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EVALUATION OF WIRELESS COMMUNICATION FOR A DISTRIBUTED GENERATOR IN SMART MICROGRIDS

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Abstract. *The increasing demand of electricity results in a necessary expansion of the energy matrix through alternative sources, including consumer's small power generators in low or medium voltage. In this microgrid scenario, one of the challenges is the automation of network communication among different devices, such as generator controllers, smart meters, etc., in order to facilitate the required exchange of information and enable networked control. Therefore, this paper presents a preliminary simulation study of a microgrid (MG) with a distributed generator (DG) remotely controlled via a wireless communication. In the co-simulation scheme, the electrical system was implemented using PLECS blockset, while the wireless network was designed using the TrueTime toolbox. In this MG application, the use of a ZigBee network to control the active power generation of the DG is evaluated under different network parameters such as loss probability and distance between the devices. Simulation results show the effectiveness of the networked solution for MG development. The results of some important variables show that the co-simulation scheme provided a joint solution for analysis of communication networks, control of the DG and modeling of the electrical grid in smart microgrids.*

Keywords: *Co-simulation, Smart Microgrids, PLECS, TrueTime, ZigBee.*

1. INTRODUCTION

A Smart Grid (SG) is an electricity network that can intelligently and automatically integrate the activities of all users connected to it such as generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies (Vijayapriya & Kothari, 2011). The increasing use of electricity in recent years has demanded the adoption of policies that would encourage the use of low and medium power distributed generation (DG) technologies, including renewable energy or alternative sources and energy storage elements (El-hawary, 2014) Considering the several challenges in changing the electricity network, microgrids have emerged as an economically and feasible option. A microgrid (MG) is generally known as a local and small scale grid consisting of distributed generating stations along with consumer loads (Mahmoud *et al.*, 2014). In MGs, generating stations are usually designed in a way the power can directly flow from the generators to the loads without having to pass through the transmission network. Microgrids also support a flexible and efficient electric grid, by enabling the integration of renewable energy sources such as solar and wind and facilitating the deployment of DGs. Moreover, the use of local energy sources attending local loads supports reducing energy losses in transmission and distribution, providing efficiency to the electric (Guerrero et al., 2010).

Regardless of having some benefits of MG, there are some challenges related to this such as implementation needs, security and control requirements among others. One of the main issues in discussion for the SG development is the communication among the devices to be installed in the environment, such as smart meters, energy storage systems, management and control systems, users and the DGs (IEEE, 2001; Gungor *et al.*; 2011; Souza *et al.*; 2015). Different communication technologies can be used for different purposes and requirements of each specific smart grid application. There are several papers addressing communication technologies, requirements, architectures and standards for SGs (Gungor *et al.*, 2011; 2013). An extensive revision about communication technologies and standards is present in Gungor *et al.* (2011), compiling the benefits of wired and wireless solutions for different applications. Gungor *et at.* (2013) proposes an architecture for SGs consisting of three layers: application layer, the power layer, and the communication layer. A description about these layers along with a discussion about its communication requirements such as latency, data rate, security and reliability is presented. Sabbah *et al.* (2014) discusses about some challenging aspects related to the architectural model for SGs proposed by the National Institute of Standards and Technology (NIST, 2014). This paper also focus on the analysis of routing protocols for smart grids, providing detailed review of existing protocols and a comparison between them.

In view of the SG scenario, modeling and simulation tasks are also challenging but promising. The integration among different areas creates a tradeoff between reliable scenarios and results with the difficult to develop them. Mahmoud *et al.* (2014) presents an overview of recent developments in modeling and control methods of MGs, including a detailed description about microgrids and its modes of operation. This revision papers attests that the MG modeling and control depends on the components used for the microgrid (DG unit, energy-storage unit, controller unit and conventional load) and discusses recent techniques available on literature. A distributed networked control is used in order to implement a secondary control in a cascaded controlled MG is presented in *Shafiee et al.* (2014). Even though this paper considers the networked MG, there is no concern with the type and dynamics of communication link used, which can be seen as an optimistic assumption on the literature of networked control systems. A simplified fixed communication latency link is used in the experiments.

