SGcoSim: a co-simulation framework to explore smart grid applications

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Article Info

Article history:

Received Aug 26, 2024
Revised Jul 21, 2025
Accepted Sep 14, 2025

Keywords:

Co-simulation
Demand response
Smart grid
Volt/VAR optimization
Wide area monitoring

ABSTRACT

Under the smart grid concept, new novel applications are emerging. These applications make use of information and communication technology (ICT) to help the electrical grid run more smoothly. This paper introduces SGcoSim, a co-simulation framework that integrates power system modeling and data communication to enhance smart grid applications. The framework utilizes OpenDSS for simulating power distribution components and OMNeT++ for communication modeling, enabling real-time peer-to-peer interactions via wireless sensor network (WSN) techniques. Virtual cord protocol (VCP) is deployed for efficient routing and data management within the field area network. SGcoSim's functionality is demonstrated through two case studies: a phasor measurement unit (PMU)-based wide-area monitoring system and an integrated volt/VAR optimization with demand response (IVVO-DR) application. Results indicate significant reductions in energy consumption and power losses, highlighting the capabilities of SGcoSim.

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1. INTRODUCTION

To improve power networks, the smart grid integrates a significant number of elements such as distributed generators, communication technologies, computer and intelligence, sensing, and control. New applications such as smart metering infrastructure, demand response, and integration of distributed energy resources have evolved as a result of the smart grid. Emerging smart grid applications have the potential to optimize the operation of the power network, resulting in a reduction in energy demand. Using phasor measuring units (PMUs) to perform real-time wide-area monitoring is a crucial strategy to respond quickly to network changes and avoid major problems such as power outages and damage. The basic purpose of Volt/VAR optimization is to run the various Volt/VAR control devices as efficiently as possible in order to save energy and keep the voltage within acceptable limits.

There are two components of Volt/VAR control: Volt control and VAR control. To reduce power usage, the Volt control employs the conservation voltage reduction (CVR) idea. It lowers the voltage at the end user, which saves power usage. It is assumed that when the voltage is low, the devices will consume less power. The voltage at the load tap changer is controlled by CVR. VAR control attempts to reduce power losses by injecting or absorbing reactive power. Capacitor banks were once the only way to add or remove reactive power. Inverters and other power electronics can now be utilized to inject or absorb reactive power from PV systems and storage elements. In this article, it is assumed that the system includes capacitor banks, photovoltaics (PVs), and storage devices that can inject or absorb reactive power.

Demand response (DR) is one method to reduce demand during periods of excessive demand. It shifts a portion of the load from high-demand to low-demand periods. The periods of high and low demand are not constant. On a working day, for example, the early evening and early morning can be high-demand periods. This will eliminate the need for corporations to build new power plants to meet peak demand.

In recent years, there has been a lot of studies done on the issue of integrating power systems and information and communication technology (ICT) simulators, with the majority of the solutions concentrating on the usage of specific smart grid principles in distribution systems, such as distributed generation, aggregated loads, and microgrids. Most of these co-simulators used predefined delays to model data communication networks, and it is crucial for delay-sensitive applications that co-simulators truly replicate the complete network stack. Additionally, there are not many co-simulators that incorporate sophisticated optimization techniques inside the co-simulator.

The work presented in [1] focuses on protection approaches and wide-area measurements and control. It provides a simple approach to simulate data communication networks. In [2] the integration of OMNeT++ with PowerFactory, a commercial power system analysis software, is detailed. In [3] the co-simulation framework couples open distribution system simulator (OpenDSS) with OMNeT++, using the hypertext transfer protocol for the data exchange between the two components. Because of the importance of communication in smart grids, the combination with OMNeT++ is also planned for modular simulation of complex systems (MOSAIK) [4], [5]. The paper [6] presents methods to evaluate critical lines and nodes in cyber-physical power systems (CPPS) from three perspectives: network information, properties, and structure. The authors in [7] have introduced a hybrid synchronization scheme using synchrophasors and generic object-oriented substation event (GOOSE) messages for rapid and automatic reconnection in power systems. It leverages direct PMU communication to reduce latency and costs, coordinating AVR and turbine governor control. Real-time simulations validate the method's effectiveness and interoperability. A nother CPPS testbed has been presented in [8] that employs co-simulation to analyze optimal power flow (OPF) strategies with distributed energy resources (DERs). It dynamically optimizes power network losses and operational costs, adapting to varying DER penetration levels. Experiments on an IEEE 39-bus system confirm that the approach enhances grid stability and efficiency. The work in [9] presents a co-simulation framework integrating real-time simulators (real-time digital simulators (RTDS), Typhoon, OPAL real-time (OpalRT)) and network simulator (NetSim) to evaluate smart grid communication performance. It examines throughput, delay, and jitter in private and public network scenarios using a Conseil International des Grands Réseaux ?lectriques (CIGRE) benchmark system. Results highlight stable throughput but increased delay and jitter in public networks, underscoring private networks' suitability for delay-sensitive smart grid operations. Some frameworks have been proposed to study cyber-attacks [10]–[12]. An overview of some co-simulation frameworks for smart grid analysis is given in [13].

