A Co-simulation Framework for Distribution Network Analysis: Case Study of Hosting Capacity Analysis

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Abstract— This paper presents a co-simulation framework between OpenDSS and MATLAB to execute complex studies on distribution networks. The framework is demonstrated by analysing the hosting capacity on an IEEE 123-node feeder. In addition, this paper also proposes a two-stage approach for distributed generation (e.g. rooftop PV systems) or load (e.g. EV charging) hosting capacity of a distribution network. The first stage computes the maximum hosting capacity of each node and then sets out an upper boundary on node hosting capacity. The second stage computes the overall (i.e. network level) hosting capacity by optimising the hosting capacities of all the nodes. The analysis showed that hosting capacity varies based on the location of DG or demand, and network topology. The presented co-simulation framework can be easily extended to perform any complex studies on modern distribution networks, and this framework can serve as a guideline to develop other co-simulation frameworks (e.g. PowerFactory with Python).

Index Terms--Co-simulation, distribution network, distributed generation, hosting capacity, particle swarm optimisation.
I. INTRODUCTION

Modern distribution networks are increasingly featured with power electronic (PE) interfaced generation and demand due to the rapid development of semiconductor devices (e.g. IGBTs, MOSFETs, SCRs, etc.). From the generation perspective, inverter-interfaced PV systems (e.g. rooftop PV and residential wind generation systems) are seeing much greater penetration, because of which distribution networks have changed their tendency from passive unidirectional power flow systems to active bidirectional power flow systems. From the consumption perspective, traditional low efficient demand is getting replaced by energy-efficient devices at a low-power level (e.g. LED lamps), medium-power level (e.g. desktop PSUs) and high-power level (e.g. EV chargers) [1]. One should note that almost all of the energy efficient loads employ power electronics.

Finally, in the context of the smart grid, the grid infrastructure itself is also being upgraded by replacing the conventional network components with PE-based electric equipment (e.g. FACTSs, HVDCs, solid-state transformers, etc.). Hence, advanced simulation tools are required to analyse the potential (positive or negative) impacts of PE devices on the planning, operation, control and protection of modern distribution networks.

Currently, the openly available distribution test feeders are mainly prepared by the test feeder working group from the distribution system analysis subcommittee (DSAS) and are intended for different types of analysis (e.g. testing new algorithms, short circuit analysis, etc.) [2]. EPRI has developed an open source software (OpenDSS) for modelling the distribution networks, and it also provides the complete data for modelling both EPRI and IEEE test feeders.

When compared with the other commercial power system analysis software, the biggest advantage of OpenDSS is that it is fully open source and can allow the user to control all the network components and simulation modes. The OpenDSS user interface can be accessed either through scripts (with pre-defined syntax) within the executable version of the software or through the Windows Component Object Model (COM) interface. The main benefit of the COM interface is that the OpenDSS engine can be imported into other programming languages, because of which co-simulation with other software is possible. For example, a co-simulation framework is developed between OpenDSS and NI LabVIEW in [3]. In [4], a co-simulation platform of power and communication networks is developed using OpenDSS and OMNet++. In [5] and [6], the co-simulator of OpenDSS and Simulink is developed to achieve a quasi-static time-series simulation by interacting the EMT simulation of specific types of devices (e.g. PV and EV) with the phasor domain simulation of the distribution network.

To further enhance the co-simulation capability of OpenDSS, this paper presents a co-simulation framework between OpenDSS and MATLAB. The paper is organised as follows: Section I briefly reviews the current developments on the co-simulation of OpenDSS with other software. Section II first discusses the main features of the COM interface, followed by a description of the development procedure of the co-simulation framework. Section III demonstrate the co-simulation framework by analysing the hosting capacity of IEEE 123-node test feeder. The main conclusions and future work are summarised in Section IV.
II. CO-SIMULATION FRAMEWORK FOR DISTRIBUTION NETWORK ANALYSIS

In this section, the detailed implementation procedures of the three main types of HC assessment approaches will be given, to be applied in the case study in Section III. For the statistical HC assessment approaches, the streamlined approach is used as an example here, as it is a standardised method implemented in commercial software like CYME, Synergi and Milsoft, and can perform the HC assessment on a system-wide basis with less computational efforts. Regarding the optimisation-based HC assessment approach, the implementation procedure of the proposed two-stage approach will be discussed in this section.

