A CO-SIMULATION TOOL FOR ACTIVE DISTRIBUTION NETWORKS

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ABSTRACT

A co-simulation tool for active distribution networks is presented that links Open Distribution System Simulator with ns-2 Network Simulator software for conjunct simulations of electrical and communication systems. The tool allows examining the effects of communication delays and failures during the operation of active distribution networks, with distributed energy resources controlled by a distribution management system through wireless communication links.

I. INTRODUCTION

The development of the future energy system will be based on planning and management of the distribution system in accordance with the active distribution network (ADN) concept. As stated by CIGRE Working Group C6.11 - Development and operation of active distribution networks – an ADN is defined as a network which has systems in place to control a combination of distributed energy resources (DERs), and where distribution system operators (DSOs) have the possibility of managing the electricity flows using a flexible network topology [1]. This definition intrinsically refers to a smart network that involves automation and controls to ensure that the power distribution system not only remains within its operating limits but it is also managed in an optimal way.

The ADN operation requires the extensive use of information and communication technology (ICT) and innovative control systems in order to enable the management of DERs and of the expected growing number of electric vehicles. In ADN context, therefore, ICT is not a simple add-on of the electrical system, but its availability and efficiency is essential to the operation of the entire power distribution system. In fact, the electric system will be managed and controlled by means of the ICT network that will allow a bidirectional exchange of large amount of data, creating a keen interdependence between the electric system and the ICT system. Within the ICT system, as well as within the electric system, there will be components that are subjected to faults (antennas, routers, modems, etc.) and malfunctioning, and these undesired events, may reflect upon the power system operation as system reliability reduction, or as service interruption [2].

Co-simulation is then essential for analyzing different issues related to ADN, since it allows simulating the power distribution system and the ICT system behavior simultaneously, taking into account the interdependences among the two systems.

Co-simulation platform features depend on the ADN issues of interest, and they are related to the time span of the power system phenomena under study, as classified in table I.

Table I. Power system phenomena

Power system phenomena		Time span
fast	Fast acting protection	10 ms -100 ms
	Network fault management	100 ms -1 s
slow	Network overload (current/voltage)	1 s – 10 s
	Frequency control	10 s -10 min

According to Tab. I, it is clear that when a fast dynamics operation phenomena is studied, the impact on power system operation of communication latencies/delays and of ICT temporary faults are the main aspects in co-simulation analysis. The co-simulator has to simulate the whole series of latencies (measurement and state estimation, signal transmission to DMS, DMS analysis and decision, signal transmission to actuator, actuator intervention), and compare the results with the admissible phenomenon duration. In fast dynamics operation (e.g. network failure management and reconfiguration) intervention should be complete before 100 ms ÷ 1 s. On the other hand, when studying slow dynamic phenomena, an ICT temporary failure should not compromise the operation of electric system whereas the latency is not as important as in fast dynamic studies. Nevertheless, co-simulation is important for supporting decision when planning ADN, verifying correct operation of the network, performing reliability studies with probabilistic methods. The present paper is focused on slow dynamic application. A tool that permits examining the consequences of communication delays and failures in the active distribution network operation is presented and the impact of communication packet size on smart grid applications is proposed.

II. CO-SIMULATION TOOL

II.1 General architecture

The architecture for the joint power and ICT systems simulation has been developed by the authors in [3] and used in the present paper. This co-simulation tool adopts *Open Distribution System Simulator* (OpenDSS) as power system simulator, whereas *Network Simulator 2* (ns-2) is employed as discrete event simulator for the communication system. Both software products are free and open source. MATLAB® works as run time interface (RTI) between OpenDSS and Network Simulator version 2 (ns-2). Fig. 1 shows schematically the architecture of the co-simulation tool.

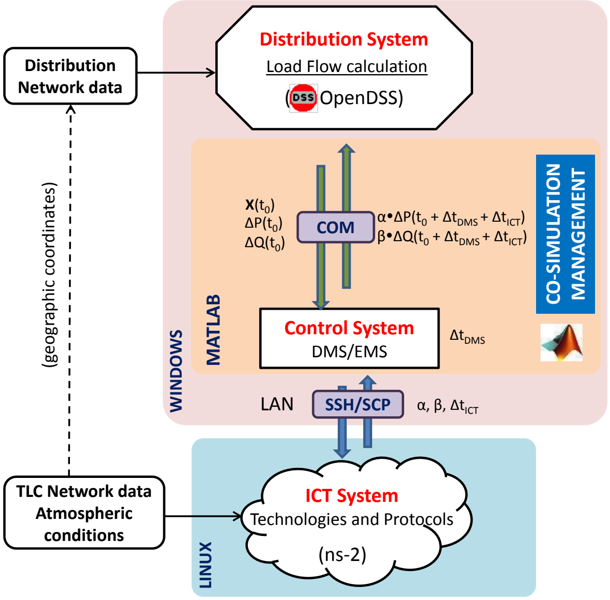

Figure 1. Co-simulation architecture as showed in [3].