In general, these frameworks lack the integration of explicit optimization tools and do not provide the capability to explore techniques derived from wireless sensor networks. The proposed framework, SGcoSim, makes it possible to explore approaches that require optimization. Additionally, it allows testing approaches from Wireless sensor networks in the field of smart grid.

2. SGCOSIM

In this section we introduce SGcoSim framework, which is an extension of SGsim [14]. Two types of networks should be considered when dealing with smart grid applications, namely the electricity network and the communication network. The electricity network builds the existing components of the power grid such as loads, DER and storage. OpenDSS [15] is chosen to simulate the electricity network while OMNeT++ [16] is employed to simulate the data communication network. In the previous implementation we employed component object model (COM) to enable the communication between OMNeT++ and OpenDSS. COM is a binary-interface standard that allows different software components to communicate and interact, regardless of the programming language used to create them. It enables code reuse and modular design as well as inter-process communication (IPC).

In the updated implementation, in addition to COM server, we employed object linking and embedding (OLE) to perform the communication between the two simulators. OLE is built on top of COM and allows embedding and linking to documents and objects between applications. This way, we do not need a dynamic-link library (DLL) to enable the communication and therefore it is easier to install. INET Framework [17] is used to build the data communication network. It has well-tuned components such as TCP/IP, Ethernet and 802.11. The fact that the nodes in the power grid are almost static makes the smart grid a potential application for WSNs. We adopted approaches from WSN for routing and data management in the grid. We used VCP for routing and data management inside the electricity network. VCP is a lightweight and scalable routing protocol that Constructs a virtual linear topology (a "cord") over a distributed network. It assigns each node a unique virtual coordinate or position along this cord. Additionally, it uses these coordinates for efficient routing, neighbor discovery, and resource location.

2.1. Electricity network

The electricity network should be supplied as a script to the simulator. It contains the different components and the interconnections between these components (topology). In addition to conventional power grid components such as cables and transformers, OpenDSS has the ability to simulate several types of loads, supplies, and storage systems. It provides several models for the load such as constant impedance, constant P and Q, and ZIP load models. Moreover it provides simulation models for renewable energy sources such as a PVs. OpenDSS allows different solution modes from very low time step size (micro seconds), that is required to capture the transient signals, to yearly simulation experiments.

2.2. Data communication network

The nodes in the network are capable of data look-up, routing and storing. Any component of the power grid (e.g., a House) is equipped with a wireless node which enables it to communicate with other nodes. Furthermore, it is possible to place nodes inside the network to insure network connectivity. This makes it possible to build a relatively cost-effective field area network owned by the electricity company. This way, electricity distribution companies can install smart grid applications to enhance the operation of the power grid. VCP [18], [19] is a distributed hash table (DHT)-based routing and data management protocol for WSN. It combines data look-up and routing in a protocol that offers peer-to-peer communication. VCP maintains a virtual cord that connects all nodes in the network and allows data pieces to be inserted into sensor nodes and retrieved. Using the `put` command, the Controller can store its position inside the network. This way, other nodes can retrieve this information using the `get` command. All nodes use the same hash function to map data into the cord. For instance, if the hash value of `Controller` is 0.41, then the data corresponding to the controller should be stored at node 0.43 which is the succeeding node of 0.41. Now, if another node needs this information, then it uses the same hash function to retrieve the required information (e.g., `House6` needs the position of `Controller`).

