A Combined Transmission and Distribution System Co-Simulation Framework for Assessing the Impact of Volt/VAR Control on Transmission System

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Abstract—Conventionally, analysis tools used by utility engineers are designed to work for a single domain i.e. either for transmission or for distribution system analysis. With continued growth of demand side participation in energy transaction, it is imperative that analysis is carried out using an approach that captures the coupling between the transmission and distribution systems. A framework for this combined analysis of transmission-distribution system is developed in this paper using open-source transmission and distribution system analysis tools. A novel synchronization architecture is used to design a co-simulation framework with tight coupling protocol to study the impact of bulk Volt/VAR control on transmission system. Feasibility of developed approach is demonstrated using combined transmission and distribution simulation of multiple IEEE 13-node distribution feeders interfaced to small and medium scale transmission systems, namely, IEEE 9-bus and IEEE 118-bus test systems.

Index Terms—Co-Simulation, Volt/VAR optimization

I. INTRODUCTION

Increased participation of demand side resources have posed a challenge to the conventional way of separately analyzing transmission and distribution systems. For instance, consider the transient stability analysis of a system. Transient stability studies are conducted using positive sequence simulation of transmission network, where the loads at a bus are equivalenced. During a transient event, depending on the the voltage and frequency ride through settings of the inverter connected roof top solar installations on the distribution side, the roof top PV installations may go offline and come back online in a span of minutes. The conventional analysis using transmission network with equivalenced load will not capture this phenomenon. This leads to non-realistic analysis scenarios which could ultimately prove detrimental to secure operation of power grid.

A combined transmission and distribution system simulation framework would allow the operators to conduct analysis on a realistic platform. This would help understand the coupling between the transmission and distribution system better. This in turn would help operate the power grid with improved security and efficiency. Volt/VAR control (VVC) applications would benefit immensely from the proposed approach, where the effect of VVC is not just studied on a single distribution feeder, but on a platform designed to capture the coupling between the different components i.e. transmission system, and other distribution feeders connected through the transmission system.

A. Literature Review

Power system literature on co-simulation can be broadly classified into two categories: 1) a generic co-simulation approach and 2) a co-simulation approach that is specific to combined simulation of transmission and distribution systems. The proposed approach falls under category 2. Hence, only the literature that is relevant to this category is presented.

Reference [1] presented a Schur complement based approach to co-simulation using the Nordic transmission system. Equivalenced loads in the original system were replaced by distribution networks and comparative study was presented. In co-simulation approaches, a subset of the DSs interfaced to TS actively contributes to the system dynamics during a disturbance event while other DSs are latent. A switching algorithm to selectively choose the active DSs while maintaining the accuracy of the simulation was presented in [2].


Reference [7] developed a message passing interface between one or more instances of GridLAB-D and a smart grid simulator. The developed platform was then used for demand response. GridSpice, a cloud based deployment of GridLAB-D coupled with Matpower was introduced in [8], [9]. Reference [10] used an iterative co-simulation between equivalents of transmission and distribution system for optimizing reactive power balance between transmission and distribution grid.

The following unique contributions are made in this work,

- A new architecture for synchronization between the different instances of distribution and transmission system simulators is introduced.
- We demonstrate the applicability of the proposed co-simulation framework for assessing the impact of VVC
on transmission system through the use of tight coupling scheme to obtain consistent boundary conditions.

Assessing the impact of VVC on transmission system depends on the ability of the developed framework to capture the coupling between transmission and distribution system and also between the different distribution systems coupled through the transmission system. For instance, the total load seen at the transmission side for a given distribution feeder affects the voltage at point of common coupling (PCC) of other TS-DS interfaces. This in turn affects the set-points of controllable devices at the substation and also the devices along the feeder. This tangible coupling effect can be captured through the proposed co-simulation approach. This in turn allows assessment of VVC impact on transmission system.