In this context, co-simulation tools that allows the integrated modeling and simulation of communication networks, electrical systems and control strategies in the same environment are of key importance for the development of comprehensive smart microgrid testbeds, instead of (or before) their experimental implementation. Therefore, this paper presents a preliminary simulation study of a simplified smart MG with DG modeled in the PLECS toolset, controlled through a ZigBee wireless network modeled using the TrueTime toolbox. Both tools are integrated in Matlab/Simulink in which the control system was designed.

2. DESCRIPTION OF THE CONSIDERED SMART MICROGRID

The network labeled in Fig. 1 as "main grid" is composed by a single-phase power source and resistive-inductive (RL) line impedance and it resembles a real network. The load is resistive with 10 kW nominal power. The values of voltage and current are measured at the point of common coupling (PCC), allowing to observe the load behavior. A dashed line between the main grid and load + DG represents the PCC.

Considering the described MG, a 10 kW DG with one photovoltaic (PV) generator was inserted in parallel with the load. However, to analyze the behavior of the MG with the DG and control system, the applied set point value was set to 5 kW and it was measured by the PCC voltage reference with generated current. The DG goal is to generate the fundamental active power (P_1) that will be consumed by the load.

The MG with DG system, called SG, was implemented using the TrueTime control toolbox with a ZigBee which is one of the most used wireless networks for this type of application (Luan *et al.*, 2009).

2.1 Smart Grid Operation

The SG was implemented using the PLECS Blockset. In Fig. 1, the blue lines represent the connection cables of voltage and current signals (v_{PCC} and i_{GD}, respectively) that are sent to the dashed block called sensor (P_{meas}) in Node 1, which means to the "sensor / actuator" group. The P_{meas} is sent via ZigBee (represented by the green dotted lines) to the Node 2, called "control", which controls the generated power. The signal from the difference between the reference power (P_{ref}) and P_{meas} is sent to a proportional integral block (PI_1) that emits an output power (P_{out}) from Node 2 to the power block in the Node 1, thus the reference current i_{ref} is extracted. Subtracting i_{DG} from i_{ref}, the result is sent to a Proportional Integral block (PI_2) giving a PWM signal that is sent to the DG inverter. The entire control involving the Node 1 and Node 2 was developed using TrueTime toolbox and SG was developed using Matlab Simulink software.

The power term P_{meas} corresponds to the measured active power generated by the DG and it is calculated using equation (1).

$$P_{meas} = \frac{1}{T}\int_0^T v_{PCC}^1 . i_{DG} dt \ , \quad (1)$$

on which v^1_{PCC} is the fundamental component of the measured voltage at PCC.

The error between P_{ref} and P_{meas} goes to a proportional-integral controller (PI_1), and the resulting power value Pout is converted to current reference for the DG (i_{ref}) by using equation (2):

$$i_{ref} = \frac{P_{out}}{\left(V^1_{PCC}\right)^2} v^1_{PCC} , \quad (2)$$

on which $V^1{}_{PCC}$ is the RMS value of $v^1{}_{PCC}$. Finally, the error between i_{ref} and i_{DG} goes through another proportional integral controller (PI_2) and is applied to the inverter by using pulse-width modulation (PWM).