2.3. Simulator components

The simulator components consist of:

a. Power grid model: A script feeds OpenDSS with information on the various components of the power grid and their interconnections. It includes transmission lines, transformers, generators, and loads.
b. Load (OpenDSS side): A text file contains the load value at different time steps.
c. Load (OMNeT++ side): A program that represents the behavior of the load (e.g., House). It is possible to connect/disconnect, scale up/down, or change the power factor of the load at run-time.
d. Supply (OpenDSS side): This file provides a time series of the production of a DER.
e. Supply (OMNeT++ side): A program that represents the behavior of a supply (e.g., PV). Similar to the load component, this component makes it possible to connect/disconnect, scale up/down, or change the power factor of the supply at run-time.
f. SGSimInterface: it enables the communication between OpenDSS and OMNeT++.
g. Solver: This component synchronizes the operation between the power simulator (i.e., OpenDSS) and the data communication simulator (i.e., OMNET++). The communication between the simulators is done using COM and OLE interface.
h. Device: It represents power grid devices (e.g., batteries, switches, and capacitor banks). This component can be controlled over the COM interface.
j. Sensor: It collects data from a single component (e.g., bus, load, or DER) and sends it to other components. For example, the phasor measurement unit (PMU) is a sensor that uses simulated TCP/IP packets to send

data to the PDC interface. The data is formatted according to a standard (e.g., IEEE c37.118) so that real components (e.g., phasor data concentrator (PDC)) can receive the packets.

k. Controller: This component controls the operation of different units within the grid. It changes the set points of these units by solving an optimization problem. It sends an xml file that describes the grid to a solver and then receives the new set points and then adapts these set points. It controls the voltage, active and reactive power of elements such as PV, battery and On load tap changer (OLT).

l. PDC interface: This element is an interface between the simulator and a real measurement unit such as OpenPDC [20]. For such an application, the simulation should be run using a real-time mode.

2.4. Phasor measurement units

A phasor measurement unit (PMU) is a device that measures power system-related quantities at a high rate (e.g., 120 times per second). It determines the amplitude and angle of a power quantity like voltage or current. It also monitors frequency, temperature, and other factors. A high-precision timer is used to stamp the readings. GPS is commonly utilized to produce a precise time stamp for this purpose. The measured values are encoded using a standard (for example, IEEE c37.118) and then communicated across data communication networks.

2.5. A phasor data concentrator

A phasor data concentrator (PDC) gathers information from a variety of sources, including PMUs and other PDCs. It creates a system-wide measurement set by correlating phasor data by time-tag. As a result, it is critical to stamp the reading with a precise time. PDCs examine the phasor data for various quality issues and add relevant flags to the linked data stream. It looks for disturbance flags and saves data files for later examination. It also keeps track of the total measurement system and displays and records the results. A direct connection to a SCADA or an energy management system (EMS), which can be used to monitor and regulate things like electricity, is one of the special outputs available. The open-source phasor data concentrator (openPDC) is a system for managing, processing, and responding to fast-changing phasor data streams. The openPDC, in particular, is capable of handling any sort of data that can be described as time-stamped measured values. These measured values are simply quantitative amounts acquired at a source device. They are also known as points, signals, events, time-series values, or measurements. Measurement types include frequency, current, and voltage. With the help of additional sensors, we can measure temperature and humidity. A precise time stamp is taken when a value is measured, commonly using a GPS clock. The value is then streamed to the openPDC, where it can be time-aligned with other incoming measurements, allowing an action to be taken on a large slice of data that was all measured at the same time.

2.6. IEEE c37.118

In SGcoSim, the IEEE c37.118 standard has been implemented. The standard describes how synchronized phasors in power systems should be measured. It contains both a method for quantifying the measurement and tests to confirm that it is accurate. A data transmission protocol is also established. There are various message formats for transmitting this data in a real-time system. Synchrophasor measurements must be precisely synced to UTC time. The system must be able to receive time from a highly reliable source, such as the global positioning system (GPS), according to the specification. All message frames begin with a 2-byte SYNC word (0xAA and 8 bits that indicate the frame type), followed by a 2-byte FRAMESIZE word, and a 2-byte IDCODe word. A timestamp made up of a four-byte second of the century. A check word (CHK), which is a CRC-CCITT ends each frame. In this CRC-CCITT, the generating polynomial $X16 + X12 + X5 + 1$ with a starting value of (hex FFFF) is employed. SYNC is an acronym for ”synchronization.” The first word is sent first, followed by the check word. Phasor and frequency values can be transmitted in either a 16-bit integer or a 32-bit floating-point format. Implementing this standard allows existing software, such as the phaser data concentrator, to be integrated. Figure 1 displays the data that OpenPDC receives from a PMU. It also enables the exploration of methodologies that require real-time data.

2.7. Optimization tools

One of the smart grid’s primary goals is that it makes the operation among different entities more efficient. This goal can be achieved using optimization techniques. In the SGcoSim framework, it is possible to contact a server to solve an optimization problem. The optimization problem should be written in a modeling language such as GAMS. then an xml file can be sent to a server such as NEOS SOLVERS [21]. It is also possible to integrate optimization tools such as NLopt [22] and lpSolve [23].