The rest of the paper is organized as follows. The necessary theory for the proposed co-simulation approach is developed in Section II. This includes a detailed discussion on interface protocol. Interface architecture is developed in Section III. Results and discussion cover Section IV, where feasibility of the developed platform for assessing bulk impact of VVC on transmission system is demonstrated through a small sized IEEE 9-bus transmission system and a medium sized IEEE 118-bus test system, where one or more loads are replaced with IEEE 13-node distribution system feeder. Conclusions are drawn in Section V.

II. COMBINED TRANSMISSION AND DISTRIBUTION CO-SIMULATION FRAMEWORK

A. Modeling and Information Exchange

A brief introduction to power system modeling is given in this section, which is followed by discussion on the special treatment of boundary buses and their associated variables within this co-simulation framework.

Quasi-static simulation of the power system is concerned with solving for complex voltages that satisfy the complex power requirement at all buses - a powerflow study. This requires solution to algebraic equations represented generically as in (1).

\[ 0 = g(y) \]  

Recall that the lumped loads in transmission system simulator (TSS) are to be replaced with a distribution feeder modeled in distribution system simulator (DSS). Hence, every load bus that is to be replaced with a distribution system becomes a boundary bus, and the associated variables form boundary variables, while the difference in these variables seen on the TSS and DSS side are referred to as boundary conditions. The iteration protocol for these boundary conditions is discussed in detail in Section II-B.

Let us rewrite (1) to describe the co-simulation approach as given in (2).

\[ 0 = g(y, r(z)) \]  

In a similar way, the algebraic equations that represent the DSS can be written as in (3).

\[ 0 = h(z, s(y)) \]  

where,

\[ s(y) = \begin{bmatrix} \bar{V}_{DS,a} \\ \bar{V}_{DS,b} \\ \bar{V}_{DS,c} \end{bmatrix} \]  

\[ r(z) = \overline{S}_{TS,+} \]  

An illustrative schematic of the information exchange process is shown in Fig. 1. Equations (2) - (5) allow interfacing positive sequence TSS to 3-phase DSS.

B. Tightly Coupled Interface Protocol

At each discrete time instance of TSS simulation, \( s(y) \) is computed from the solution of that time-step and passed to DSS. The exchanged information is used to set the voltage magnitude value of DSS at PCC using (6).

\[
\begin{bmatrix}
\bar{V}_{DS,a} \\
\bar{V}_{DS,b} \\
\bar{V}_{DS,c}
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\cdot
\overline{S}_{TS,+}
\]  

DSS then solves (3), from which current injection at PCC is obtained as given in (7).

\[
\bar{T}_{DS} = 
\begin{bmatrix}
\bar{T}_{DS,a} \\
\bar{T}_{DS,b} \\
\bar{T}_{DS,c}
\end{bmatrix}
\]  

The obtained value of \( \bar{T}_{DS} \) is then used to compute \( \bar{T}_{TS} \) as follows:

\[
\begin{bmatrix}
\bar{T}_{TS,0} \\
\bar{T}_{TS,+} \\
\bar{T}_{TS,-}
\end{bmatrix} = \frac{1}{3}
\begin{bmatrix}
1 & 1 & 1 \\
1 & a & a^2 \\
1 & a^2 & a
\end{bmatrix}
\cdot
\begin{bmatrix}
\bar{T}_{DS,a} \\
\bar{T}_{DS,b} \\
\bar{T}_{DS,c}
\end{bmatrix}
\]  

Where \( a = 1\angle 120 \). The current injection at PCC obtained from (8) is then used to obtain positive sequence complex power injection at PCC as:

\[
\overline{S}_{TS,+} = 3 \cdot \bar{V}_{TS,+} \cdot \bar{T}_{TS,+}^\prime
\]  

The obtained value of \( \overline{S}_{TS,+} \) is used as the total power requirement for the said load bus. The tightly coupled protocol
Start Transmission (TS) and distribution system (DS) simulator. 