The whole process of co-simulation is managed by MATLAB® under which the distribution/energy management system (EMS/DMS) is also implemented. Communication between MATLAB® and OpenDSS is made possible by a Component Object Model (COM) interface of OpenDSS, implemented on an in-process server DLL version of the program. Integration of ns-2 in the co-simulator is obtained through a SSH/SCP interface that allows Windows SO to communicate with a Linux virtual machine, where ns-2 is installed, as ns-2 is a software which runs on UNIX systems.

The MATLAB® event-coordinator commands OpenDSS to perform power flows according to a specific time scale that is related to the time granularity imposed by the simulation.

Several communication technologies can be simulated by ns-2, e.g. WLAN, GPRS, UMTS, Bluetooth, WiMAX, although it sometimes requires incorporating third part users modules [4]. In this paper, ns-2 has been used to simulate a WiMAX communication where weather conditions (e.g. to take into account its impact on signal transmission), the terrain orography, and the position of DERs in the network under study can be modeled in detail. In case of optimal control applications, the MATLAB® EMS/DMS proposed by the authors generates DER set-points that are sent to the relevant units. The software ns-2 elaborates the input from DMS/EMS before the new set points (ΔP, ΔQ) are sent to DERs for changing the network power flows, with their control and communication delays, respectively Δt_{DMS} and Δt_{ICT}, and the binary parameters (α, β) that take into account signal lost effects due to communication impairments.

This approach differs from the one followed by [5], by the adoption of a distinct run time infrastructure which provides a full integration between Linux and Windows operative systems making possible the simultaneous communication between OpenDSS and ns-2, under the coordination of a DMS for active network management. Furthermore, a complete tool with graphical user interface (GUI) has been developed, which permits the user to choose the electric network to be simulated between some typologies (rural, urban, industrial), change load and generation profiles, and different atmospheric conditions for the simulation of active distribution systems.

II.2 Distribution Management System

The DMS is the core of the active management tool. It supervises the network operation by gathering measures of the main electric parameters and, when necessary, modifies the set points of DERs (e.g., generators, storage devices, and responsive loads) in order to optimize the network management and minimize costs according to the optimization algorithm, which is subject to technical (e.g. node voltages and branch power flows during normal and emergency conditions) and economic constraints (e.g. costs for dispatching active resources and joule losses).

The Objective Function (OF), which is minimized by the DMS, is the sum of the costs (1):

$$\min\left\{C_{P\_GD} + C_{Var} + C_{AD} + C_{DES} + C_{losses}\right\} \quad (1)$$

where C_{P_GD} is cost for active power dispatching, C_{Var} is the cost for reactive power dispatching, C_{AD} is the cost for demand side integration, C_{DES} is the cost for distributed energy storage dispatching, C_{losses} is the cost for energy losses [6].

The optimization interface allows choosing which component of the whole objective function should be activated during the management of the network. For instance, if no active demand is available the cost C_{AD} will not be considered or if only active power will be dispatched the remaining terms of the objective function will be neglected.

II.3 Communication System

In this application the wireless technology WiMAX has been chosen to simulate ADN management. WiMAX is a wireless technology that has reached a broad consensus in the Literature as a strong candidate for smart grid communication system, thanks to its wide coverage area (up to 50 km) and high data rate values (up to 75 Mbps) [7]. One of the key strengths in WiMAX is the orthogonal frequency-division multiplexing (OFDM) encoding method that allows obtaining a good exploitation of bandwidth and a strong reduction of interferences. It also allows implementing an adaptive transmission through which the algorithm is able to choose the better modulation scheme (BPSK, QPSK, 16-QAM or 64-QAM) according to the distance between transmitting and receiving antennas, channel disturbances, or the Quality of Service associated with the data transmission.