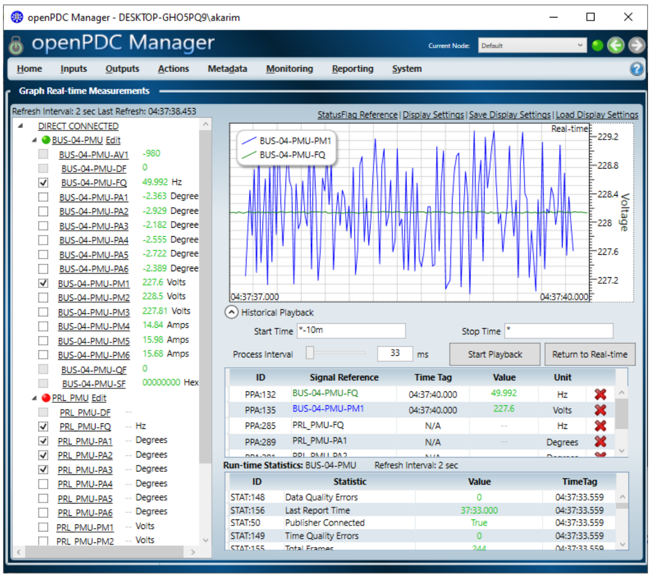


Figure 1. Screenshot of OpenPDC manager

3. CASE STUDIES

The following subsections present two case studies considered in this study. The first case study demonstrates how our tool can be utilized to explore real-time applications. The second case study illustrates the detailed use of an optimization framework to enhance the operation of the power grid.

3.1. Wide area monitoring

Wide area monitoring consists of a set of measurement devices that provide the control central with information in real-time to operate the grid reliably. This is important during disturbances and dynamic conditions. This information can be utilized to provocatively perform the required steps to avoid problems in the grid such as outages. PMUs collect and send it to PDCs. SGcoSim can be used to study approaches that require real-time data, e.g. power quality related approaches. For these applications, the simulator should run in real-time mode.

3.2. Integrated Volt/VAR optimization and demand response (IVVO-DR)

SGcoSim creates loads based on the baseline load profile at the start of a simulation experiment. A central component can collect the essential data for a given application using communication capabilities, and the controller can then transmit commands to the various elements to operate the network properly. Volt/VAR optimization can be utilized to optimize the voltage profile using the available VAR resources. Low voltage levels can be maintained here, resulting in a reduction in power usage. Consequently, power losses will be decreased, as will overall energy usage. Simultaneously, we must make the most of the PVs. As seen in (1), the goal of the optimization problem is to reduce power demand and loss while maximizing PV utilization for T time steps and N buses.

$$min \sum_{t=1}^{T} \{Losses(t)\delta t + \sum_{i=1}^{N} (P_G(t,i)\delta t - P_S(t,i)\delta t)\} \tag{1}$$

Where $Losses(t)$ is the power losses at time t. $P_G(t,i)$ is the power generation on bus i at time t and $P_S(t,i)$ is the power from the solar panels. SGcoSim creates loads based on the baseline load profile at the start of a simulation experiment. A central component can collect the essential data for a specific application using the communication capabilities, and then the controller can process it. Several limitations apply to this optimization issue. As seen in (2) and (3), the first restriction is the power balance at each bus. Equations (2) and (3) represent active and reactive power values respectively.

$$P_G(t,i) + P_S(t,i) + P_D(t,i) - P_C(t,i) - P_L(t,i) - P_E(t,i)$$

$$= \sum_{k=1}^{N} v(t,i)v(t,k)(G_{ik}cos(\theta(t,i,k)) + B_{ik}sin(\theta(t,i,k))) \tag{2}$$

$$Q_G(t,i) + Q_S(t,i) - Q_L(t,i) - Q_E(t,i) + Q_C(t,i) + Q_B(t,i)$$

$$= \sum_{k=1}^{N} v(t,i)v(t,k)(G_{ik}sin(\theta(t,i,k)) - B_{ik}cos(\theta(t,i,k))) \tag{3}$$