A. Features of the COM Interface in OpenDSS

To get access to OpenDSS within a different software (e.g. Matlab), the first step is to activate the OpenDSS engine and create the COM interface within the software. There are generally two different approaches to communicate with OpenDSS through the COM interface. The first approach is to use the text function of the COM interface, where the commands and results can be sent to and received from OpenDSS through normal scripts. The second approach is to use the Direct DLL to directly create or modify grid network components, simulation modes, etc., through the accessible handles of all network components and simulation modes provided by the COM interface. As the text function of the COM interface has the inherent advantage of defining multiple parameter values of a circuit component through a single text command, it is suitable for defining new network components while the Direct DLL can be effectively applied for modifying certain values of any given component or receiving simulation results from the OpenDSS engine.

Currently, EPRI employs a script-based approach with predefined text commands to model the distribution networks. The script-based approach is not only inconvenient for modifying network configurations, but also requires a lot of time to model the networks, especially when the network possesses several nodes and lines. Moreover, the script-based approach required to develop the generalised text command framework for conventional network components as different component categories require different commands. Finally, studies like HC assessment may require several (even thousands) of power flow runs with different network configurations and component settings. Modification of the network configurations and component settings through the text command of the COM interface in external loops (coded in other software, e.g. MATLAB) can significantly reduce the computational time.
B. Co-simulation Framework between OpenDSS and Matlab

The proposed co-simulation framework can be divided into two phases: the initial network building phase and network modification phase. The first phase focuses on modelling the base network with no modification; and separates the network data from the text commands (Figure 1). The network data has a specific data structure (Table I) which consists of information from several network components: generators, loads, line types, lines, transformers and taps, capacitors, reactors, etc. Once the network data structure is prepared, it will be sent to the text command framework which further guides the OpenDSS engine to build the network components (mentioned in the data format). The text command framework is basically made up of predefined text commands as mentioned in the OpenDSS manual [7].

![Figure 1. The network model development of the co-simulation framework.](image)

**TABLE I. The Network Data Structure for the Co-simulation Framework.**

<table>
<thead>
<tr>
<th>Reactors</th>
<th>name</th>
<th>phases</th>
<th>bus1</th>
<th>bus2</th>
<th>r</th>
<th>x</th>
<th>normamps</th>
<th>emergamps</th>
</tr>
</thead>
<tbody>
<tr>
<td>LineCodes</td>
<td>name</td>
<td>npasses</td>
<td>nmatrix</td>
<td>xmatrix</td>
<td>cmatrix</td>
<td>units</td>
<td>normamps</td>
<td>emergamps</td>
</tr>
<tr>
<td>Lines</td>
<td>name</td>
<td>phases</td>
<td>bus1</td>
<td>bus2</td>
<td>length</td>
<td>units</td>
<td>linecode</td>
<td>geometry</td>
</tr>
<tr>
<td>Loads</td>
<td>name</td>
<td>phases</td>
<td>bus1</td>
<td>bus2</td>
<td>kv</td>
<td>model</td>
<td>conn</td>
<td>kw</td>
</tr>
<tr>
<td>TXs</td>
<td>name</td>
<td>phases</td>
<td>windings</td>
<td>buses</td>
<td>transfo</td>
<td>vreg</td>
<td>band</td>
<td>ppratio</td>
</tr>
<tr>
<td>caps_control</td>
<td>name</td>
<td>capacitor</td>
<td>element</td>
<td>terminal</td>
<td>type</td>
<td>ppratio</td>
<td>crratio</td>
<td>onsetting</td>
</tr>
<tr>
<td>generators</td>
<td>name</td>
<td>phases</td>
<td>bus1</td>
<td>kv</td>
<td>model</td>
<td>conn</td>
<td>kw</td>
<td>kvar</td>
</tr>
</tbody>
</table>
The second phase modifies the base network as per the requirements of a given study which basically involves the modification of existing components or adding new components. This paper employs direct DLL approach to modify the parameters of interest as this approach is much faster than the script-based approach. The steps in implementing the DLL approach are mentioned in Fig. 2. The complete details of direct DLL library are available in the OpenDSS manual [7].