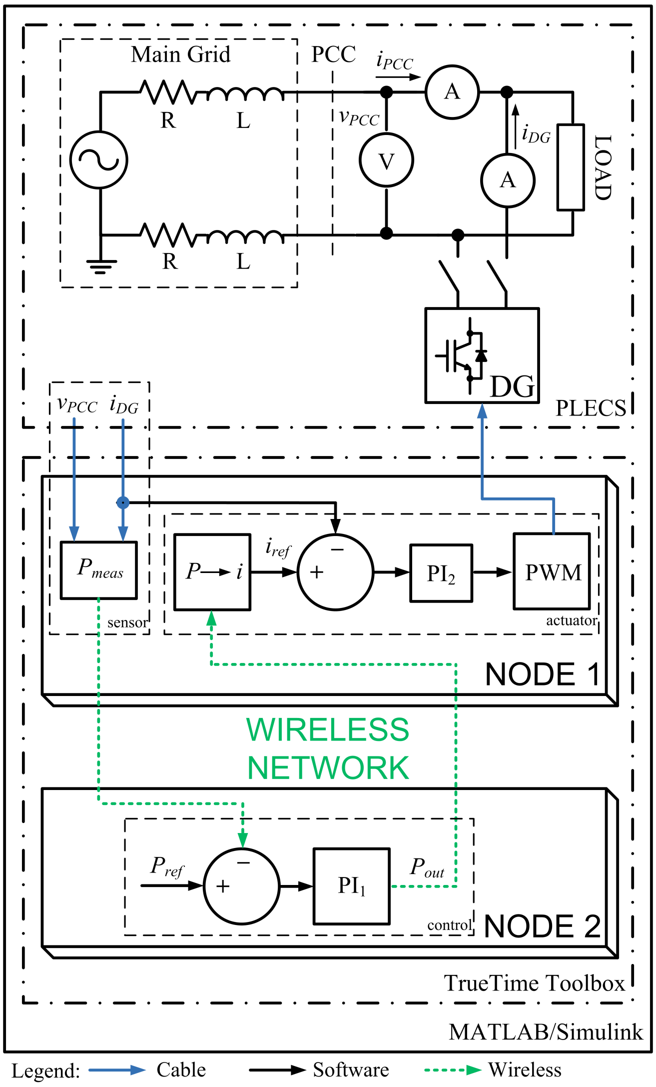


Figure 1. Co-simulation scheme for smart microgrids

2.2 Wireless Network

On this application, the active power generation is remotely controlled through a wireless communication network. Fig. 1 presents the proposed communication network and the information exchanged among each device.

The wireless communication occurs between two devices, named Node 1 and Node 2. Node 1 may be a microcontroller or a DSP responsible for the low levels functions, such as to process the measured data from the voltage and current sensors to calculate P_{meas}, current control and also sending switching signals to the DG inverter. Node 2 is responsible for high level functions, i.e., the active power control. Additional functions may be addressed to Node 2, e. g., supervisory control, user interface and communication with utilities or smart meters.

On this preliminary study, the value of P_{ref} was constant and fixed on Node 2's script, but in practice (e.g., on a PV generator) it might be sent by Node 1 to Node 2, which might apply additional strategies (e.g., saturation) into P_{ref} instead of use it as proposed on the control diagram from Fig. 1. Thus, the data exchanged between Node 1 and Node 2 are active power values (P_{meas} and P_{out}) which may be transmitted with a sampling rate of at least the fundamental frequency of the grid. The communication network was simulated using the TrueTime toolbox for Matlab/Simulink.

3. RESULTS AND DISCUSSION

3.1 Description of Evaluation Parameters

The voltage supplied by the main grid is 127 V/60 Hz, with 5% of 5th harmonic. The values of RL line impedance are R = 11.9 mΩ and L = 52 μH. The load is 10 kW resistive and the nominal power of the DG is also 10 kW. Simulation total time is 10 s and it is assumed for this time interval that the maximum power that could be injected by the DG was 5 kW, and then Pref is fixed in 5 kW. Moreover, the DG was turned on at t = 0.1 s.

The TrueTime Wireless Network block was used to represent the wireless network in the proposed smart MG. The wireless network block simulates medium access and packet transmission. In this paper, the IEEE 802.15.4 (ZigBee) wireless network was defined. The following configuration parameters were used in the simulations: Data rate of 250Kbits/s, Minimum frame size of 272 bits, Transmit power of 30 dbm, Receiver signal threshold of -48 dbm and Pathloss exponent (1/distance^x) of 3.5. In addition, for the first experiment the distance between the devices was defined to 20m and the network loss probability to 0% (ideal).

Table 1 presents the usage percentage on which every task/network transmission was active (t_{ON}) and inactive (t_{OFF}) in each node (send/receive data, communication test, etc.). The number associated with each device in the Fig. 2 corresponds to the number of the node (Node 1 – Sensor/Actuator and Node 2 – Controller). One may observe that all the tasks/network transmission remained inactive during the most part of the simulation time. This information is important due to the fact that the devices power consumption is strictly related to the t_{ON} of the tasks. For the two nodes on the Fig. 1, the following tasks and network transmissions were defined:

- ✓ Node 1: 1 - Sending P_{meas} to Node 2 (frequency - f = 60 Hz), 2 - Receiving Pout from Node 2, 3 - Testing communication with Node 2 and optimizing power consumption (f = 30 Hz), 4 - Replying to the communication test;
- ✓ Node 2: 1 - Receiving P_{meas} from Node 1, calculating Pout and sending it to Node 1 (f = 60 Hz), 2 - Testing communication with Node 1 and optimizing power consumption (f = 30 Hz), 3 - Replying to the communication test.