Since ns-2 does not include WiMAX protocols in its libraries, an ns-2 WiMAX module proposed by the National Institute of Standards and Technologies (NIST) was adopted. It provides a number of features including OFDM PHY layer, fragmentation and de-fragmentation, mobility extension (802.16e), etc. On the other hand, NIST module does not provide support for adaptive transmission, so modulation scheme has to be set by the user before simulation.

ns-2 also offers few simple propagation models (e.g. free space model, two ground reflection model, shadowing model). Therefore a more robust and reliable model has been adopted in order to better simulate propagation attenuation with different site and weather conditions. According to Longley-Rice model, proposed by the National Telecommunication and Information Administration (NTIA), adopted in this tool, the attenuation $A_{LR}$is given by (2):

$$A_{LR} = \begin{cases} A' & \text{se } A' \le 0 \\ A'\dfrac{29 - A'}{29 - 10A'} & \text{otherwise} \end{cases} \quad (2),$$

where A' is a parameter that is dependent on different statistical variables related to seasonal random variability (V_{05}), random variability in time (Y_T), location (Y_L), and situation (Y_S) from a previously calculated reference attenuation value A_{ref}, as in (3) [8,9]:

$$A' = A_{ref} - V_{05} - Y_T - Y_L - Y_S \quad (3)$$

The Longley-Rice model provides attenuation according to long-term predictions. In a real operative situation, circumstantial events, such as rain, fog, snow, etc., represent a strong share in signal attenuation in communication links. Therefore, a new term is added to Longley-Rice attenuation. This term is based on ITU Recommendations (ITU-R P.838-3), and takes into account the rainfall rate R in [mm/h] as in (4):

$$A_{TOT} = A_{LR} + kR^{\alpha}d \quad (4)$$

where d is the distance between antennas, and k and α are two coefficients dependent on frequency and polarization [10].

II.4 Co-simulation synchronisation

One main aspect that has to be analyzed when developing a co-simulation tool is the synchronization between the two pieces of software (power system simulator and ICT simulator) that are included into the co-simulator. Synchronism management can be classified into two types: time-stepped and event-driven. Time-stepped co-simulators set a constant synchronization interval, after which power system and ICT simulations break in order to exchange data. This kind of synchronization was used for instance in [11], where three different software were used: PSCAD/EMTDC and GE Power Systems Load Flow software (PSLF) that simulate the power network, and ns-2, which simulates the telecommunication system.

In event-driven co-simulators each power system simulation cycle is regarded as a discrete event. A co-simulation manager determines if power system events cause an ICT system call, then simulation stops and simulators update their data. Since there is not a fixed time step, because the sequence of simulations depends on the sequence of events, synchronization errors are minimized, as well as the duration of the whole simulation. For instance, in [12] ns-2 is adopted as telecommunication simulator, whereas PSLF is chosen as power system simulator, and an event scheduler coordinates the events of both software products and consequently the sequence of simulations.

The co-simulation tool proposed in this paper falls into event-driven synchronization category: when the co-simulation starts, the RTI runs OpenDSS through the COM interface, which performs recursive power flows every 100 ms. When a contingency is detected, the RTI stops OpenDSS, the DMS elaborates corrective actions that are then sent to active nodes by means of the telecommunication network taking into account latencies or possible communication signal losses.

III. CASE STUDY

The proposed co-simulation tool has been applied to the network showed in Figure 2.

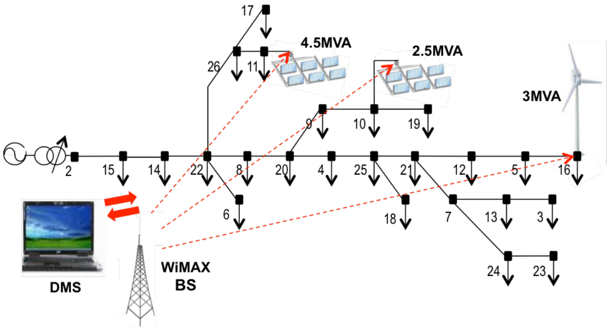

Figure 2. Sketch of the simulated electric network.

The network is a rural Italian representative network developed by the researchers of the ATLANTIDE project [13]. In order to emphasize the use of the DMS, only one feeder is considered, and the power supply is relatively high if compared with the load demand. In more detail, the feeder is about 15 km long with lateral branches, with 26 MV nodes supplied by one HV/MV substation. Three DERs are considered: one 4.5 MVA PV power plant in node 11, one 2.5 MVA PV power plant of size in node 10, and one 3 MVA wind generator in node 16. These active nodes may provide voltage regulation support with the active and reactive power dispatching under DMS request. The load comprises a mix of agriculture, residential and small industrial customers with the total peak demand of about 4MVA.