III. THE APPLICATION OF THE TOOL: CASE STUDY ON THE HOSTING CAPACITY ANALYSIS OF DISTRIBUTION NETWORK

This section demonstrates the application of the proposed co-simulation framework by analysing the hosting capacity (HC) of a distribution network (IEEE 123-node distribution feeder, Fig. 2) using the proposed framework. Hosting capacity is defined as the maximum amount of low carbon technologies (LCTs) that can be connected to a distribution network without adversely affecting the network operation [8]. It becomes increasingly important to assess the HC of a distribution network due to the increased proliferation of DGs and EVs in the distribution network.

The existing literature on HC analysis has mainly focused on two aspects: 1) HC assessment for a given network configuration [9]-[11] and 2) HC assessment considering network reconfiguration and/or reinforcement [12]-[14]. In either of the cases, similar methods are employed which can be generally categorised into stochastic approaches [11] and optimisation-based approaches [10]. Both approaches require thousands of power flow executions, especially when the considered network involves several nodes and lines. Being extremely fast in executing power flow simulations, OpenDSS with the proposed co-simulation framework (Section II) can calculate the HC more effectively than analyzing HC in OpenDSS alone.
A. Description of the IEEE 123 Node Feeder

The IEEE 123-node test feeder (Fig. 3) supplies a total demand of 3.49 MW and 1.82 MVar at the nominal voltage of 4.16 kV. The loads are of both single-phase and three-phase and modelled as constant power, constant current, and constant impedance types. The customer connection points are marked with blue dots in Fig. 3. The upstream network beyond the substation transformer (at Node 150) is modelled as a voltage source (4.16 kV, 60 Hz). The network also consists of four voltage regulators and four shunt capacitors to regulate the voltage. The network also has eleven switches (with two states: Open and Closed) in order to reconfigure the network during fault and contingency conditions. This paper, using the proposed co-simulation framework, computes the HC of IEEE 123-node feeder under three different topologies. The reason for this is to analyse the impact of network topology and meshes on HC. The status of the switches (Table II) is selectively changed to prepare a radial topology (T1), a slightly meshed network (T2) and a heavily meshed network (T3).

<table>
<thead>
<tr>
<th>Topology</th>
<th>Status of Switches</th>
<th>Topology feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>S7</td>
<td>Open</td>
<td>Radial</td>
</tr>
<tr>
<td>S8</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>Closed</td>
<td>Slightly meshed</td>
</tr>
<tr>
<td>T2</td>
<td>Closed</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>Closed</td>
<td>Heavily meshed</td>
</tr>
</tbody>
</table>

Note: except S7 and S8, all the other switches are closed for all three topologies.
B. Two Stage Approach for Hosting Capacity Assessment

HC of a distribution network depends on several attributes of the network: location and number of phases of DG and/or load, load type, number of DGs and loads, DG type, etc. Hence, the following assumptions are made during the analysis: a) the load nodes in the base network are considered as the target nodes to place DG or new load; b) the DG or new load has the same number of phases available at target nodes; c) the DG or new load is modelled as a constant power type with a power factor of 0.98; d) the time variation of original loads is ignored.

The operational security limits (node voltages and cable/overhead line ampacity limits) are mentioned in Table III. This paper employs a metaheuristic optimisation solver (Particle Swarm Optimisation, PSO) to maximise the aggregated amount of DG and/or new loads. The solver is implemented in Matlab and integrated with the developed co-simulation framework. The detailed mathematical formulation and implementation of a PSO solver can be found in [15].