The value of the reactive power generation at bus I is represented by $QG(t,i)$. The active and reactive power from the solar system are represented by $PS(t,i)$ and $QS(t,i)$. Active and reactive load are represented by $PL(t,i)$ and $QL(t,i)$. The battery power charge and discharge are represented by $PC(t,i)$ and $PD(t,i)$. The battery reactive power is $QB(t,i)$. Active and reactive elastic loads are represented by $PE(t,i)$ and $QE(t,i)$. The reactive power caused by a capacitor bank is $QC(t,i)$. The voltage at bus I is $v(t,i)$. The real and imaginary components of the admittance from bus I to bus k are Gik and Bik, respectively. The phase shift between buses I and k is $theta(t,i,k)$. The loads at the dwellings are modeled as ZIP loads using the parameters described in [24]. The ZIP model depicts a load's change (with voltage) as a composite of three forms of constant loads: Z, I, and P, which stand for constant impedance, constant current, and constant power, respectively. The current active and reactive loads are given by the equations (4) and (5) as a function of the current voltage (V). The design active and reactive power are represented by the constants $P0$ and $Q0$, respectively. The design voltage is $v0$.

$$P_L(t,i) = P_0(t,i)\left[Z_P\left(\frac{v(t,i)}{v_0}\right)^2 + I_P\left(\frac{v(t,i)}{v_0}\right) + P_P\right] \tag{4}$$

$$Q_L(t,i) = Q_0(t,i)\left[Z_Q\left(\frac{v(t,i)}{v_0}\right)^2 + I_Q\left(\frac{v(t,i)}{v_0}\right) + P_Q\right] \tag{5}$$

Equation (6) represents the equation of solar panel active and reactive power.

$$P_S(t,i)^2 + Q_S(t,i)^2 \leq (S_{S_i}^{max})^2 . \tag{6}$$

The inverter's design imposes a restriction on reactive power.

$$-S_{S_i}^{max}sin(\phi) \leq Q_S(t,i) \leq S_{S_i}^{max}sin(\phi) . \tag{7}$$

The energy losses are shown in (8).

$$Losses(t) = \frac{1}{2}\sum_{i=1}^{N}\sum_{k=1}^{N} G_{ik}(v(t,i)^2 + v(t,k)^2 - \qquad 2v(t,i)v(t,k)(cos\theta(t,i,k)))$$

The value of the voltage at the costumer side must be within the standardized limits. The following equation guarantees that the costumer voltage value doesnt go beyond the acceptable limits.

$$v_{min} \leq v(t,i) \leq v_{max} \tag{8}$$

The energy balance at the battery can be expressed as

$$E(t+1,i) = E(t,i) + \eta P_C(t,i)\delta t - \frac{P_D(t,i)\delta t}{\eta} , \tag{9}$$

where $E(t,i)$ is the energy inside the battery at bus i at time t. The relation between the active and reactive power with respect to the battery can be written as in (11) and (12).

$$P_C(t,i)^2 + Q_{bat}(t,i)^2 \leq (S_{bat_i}^{max})^2 \tag{10}$$

$$P_D(t,i)^2 + Q_{bat}(t,i)^2 \leq (S^{max}_{bat_i})^2 \tag{11}$$

The reactive power is limited by the power design factor.

$$-S^{max}_{bat_i} \leq Q_{bat}(t,i) \leq S^{max}_{bat_i} \tag{12}$$

The elastic load should be run in a specific period (from T1 to T2). For instance, an EV is considered as an elastic load EL_i and should be ready at 7 AM.

$$\sum_{i=T1}^{T2} P_E(t,i) = EL_i \tag{13}$$

The capacitor bank can be either on or off. So we need a binary variable $xc(t,i)$ to represent the relation between the installed capacitor bank CAP_i and the injected reactive power $Q_C(t,i)$.

$$Q_C(t,i) = xc(t,i)CAP_i \qquad\qquad xc(t,i) \in \{0,1\} \tag{14}$$

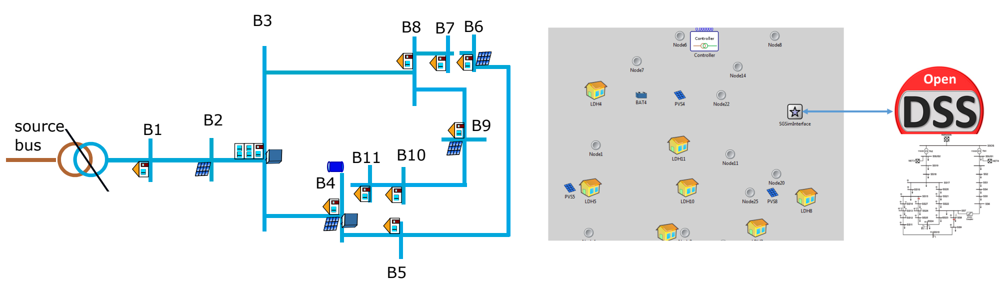
This optimization is done in two stages. In the first stage, we use a long optimization horizon (e.g. 24 hours) to find the optimal periods to run the elastic loads. Then in the second stage, we run the optimization problem during the operation of the system with a short optimization horizon to find the optimal set points of the different components such as reactive power from the PVs, batteries, and capacitor banks. The control variables are the voltage at the transformers, reactive power from the PVs, batteries, and capacitor banks, charging and discharging time of the batteries, and the run time of the elastic loads. Each component measures and reports its power usage to the controller in order to apply this technique. The controller creates and transmits an optimization problem to a solver. The results are returned by the solver. After receiving the results, the controller adjusts the voltage at the load tap changer and sends the set points to the PVs, capacitor banks, elastic loads, and batteries.