Table 1. Simulation Results for the Smart Microgrid with 20m of distance and without network loss

	Wireless Network Usage (%)	Node 1 Processor Usage (%)	Node 2 Processor Usage (%)	DG Performance - Active power generated (ITAE)
t_{ON}	4.76	12.25	4.51	
t_{OFF}	84.37	79.86	95.17	4130.7
t_{WAIT}	10.87	7.89	0.32	

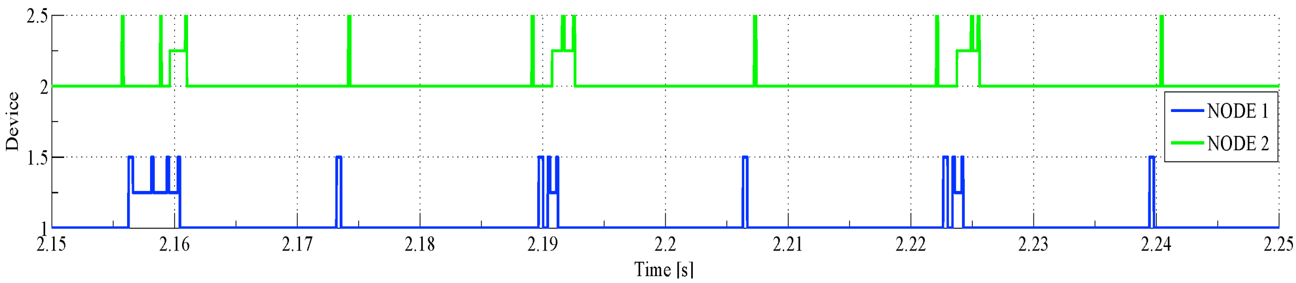


Figure 2. Detail of Wireless Network Usage by MG Nodes (Node 1 – Sensor/Actuator and Node 2 – Controller)

The value of ITAE (Integral of Time multiplied by the Absolute of Error) is one of the performance indicators most commonly used to assess quality control. It is based on the error of the controlled variable, i.e., the difference between the setpoint and the current value of the process variable and the control signal amplitude. The ITAE value is obtained using equation (3) and is indicated to reduce the contribution of the large initial errors integral performance value and emphasize the errors that occur later in the response.

$$ITAE = \int_0^T t|e(t)|dt \tag{3}$$

Fig. 3 presents P_{meas} and the active power at PCC (P_{PCC}), which was calculated similarly to equation (1) during the simulation. After the DG was connected to the grid, the active power injected reaches P_{ref} in less than 4 s and remains constant, while P_{PCC} has reduced. At this point, the load consumes the 5 kW generated by the DG and 5 kW from the main grid.

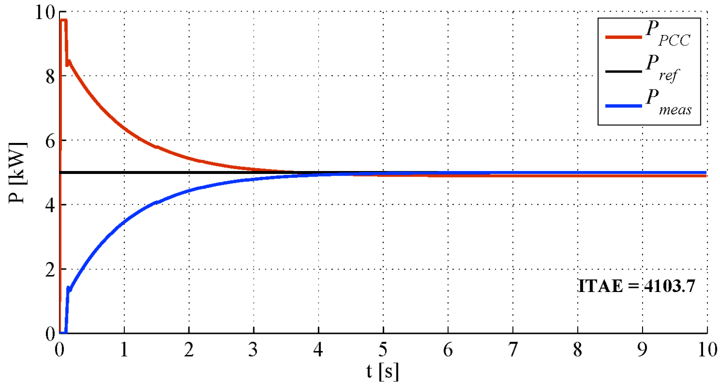
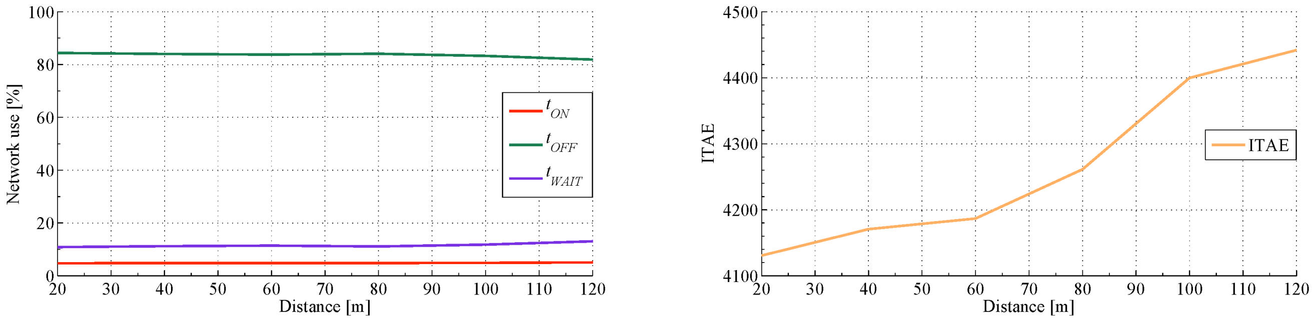