- Initiate server on TS
- Accept client connections from GridLAB-D
- Set TS-DS boundary bus voltage on DS based on TS solution
- Send sync point from TS to DS
- Compute DS solution
- Send boundary bus complex power injection from DS to TS
- Tight coupled
- Consistent boundary condition?
- Yes
- No
- Move forward to next time-step
- Repeat until simulation end time
- Yes
- Adjust loading on TS

Figure 2: Overview of the proposed approach

<table>
<thead>
<tr>
<th>TS</th>
<th>DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SERVER</td>
<td>CLIENT</td>
</tr>
<tr>
<td>CLIENT</td>
<td>SERVER</td>
</tr>
</tbody>
</table>

Figure 3: Single instance

repeats the process iteratively until consistent boundary conditions are obtained. Boundary condition consistency is checked using (10).

\[ |r(z)^{i} - r(z)^{i-1}| \leq \epsilon \]  

(10)

Overview of the proposed approach is shown schematically in Fig. 2.

III. INTERFACE ARCHITECTURE

The TSS used in this work is of static nature. Matpower [11] is used as the static TSS. GridLAB-D [4] is used as the DSS. To understand the rationale behind the proposed architecture and the advantages that it provides, we first provide a brief overview of the internal workings of GridLAB-D. The input file, i.e., the glm file, that describes the system is first read by GridLAB-D, following which, all the required objects are set up and the requested computation is executed by solving the resulting equations, and the program then terminates. In the server mode, GridLAB-D follows the same approach with the exception of the following behavior. The program sets up a server at a default or user-defined port. This port allows the user to set/get object properties. When an object property is changed, GridLAB-D recomputes the distribution system equations to get the solution for the new condition. The object states, i.e., the solution, is then updated and the process is repeated.

In the co-simulation framework, one of the challenging tasks as noted by [12], is the synchronization between the different simulators. To this end, a synchronization server, as described in Fig. 3, is added on the TSS side. Each of these instances of GridLAB-D will run in the server mode on a dedicated port, to which the TSS client would connect to and set/get relevant information. In a similar manner, all of the synchronization clients on GridLAB-D would connect to the TS server for synchronization calls. A schematic representation of this operation for single and multiple instances of GridLAB-D connecting to TSS is shown in Fig. 3 and 4 respectively. It is worth mentioning that Matpower was run in octave - an open source alternative to Matlab. All the communication between Matpower and GridLAB-D happens through sockets using TCP.

IV. RESULTS AND DISCUSSION

The test scenarios evaluated in this section serve two purposes, 1) showcase the flexibility of the proposed approach - Sections IV-B and IV-C illustrate this, 2) Evaluate the impact of VVC applied on multiple distribution feeders as seen from the transmission system - Section IV-D demonstrates this.

A. Test Systems

Two transmission side test systems, namely, IEEE 9-bus and IEEE 118-bus test systems are used in this work. The IEEE 13-node feeder is used as the distribution system. The IEEE 13-node distribution feeder is modified by adding a capacitor bank.
The algorithm that is implemented in Gridlab-D for VVC is based on [13]. The design philosophy of [13] is reduction of demand and/or energy losses as well as improvements in the voltage profile. The VVC optimization problem is set to maximize loss reduction. Depending on the implemented VVC algorithm the phenomenon studied will differ, for instance, keeping the voltages within bounds as opposed to load reduction. In this case, due to the VVC algorithm used in this work, reduction in load demand and energy loss results are presented.

B. Case 1: All Loads Replaced With Distribution Feeder

For this test case, the IEEE 9-bus test system is used as the transmission network. The loads at buses 5, 6 and 8 are replaced with IEEE 13-node distribution feeder. Each distribution feeder is run by invoking an instance of GridLAB-D. Therefore, three separate GridLAB-D instances are invoked in server mode on different ports. These ports serve as the communication gateway between transmission network simulator (Matpower) and GridLAB-D.

Each of the three loads are scaled appropriately to allow interfacing. A typical load curve as seen at ERCOT as given in [14] is used as the daily load shape for each distribution feeder. For sake of simplicity, all load instances were assumed to have the same load shape with different loading values. As discussed previously, the presented approach captures the coupling between the transmission and distribution systems and also between the different distribution systems coupled through the transmission network - a distinguishing feature compared to other approaches.