4. EVALUATION

In this section we evaluate the two case studies. We used a modified version of the network presented in [25] as shown in Figure 2(a).

4.1. Data communication network

We deployed 55 nodes in an area of size 800 m × 2,400 m. After the initialization of the cord, each node uses `put` to store its location on the cord. This way, any two nodes can communicate in a peer-to-peer way. The nodes send the power and voltage to the controller. The controller sends an XML file with the optimization problem to a solver and when it gets back the solution, it sends commands to the different components. A partial view of the network is shown in Figure 2(b).



(a) (b)

Figure 2. The test power grid and communication networks (a) the one-line diagram of the power grid and (b) partial view of the network in OMNeT++. Each component such as a house or PV is equipped with a wireless node. Additional nodes are deployed to maintain the network connectivity

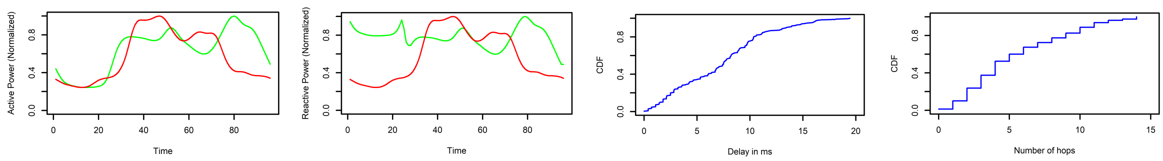
4.2. Power grid

The network consists of loads and PVs (solar panels), energy storage units, capacitor banks, and an on-load tap changer (OLTC). Standard load profiles, which give the active power demand of families as well as other types of loads, are used to produce demand and supply (e.g., companies and factories). To describe the stochastic behavior of a single load, values are sampled from these profiles and superimposed with stochastic functions. Some load profiles and delay traces are shown in Figure 3. Typical active and reactive load profile are shown in Figures 3(a) and 3(b). The green line represents a residential load profile, while the red line represents a commercial load profile. We assume that 2% of the load at each bus is elastic. We defined the following electricity network configuration:

a. Case 0 : 4 PVs, 20 kVA each, 2 storage systems 10 kw/13kWh each, a capacitor bank of size 10 kVA.
b. Case 1 : This case is similar to case 0, but in this case we have 11 PVs, i.e., a 20 kVA PV at each bus.
c. Case 2 : This case is similar to case 1, but in this case we increased the PV to 40 kVA PV at each bus.
d. Case 3 : This case is similar to case 1, but we increased the load by 25.

At the beginning, we look at the data communication network and explore two important metrics, namely delay and number of hops. Figure 3(c) shows the cumulative distribution function (CDF) of the end-to-end delay in ms. About 80% of the packets need less than 10 ms to reach the destination.

Figure 3(d) shows the CDF of the number of hops that packets traverse to reach the destination. Most packets (about 80%) need less than 10 hops to reach the destination. During all simulation experiments, data delivery rate was 100%.



(a) (b) (c) (d)

Figure 3. Load profiles and end-to-end delay (a) normalized active power load profile for residential (green) and industrial (red), (b) normalized reactive power load profile for residential (green) and industrial (red), (c) CDFs of the end-to-end delay and (d) the path length

Figure 1 shows a screenshot of OpenPDC, which receives data from a PMU. The data has been sent using the IEEE37.118 standard. OpenPDC can collect and store the data so that can be used for analysis. Critical data can be analyzed quickly to detect instabilities in the network and react early to prevent serious problems. To explore the integration of Volt/VAR and DR, five different operating scenarios are defined as:

a. Scenario 0 (Static configuration): The static configuration does not use the reactive power capabilities of PVs and storage units and it holds the load tap changer at 415 volts (line-to-line).
b. Scenario 1 (VAR optimization): In this scenario we exploited the reactive capabilities of the different elements such as PVs and storage systems.
c. Scenario 2 (CVR optimization): In this scenario we changed the voltage at the OLTC to reduce the power consumption in the electricity network.
d. Scenario 3 (IVV optimization): This scenario combines scenario 1 and 2.
e. Scenario 4 (IVVO-DR): this scenario adds DR to scenario 3.