Figure 3. Output Power Responses in the MG: Generated by the DG (P_{meas}) and Consumed from Electrical Grid (P_{PCC})

3.2 Evaluation of the Distance in Wireless Communication

Considering a realistic situation in terms of communication for the MG operation, the impact of the distance between devices and the wireless loss probability were evaluated through simulation. For this analysis, the Pathloss exponent (1/distance^x) parameter in the TrueTime Wireless network block was kept the default value of 3.5 and the distance between the devices was increased. Pathloss is the reduction in power density (attenuation) of an electromagnetic wave as it propagates through space. So, the idea is analyzing if the increase in the distance will impact the result obtained for the proposed MG controlled using a ZigBee network. The probability parameter was 0% for all distances analyzed.

The results of the change in the distance for the MG are shown in Fig. 4. In Fig 4(a) it is presented the wireless overall network usage by the devices. Fig. 4(b) presents how the increase in the distance impacts the performance of the power generated by the DG.



(a) (b)

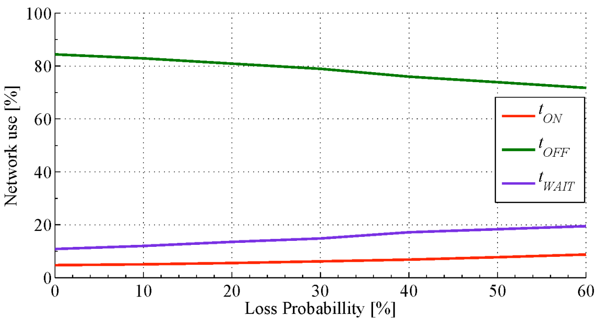
Figure 4. Impact of Distance on the MG: (a) Wireless Network Usage by Nodes, (b) Performance of DG Power Generation

It can be seen from Fig. 4 that the distance in wireless communication has a slight impact on the designed solution for the DG and MG. Figure 4(a) presents the behavior of network usage over the distance. In accordance with the Fig. 4(a), the MG solution uses around 15% of the ZigBee capacity (t_{ON} + t_{WAIT}) and there is a small increase in the contention (t_{WAIT}) and consequently a small decrease on the network availability (t_{OFF}) with distances greater than 100m. The maximum distance allowed for operation was 160m. Figure 4(b) shows the error variation (ITAE) in relation to distance. Considering the performance of DG power generation in Fig 4(b), there is a reduction of the overall performance (increase of the ITAE value) with the increase of the distance. Normalizing the ITAE values, this reduction is equivalent to 8%.