<table>
<thead>
<tr>
<th>Types</th>
<th>Criteria</th>
<th>Violation limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node voltages</td>
<td>Undervoltage or overvoltage at customer nodes</td>
<td>≤0.95pu or ≥1.05pu</td>
</tr>
<tr>
<td>Line loading</td>
<td>Maximum line loadings of all the underground and overhead lines</td>
<td>800A for the main network branches and 400A for the other service cables</td>
</tr>
</tbody>
</table>

As mentioned, HC can be influenced by the number, size and location of DGs and/or new loads [16]. Most of the existing approaches select the target nodes stochastically which basically results in several combinations of network topologies and settings. Hence, the existing approaches require heavy computational time to calculate the HC. To overcome this issue, this paper presents a two-stage optimisation approach to calculate the HC. While the first stage calculates the node-by-node hosting capacity ($HC_{ni}$), the second stage calculates network level hosting capacity using the results from the first step. It is incorrect to say that the aggregated HC of all nodes represents overall HC because the network cannot host aggregated HC without violating the operational security constraints.

The main objective of the first stage is to maximize the HC of each target node (1) one at a time. The number of target nodes decides the number of optimization problems that to be solved in the first stage. The rating of DG/load and the tap setting of voltage regulators are considered as the decision variables for the first stage optimisation. The rating of DG/load and the tap setting of voltage regulators are considered as the decision variables for the first stage optimisation. The upper and lower limits are chosen as 0-10MW for DG and new loads, and 0.9-1.1 pu for the tap settings. The result of the first stage optimisation is an upper boundary for a node level HC.

\[
\begin{align*}
\min F &= 1/P_{ni} + pf_v \times \sum_{k=1}^{NB_l} (V_{nk} - V_{nk,li})^2 \\
&+ pf_v \times \sum_{k=1}^{NB_u} (V_{nk} - V_{nk,ul})^2 + pf_l \times \sum_{k=1}^{NL} (I_{nk} - I_{nk,l})^2
\end{align*}
\]
Where: \( P_{ni} \) is the rated active power of the added DG or load at node \( i \); \( p_{fV} \) and \( p_{fI} \) are the penalty factors for violating voltage and ampacity limits (set to 1e5); \( N_{Bl} \) and \( N_{Bu} \) are the number of nodes that violate the lower boundary and upper boundary limits; \( N_L \) is the number of lines that violate the ampacity limits; \( V_{nk,ll} \) and \( V_{nk,ul} \) are the lower and upper voltage limits for node \( k \) (0.95 pu and 1.05 pu); \( I_{nk,l} \) is the ampacity limit for line \( k \) (Table III).

Once node level HC is calculated for all the nodes, the second stage computes network level HC by solving a single optimisation problem (2). The second stage optimisation problem is formulated to include node level HC (computed in stage 1) for all the target nodes. A coefficient \( k_c \) is applied to node level HCs and is optimised using PSO. Where: \( k_c \) represents the maximum allowed percentage of the power that can be taken from or injected into the network at a specific target node without affecting the HC of other target nodes and without violating operational security constraints. In addition to \( k_c \), tap settings of voltage regulators are also considered as decision variables. The co-simulation framework for both stages is implemented in MATLAB (Fig. 4). For the ease of analysis and demonstration, HC analysis is performed separately for DG and load growth in the following sections.

\[
\sum_{k=1}^{N_{Bl}} (V_{nk} - V_{nk,ll})^2 + p_{fV} \times \sum_{k=1}^{N_{Bu}} (V_{nk} - V_{nk,ul})^2 + p_{fI} \times \sum_{k=1}^{N_L} (I_{nk} - I_{nk,l})^2
\]

Where: \( N \) is the number of target or candidate nodes.

Figure 4. The implementation approach of the co-simulation framework for the purpose of HC analysis.
C. The HC Assessment with DG Penetration

This section, using the proposed HC assessment approach (Section III-B), computes DG hosting capacity of IEEE 123-node feeder under three different topologies (T1, T2 and T3). The node-by-node HCni under three topologies is plotted in Fig. 5, while the heatmap of node-by-node HC for specific topology is plotted in Fig. 6. The results indicate that HCni is highly location dependent, some nodes having HCni values as low as 0.5W (e.g. node 64 and node 66) and some other nodes having HCni values as high as 9MW (e.g. node 47). When compared with radial topology (T1), the meshed topologies (T2 and T3) sees marginal improvements (e.g. node 35 and 47). This is basically due to the closing of a switch (S7) enabling the power flow between nodes 151 and 300. Based on HCni values, network level HC (HCT) is calculated (Table IV). The results again show that meshed topologies see a marginal increase in HCT when compared to the radial topology.