Figure 4 compares the power at the transformer of the different scenarios with static configuration. The solid red line shows the power consumption of scenario 0 (static configuration) and the dashed green line shows the power consumption of scenarios 1 to 4. As can be seen in Figure 4(a), the difference between static configuration and VAR optimization is minimal. In particular at low demand periods, CVR Optimization has more power savings compared to VAR optimization, as can be seen in Figure 4(b). Integrating CVR and VAR approaches together (IVV optimization) makes it possible to reduce the power also at higher demand periods as can be seen in Figure 4(c). For the IVVO-DR scenario, the controller has moved some load from the high demand period to the lower demand period when including DR and the savings are even more clear as can be seen in Figure 4(d).

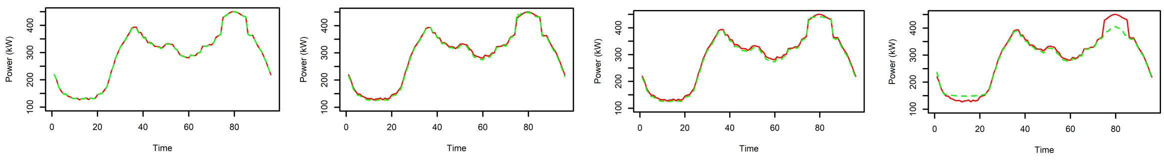


Figure 4. Power at transformer with 4 PVs, 20 kVA each, for the scenario static configuration (solid red lines) and the four optimization scenarios (dashed green lines) VAR optimization (a) VAR optimization, (b) CVR optimization, (c) IVV optimization, and (d) IVVO-DR

Table 1 summarizes the energy consumption and losses of the different scenarios during 24 hours. VAR Optimization has the lowest energy losses, but the reduction of demand is not high compared to CVR Optimization. CVR has the highest energy losses and even higher than the static scenario. This is due to the fact that lower voltage leads to higher power losses. Integrating CVR and VAR (IVV Optimization) leads to better results regarding both; demand and losses. Now integrating DR (IVVO-DR) leads to even more savings and a lower peak demand. We also explored the voltage at the buses. As can be seen in Figure 5, applying VAR optimization improves a little bit the voltage profile, i.e., it increases the voltage at the end-user side due to the VAR injection in particular when the load is high as can be seen in Figure 5(a). CVR optimization tries to keep the voltage as low as possible to reduce the power consumption based on the ZIP load model as can be seen in all other scenarios in Figures 5(b), 5(c), and 5(d).

Table 1. Results: demand and losses of the different scenarios

Approach	Demand (kWh)	Losses (kWh)
Scenario 0 (Static configuration)	6985.8	364.2
Scenario 1 (VAR)	6974.6	339.2
Scenario 2 (CVR)	6905.7	375.4
Scenario 3 (IVVO)	6861.8	352.6
Scenario 4 (IVVO-DR)	6849.8	343.2

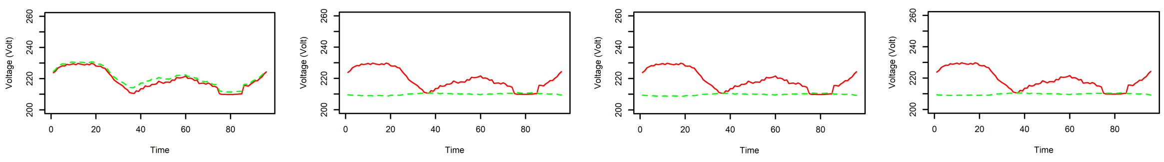
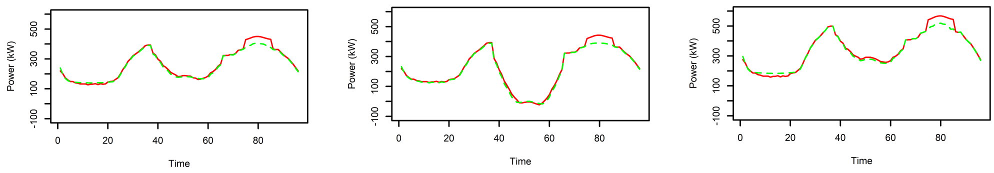


