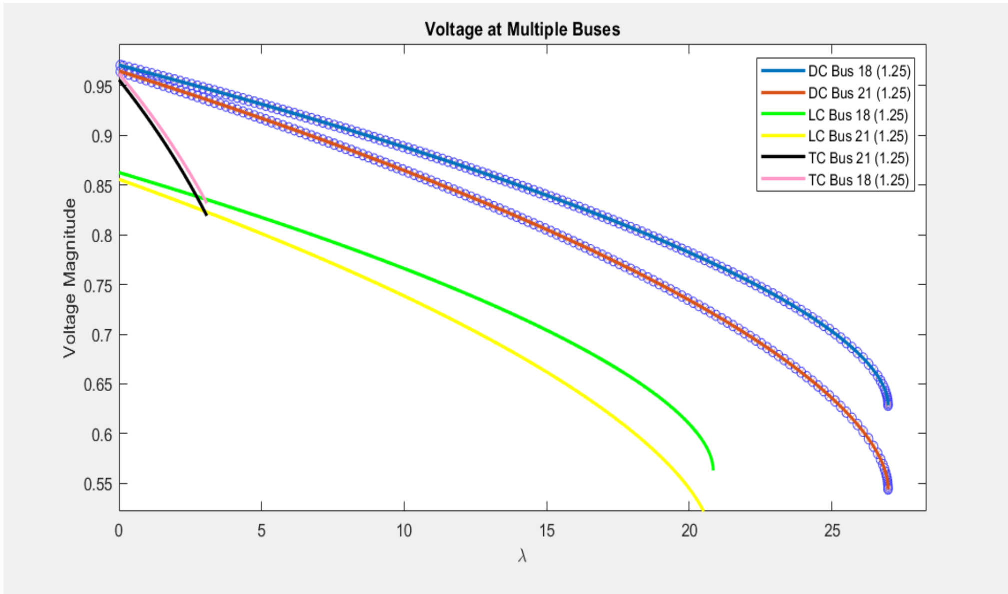

Figure 9: DC, LC, TC nose curves at 25% load growth

The CPF results comparing the load growth of DC, LC, and TC co-simulation techniques at a loading factor of 1.25 is shown in Figure 10.

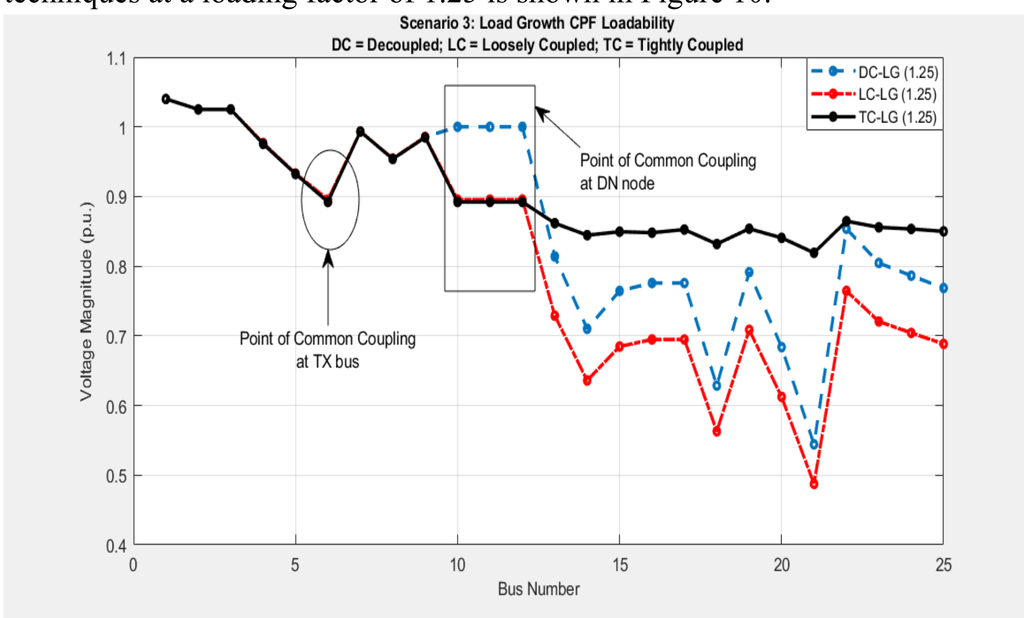

Figure 10: DC, LC, and TC voltage magnitude at 25% load growth

Summary of Findings

1. The DC model is much less accurate in comparison to the LC model. The DC model regularly exhibited an average percentage error in boundary variables that was 20 to 40 times higher than that of the equivalent LC and TC models. Furthermore, in both DC and LC models, the amount of the percentage error in the power demand variable is larger than the magnitude of the voltage at the T&D PCC.
2. The flaws in the LC model are more noticeable when the system is under stress, such as when there is considerable variability in scenarios and severe imbalance in the load. The LC model demonstrates increased inaccuracy when there are changes in scenario variability, and the comparison shows that the degree of load imbalances has a substantial effect on the accuracy of the LC co-simulation.
3. When the load imbalance is multiplied by two, the inaccuracy also doubles, regardless of the scenarios' levels. The errors in the DC and LC model worsen as the number of linked transmission and distribution (T&D) nodes in the integrated T&D system increases. When it comes to larger T&D test systems, using the DC and LC model will lead to much higher level of errors.

Conclusion

This study shows that the stability and performance of an integrated network are considerably impacted by the coupling technique used. It has been shown that the coupling technique which ensures a closer and tighter interaction between the T&D networks improves voltage stability and lower power losses. Upon analysis, the TC coupling technique has this attribute and provides significant benefits compared to the DC and LC techniques. As a result, it is the most suitable method for co-simulating T&D networks. The integration of DG improves network performance by facilitating local generation, tolerating systematic load increase, and enhancing the voltage profile of the network. However, the realization of these advantages relies on strategic placement and effective control mechanisms. The incremental expansion in load hurts the stability and reliability of the network. Noticeable reductions in voltage and power occurred in the network as the load increased from 5% to 25% over the base level. Applying CPF analysis to load growth scenarios revealed crucial thresholds where network performance deteriorated, highlighting the need for meticulous design and incorporation of adaptive monitoring methods. Subsequently, the success of the network depends greatly on the use of efficient coupling methods and adaptive measures. This study thus suggests the following for further research.

1. Studies should aim at expanding and exploring various load growth scenarios, such as region-specific patterns, to understand the impact of sudden changes and

maximum demand periods.

2. Future studies can also focus on analysing long-term trends and seasonal variations in load demand and DER output to develop flexible strategies over different time scales.
3. Future research should include dynamic and non-linear load growth patterns, fluctuations in distributed energy resource (DER) production, and forecasting models to conduct a thorough and complete examination of real-world situations.

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