A WiMAX Base Station is installed in the HV/MV substation, as interface between the DMS and the active nodes. Each active node is equipped with WiMAX Subscriber Station, connected to the IED, which reads voltages and currents and communicates with the DMS if any overvoltage or voltage drop is detected. After gathering abnormal field measurements, the DMS runs its optimization algorithm and defines new set points for the DERs.

III.1 ADN with active power dispatching

The first scenario considers a voltage regulation with active power dispatching. Fig. 3 depicts the behavior of voltages in nodes 10, 11 and 16 without any active management. In Fig. 3 it is possible to observe an overvoltage at 11:19 hours in nodes 11 and 16. Without DMS intervention, the node 10 experiences an overvoltage at 11:32 hours.

In case of active management of the network the IEDs positioned in the active nodes communicates the abnormal network states, and the DMS adopts a set-point correction for the active power generated by DERs. Fig. 4 shows the instantaneous power generated in the nodes without DMS corrections. Fig. 5 shows the DMS correction at node 16 with active power dispatching. Voltage is maintained at 1.05 p.u., and the active power is reduced by the DMS from the peak of 1.4 MW of Fig. 4 to about 1.2 MW. A total energy of 1.02 MWh is curtailed (the active power generated by DERs at nodes 10 and 11 is curtailed too).

III.2 ADN with active and reactive power dispatching

This simulation case analyzes a P-Q dispatching, and results are shown in Figure 6, with regard to node 16. Reactive dispatching makes a strong contribution in voltage regulation by avoiding the active power curtailment in favor of the dispatching of the reactive power, which is shown in Fig. 7. Fig. 7 shows that the best solution found out by the DMS optimization is based on the provision of reactive power from nodes 11 and 16.

In this case the active power curtailed is only 0.04 MWh, with a significant reduction of the expenses for the active power dispatching.

III.3 ADN with communication losses

In this scenario the lost communication connection between node 16 and DMS has been analyzed. Since TCP protocol is adopted, handshaking method reveals the lack of connectivity between node 16 and DMS; therefore node 16 is registered in a list of unavailable resources by the DMS, and the voltage regulation is then realized with only active resources 10 and 11.

Fig. 8 shows that in this case node 10 is called to participate to voltage regulation through reactive dispatching. In Fig. 9 it is shown that in node 16, although active power profile increases, voltage is limited by 1.05 p.u..

Finally, Tab, II presents how communication latencies during DMS communication to DER IED vary according to different packet sizes. The values of packet sizes are chosen according to hypothetical messages size on future distribution smart grids [14]. The found latencies are not relevant for slow dynamics phenomena like voltage regulation, but in case of fault management can be critical.