Figure 5. Voltage at bus 5 with 4 PVs, 20 kVA each, for the scenario static c onfiguration (solid red lines) and the four optimization scenarios (dashed green lines) (a) VAR optimization, (b) CVR optimization, (c) IVV optimization, and (d) IVVO-DR

Figures 6 compares the power at the transformer of IVVO-DR with the static scenario for cases 1, 2, and 3 when increasing the capacity of the solar system. For all cases, IVVO-DR has a lower power consumption in particular at the evenining as can be seen in Figures 6(a), 6(b), and 6(c). Table 2 summarizes the energy demand and losses for these cases during 24 hours. Figure 7 shows the voltage for the different cases. Increasing the PV increases the voltage as can be seen in Figure 7(a). Static Configuration can lead to over-voltage when the generation is high and the load is low as can be seen in the middle of the day in Figure 7(b). This happens because of the reverse power flow that results from the high generation of the PVs. To enable the reverse power flow, the voltage at the PV side should be higher than at the transformer. This means, the voltage should be higher than 415 volt. Now reducing the voltage at the transformer can alleviate the over-voltage problem, nevertheless it leads to another problem at the high demand periods. Therefore, static configuration is not suitable for the current/future power grid. We increased the demand by 25%. The voltage at bus 5 is shown in Figure 7(c). Here we see the under-voltage problem during two periods.

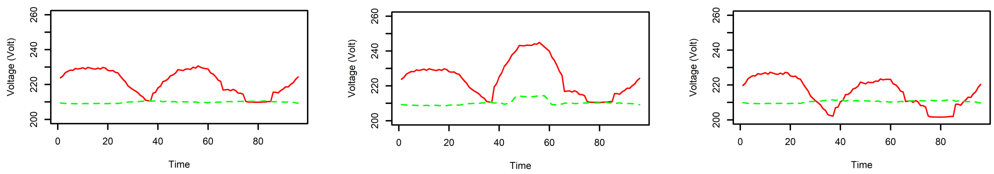


(a) (b) (c)

Figure 6. Power at transformer for the scenario static configuration (solid red lines) and scenario IVVO-DR (dashed green lines) and the three cases (a) 11 PVs with 20 kVA each, (b) 11 PVs with 40 kVA each, and (c) 11 PVs with 20 kVA each and additional 25% load

Table 2. Results: demand and losses of the different cases

Approach	Demand (kWh)	Losses (kWh)
Case 1 (Static Configuration)	6273.1	305.8
Case 1 (IVVO-DR)	6095.8	281.8
Case 2 (Static Configuration)	5241.6	296.3
Case 2 (IVVO-DR)	5015.4	272.1
Case 3 (Static Configuration)	8172.6	516.6
Case 3 (IVVO-DR)	8028.5	461.7



(a) (b) (c)

Figure 7. Voltage at bus 5 for the scenario static configuration (solid red lines) and scenario IVVO-DR (dashed green lines) and the three cases (a) 11 PVs with 20 kVA each, (b) 11 PVs with 40 kVA each, and (c) 11 PVs with 20 kVA each and additional 25% load

5. CONCLUSION

In this paper, we introduced SGcoSim, a co-simulation framework designed to explore smart grid applications. We proposed the use of WSN approaches to establish a field area network, enabling the integration of various smart grid applications. The VCP was employed to facilitate efficient peer-to-peer communication among grid components. We demonstrated some capabilities of SGcoSim through two distinct smart grid applications. The first application involved wide-area monitoring, which relies heavily on real-time communication. In the second application, we IVVO with DR, termed IVVO-DR, to effectively reduce energy consumption and power losses in an electricity distribution network. Our results indicate that combining Volt/VAR optimization with demand response significantly decreases both the overall power demand and system losses. Although demonstrated with these examples, SGcoSim is versatile and can be adapted to study various other smart grid applications and challenges, including cybersecurity threats and additional operational issues. As future work, we will work on extending the SGcoSim framework to investigate cybersecurity issues such as false data injection, denial-of-service, and spoofing attacks.

ACKNOWLEDGEMENT

The authors would like to acknowledge the German Federal Ministry for Education and Research (BMBF) and the Palestinian Ministry of Education and Higher Education (MOEHE) for the financial support under PALGER2015-34-046 (CSFPPG).

FUNDING INFORMATION

This work is partially funded by German Federal Ministry for Education and Research (BMBF) and the Palestinian Ministry of Education and Higher Education (MOEHE) for the financial support under

PALGER2015-34-046 (CSFPPG).

AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Not applicable

ETHICAL APPROVAL

Not applicable

DATA AVAILABILITY

- The data that support the findings of this study are available from the corresponding author, [AA], upon reasonable request.

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