<table>
<thead>
<tr>
<th>Topology</th>
<th>$k_r$ (%)</th>
<th>HC$_r$</th>
<th>Default demand</th>
<th>Total losses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MW</td>
<td>MVar</td>
<td>kW</td>
</tr>
<tr>
<td>T1</td>
<td>5.20</td>
<td>6.775</td>
<td>1.376</td>
<td>3.530 1.944 82.80</td>
</tr>
<tr>
<td>T2</td>
<td>4.74</td>
<td>6.905</td>
<td>1.402</td>
<td>3.534 1.946 86.75</td>
</tr>
<tr>
<td>T3</td>
<td>4.68</td>
<td>6.923</td>
<td>1.406</td>
<td>3.531 1.944 83.70</td>
</tr>
</tbody>
</table>

Figure 5. The node-by-node $H_{Cni}$ of the test feeder for DG.

Figure 6. The heatmap of the node-by-node $H_{Cni}$ of the IEEE 123 node test feeder (topology T3) for DG.
D. The HC Assessment with Load Growth

Similarly, the HC assessment is also carried with load growth (e.g. EV penetration). While Fig. 7 and Fig. 8 represent the node-by-node $H_{C_{ni}}$ under three different topologies, overall hosting capacity ($H_{C_{T}}$) for a heavily meshed topology (T3) is mentioned in Table V. The node-by-node HCs are varying between 0.3MW to 1.3MW. It was observed that some nodes (e.g. nodes 39, 43, 49, 62, 64 and 65) in meshed topology see a very marginal improvement in $H_{C_{ni}}$. Moreover, the losses in meshed topologies are 6% higher than in radial topology.

<table>
<thead>
<tr>
<th>Topology</th>
<th>$k_r$ (%)</th>
<th>$H_{C_{r}}$ (MW)</th>
<th>Default demand (MW)</th>
<th>$MVar$</th>
<th>Total losses (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>2.52</td>
<td>1.406</td>
<td>0.285</td>
<td>3.483</td>
<td>1.915</td>
</tr>
<tr>
<td>T2</td>
<td>2.51</td>
<td>1.430</td>
<td>0.290</td>
<td>3.493</td>
<td>1.922</td>
</tr>
<tr>
<td>T3</td>
<td>2.52</td>
<td>1.447</td>
<td>0.294</td>
<td>3.497</td>
<td>1.925</td>
</tr>
</tbody>
</table>
IV. CONCLUSIONS

This paper highlighted the requirement for advanced simulation tools to perform complex studies on modern distribution networks. It suggested that the co-simulation framework is the best approach to develop complex algorithms on top of the distribution network power flow engines. In this context, this paper presented a co-simulation framework between OpenDSS and MATLAB, and the framework is demonstrated by analysing the hosting capacity of a distribution network. Moreover, this paper also proposed a two-stage optimisation approach to calculate the network level hosting capacity. The results indicate the practical applicability and significance of the proposed approach.

The proposed framework can be easily extended to execute other studies focused on distribution networks (e.g. renewable penetration and curtailment analysis, demand-side-management, network planning, etc.). Although the presented framework has employed only one metaheuristic solver (PSO), other metaheuristic solvers (e.g. evolutionary computation, swarm intelligence, etc.) and even (gradient independent) conventional solvers can be easily integrated into the co-simulation framework. Hence, the proposed framework can be used as a guideline to develop co-simulation frameworks as well as performing other studies using this framework. The future work will focus on the application of the proposed co-simulation framework to perform other studies as well as developing similar co-simulation frameworks between other simulation software (e.g. DlgsILENT Power Factory and Python).
REFERENCES


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