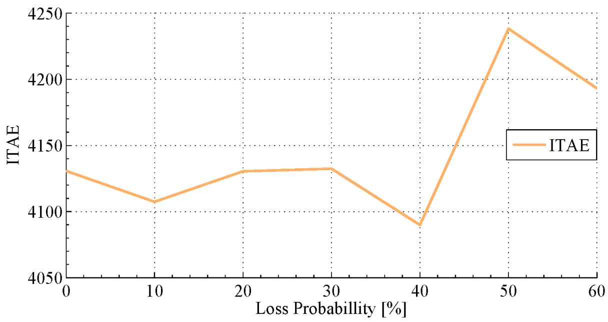
3.3 Evaluation of the Loss Probability in Wireless Communication

Since any wireless communication is non ideal, the impact of loss probability on the MG operation was analyzed. For this analysis, the Network loss probability parameter in the TrueTime Wireless network block was changed during simulations. In case of a packet loss in the wireless network, the device will have to retransmit the message. So, the idea is investigate how the increase in the loss probability can impact on the considered MG assuming a ZigBee communication link. The distance parameter was 20m for the analysis of all loss probabilities.

The results of the change in the loss probability for the MG are shown in Fig. 5. In Fig 5(a) it is presented the overall wireless network usage by the devices. Fig. 5(b) presents how the increase in the distance impacts the performance of the power generated by the DG.



(a)



(b)

Figure 5. Impact of Loss Probability on the MG: (a) Wireless Network Usage by Nodes, (b) Performance of DG Power Generation

It can be seen from Fig. 5 that the loss probability in wireless communication has also slight impact on the designed solution for the DG and MG, even though the impact on the network usage is greater. According to Fig. 5(a), the contention (t_{WAIT}) on the wireless network increases, and consequently, the network availability (t_{OFF}) decreases, with the growth of the loss probability. The MG solution is using around 31% of the ZigBee capacity (t_{ON} + t_{WAIT}) in the worst case analyzed (60% of losses). Considering the performance of DG power generation in Fig 5(b), there is a smaller reduction of the overall performance (increase of the ITAE value) with the increase of the loss probability. Normalizing the ITAE values, the greater reduction is equivalent to 4%.

Analyzing the results one may observe that the ZigBee wireless network can be used as communication link for MGs. In case of the considered MG it was able to provided the required network bandwidth and response time for the exchange of all data among the controller, DG and electrical measurements. The wireless network usage was up to 35%, indicating additional capacity for inclusion of more devices such as DGs, energy storage systems or controllers (or other MG configurations). Considering the developed distributed controller, the 5% processor usage also indicates additional capacity to simultaneously control more than one DG. The small impact verified for the change in the distance and in the network loss probability can be explained by the simplified MG configuration used in this paper. As the initial configuration consists in only two devices (DG and distributed controller) sharing wireless network resources, the network delays and jitter have not heavily impacted the overall MG performance. A greater impact of communication on the MG performance is expected with MG configurations with several devices, allowing a suitable estimation of how many devices could be supported by the ZigBee networked solution or even how many DGs could be controlled by one distributed controller.

In a nutshell the results led to the conclusion that the proposed co-simulation scheme using PLECS blockset, TrueTime toolbox and Matlab/Simulink is feasible for the analysis and design of MGs. Even though important results and parameters could be obtained, it is clear that more realistic scenarios for the MG must be incorporated with more (than one) DGs, loads and controllers. Future work will focus on the latter, aiming to incorporate other types of DGs and loads (RL, RLC) in order to evaluate the flexibility and to extend the use of the co-simulation scheme.

4. CONCLUSIONS

A preliminary simulation study of a microgrid, which was composed by DG remotely controlled through a ZigBee wireless network was presented. The co-simulation scheme developed for MGs incorporated the strengths of each tool in the same development environment (PLECS for electrical modeling, TrueTime for communication and real-time analysis and Matlab/Simulink for control design). The flexibility and the amount of output parameters that can be obtained with the co-simulation scheme represent the main differential of the solution.

For the considered microgrid assuming one DG one distributed controller, one node of the network was responsible for the inverter control and the measurements, while the second node was responsible for the active power control. The distribution of the control between two devices allows remote access and control of the active power generation by using a smart network, on which consumers and utilities would be connected and interacting.

Some important variables regarding the data exchanging, such as the time period on which every task and every message transmission was active or inactive could be simulated and discussed. The overall performance of the DG power generation was evaluated under different wireless network parameters such as loss probability and distance between the devices. For the microgrid studied in this paper, both parameters had a small impact on the MG operation.

Several other studies regarding the MG configuration (different devices, DGs and controllers) and the communication network modeling for a more realistic scenario of smart grids may be presented and are going to be focused on future.

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