The time frame for this quasi-static simulation was discretized at hourly intervals. Two simulation scenarios were run. First, the case without Volt/VAR control was run using the developed combined transmission and distribution system co-simulator. Then, the Volt/VAR control scheme developed in [13] implemented in GridLAB-D [4] is utilized to run VVC for the same scenario. The result of this comparison scenario is shown in Fig. 6a. Here, the combined effect of VVC on the transmission system is presented i.e. the total load seen by the transmission system at the three TS-DS interfaces at load buses 5, 6 and 8 is shown. The total load seen by transmission system using VVC is lower than that of the case with no control.

C. Case 2: Subset of Loads Replaced With Distribution Feeder

This test case is designed to showcase the ability of the developed framework to simulate only a selected subset of load buses as distribution feeders while the other load buses are represented as a constant power loads as is customary in transmission network powerflow studies. Specifically, load buses 11 and 82 of the IEEE 118-bus test case were replaced with appropriately scaled IEEE 13-node test feeders.

As in Section IV-B, two scenarios, with and without VVC were run. The comparison result for real power demand at load bus 11 is shown in Fig. 6b. A lower total load demand can be observed for the scenario with VVC.

Through Sections IV-B and IV-C, it can be seen that the proposed framework is flexible enough to accommodate varying level of modeling detail. For instance, a simulation to study transmission system impact as a result of VVC application on a subset of distribution feeders can be performed in the proposed framework. In a similar manner, a detailed study that requires all loads to be replaced with distribution feeders in order to assess impact of VVC on transmission system can also be performed.

D. Case 3: Evaluating Impact of VVC on Bulk Power System

The premise of this work centers around the ability of the proposed framework to accurately capture the coupling between the transmission and distribution systems thereby...
Table I: TRANSMISSION SYSTEM ENERGY REDUCTION DUE TO VVC

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total energy requirement (MWh)</th>
<th>Energy Reduction (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no-control</td>
<td>7948.87</td>
<td>7915.87</td>
</tr>
<tr>
<td>VVC</td>
<td>7910.31</td>
<td>7887.55</td>
</tr>
<tr>
<td></td>
<td>7901.55</td>
<td>7868.65</td>
</tr>
<tr>
<td></td>
<td>7922.38</td>
<td>7889.44</td>
</tr>
<tr>
<td></td>
<td>7902.98</td>
<td>7870.07</td>
</tr>
</tbody>
</table>

capturing the impact of VVC on bulk power system. This test case is used to demonstrate that. To this end, five different test scenarios with different load curves are used to compare the amount of energy reduction achieved by applying VVC on all three distribution feeders connected to the IEEE 9-bus transmission system. Graphical results of the five test scenarios is shown in Fig. 6c. Numerical results for the same is presented in Table I.

E. Computational Performance

Computational performance of the proposed approach can be split into three parts, Matpower solution time, Gridlab-D solution time and communication and parsing overhead. From our experiments, we found that communication and parsing portion of the algorithm took the most time. As the software matures the portion of time spent in communication and parsing can be expected to come down. Since this is an iterative scheme, higher number of iterations results in increased computational time. For instance the 9-bus test case took 4-9 iterations to converge to a tolerance of $10^{-4}$ PU while 118-bus test case took 3-5 iterations to converge to the same tolerance value. These results were computed over the 24 hourly dispatches for a given day. Mean solution times for the 24 dispatches were 5.45 seconds and 2.91 seconds for 9-bus and 118-bus test systems respectively.

V. Conclusions

A framework for combined simulation of transmission and distribution system was developed. A novel and efficient architecture for message passing between the heterogeneous simulators was developed. The developed framework was then used to assess bulk Volt/VAR control impact on transmission system using multiple IEEE 13-node distribution feeders interfaced to IEEE 9-bus and 118-bus test systems.

Such assessment is made possible by the proposed framework to capture the coupling between the transmission system and the distribution system. In addition, the coupling between the different distribution feeders, connected through the transmission network is also captured. This allows for a realistic analysis platform under which detailed system studies can be performed. As future work, we plan to explore the VVC problem in greater detail with regards to complexity of the VVC algorithm and analyze the computational requirement with regards to increased problem size.

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References