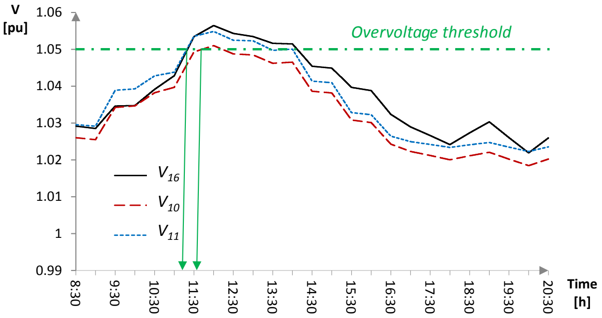

Figure 3. Voltage profiles without DMS intervention

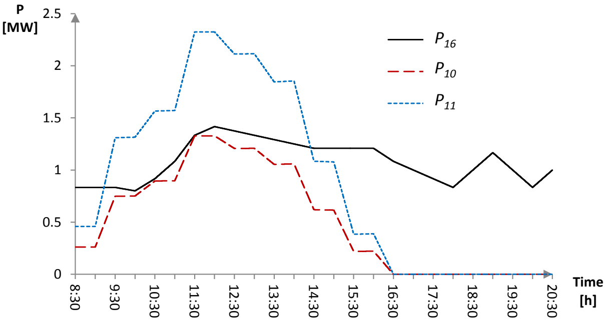

Figure 4. Active power without DMS intervention

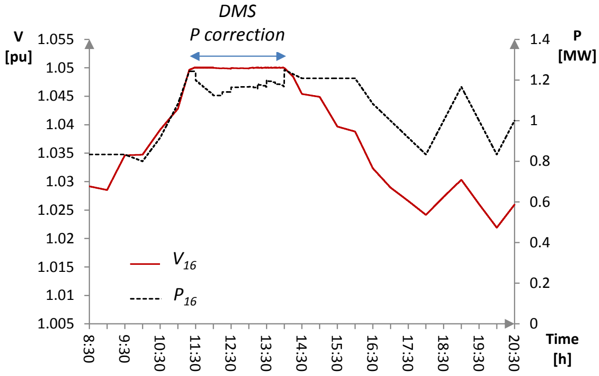

Figure 5. DMS *P* correction at node 16

IV. CONCLUSIONS AND FUTURE WORK

The paper has presented a tool for co-simulation of ADNs, which can be used to simulate active management with slow dynamics, such as voltage regulation, and the management of power flows in the networks for solving congestions. Further developments of the tool will be focused on fast dynamics issues, like fault management. It will require a revision of the software used for power system simulation that, in this version of the tool, is not able to simulate electromagnetic transients.

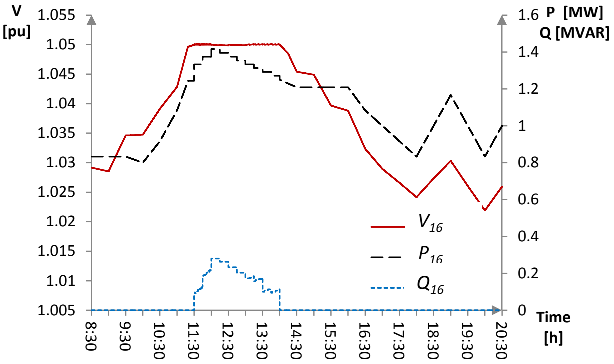

Figure 6. DMS *P* and Q correction at node 16

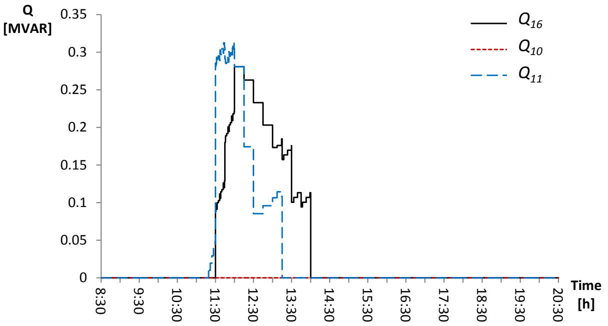

Figure 7. Reactive power dispatching

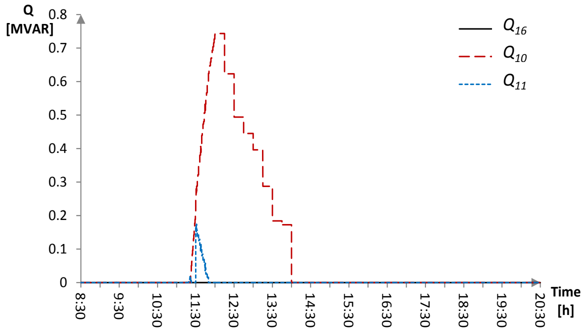

Figure 8. Reactive power dispatching in communication losses scenario

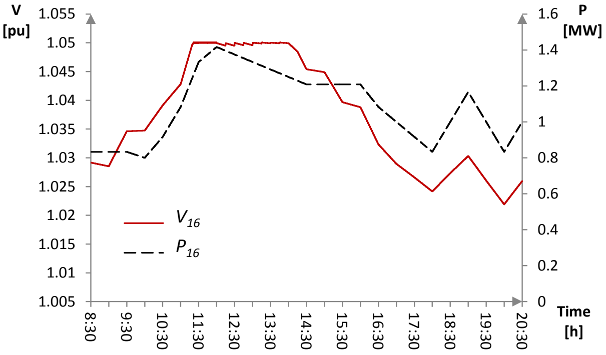

Figure 9. P and V profiles at node 16 in communication losses scenario

Table II. Signal Transmission latency

Packet size [bytes]	transmission delay [ms]
100	10,6
500	26,8
1000	42,3
1500	58,8
2000	74,3

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