Hardware in the Loop Testing of Battery-less Hybrid Systems for Off-grid Power Supply

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***Abstract*— In this paper the operation and control of battery-less hybrid systems for off-grid power supply is investigated. The load demand of the system is covered by a diesel-driven generator (DDG) and photovoltaic (PV) arrays. First, an overview of the features and operation of such systems is provided. Primary control of the system is investigated where the PV inverter curtails its active power in order to respect the minimum load ratio of the DDG and contribute to frequency control. Secondary control of the system is applied using the Hardware in the Loop (HIL) technique, where parts of the real-time simulation are replaced with actual physical components. Hardware controllable loads are activated by a hardware controller in order to respect the minimum load ratio of the DDG. An alternative method is applied where instead of controllable loads a hardware PV inverter curtails its active power production. The HIL simulation results show that both methods are effective to reduce the frequency deviation of the system and maintain the power output of the DDG above the predefined minimum requirement. The tests were performed with a combination of Controller HIL and Power HIL simulation leading to more realistic testing than Controller HIL simulation or pure digital simulation.**

***Index Terms*-- Microgrids, battery-less off-grid systems, photovoltaics, frequency control, real time digital simulation, hardware in the loop simulation.**

I. Introduction

According to the international Energy Agency, almost 20% of the world's total population does not have access to electricity and the majority of these people live in rural areas [1]. Albeit grid extension could offer a solid solution in the electrification problem, the large investment costs, the scattered population and the relatively small energy demand in these areas pose significant difficulties [2]. It has been proposed that modern microgrids that incorporate renewable sources of energy can be used as a reliable option to electrify local communities [3].

Diesel-based microgrids is a well-established and commonly used electrification method especially in the developing countries [4]. Yet, diesel-driven generators (DDG) present high operational costs that are directly proportional to fluctuations in diesel fuel's price and to the usually high transportation costs (e.g. in remote areas). Another parameter that should be taken into consideration is the reduction of fossil fuel reserves that could potentially create energy security issues [5][6]. Thus, introducing renewable energy sources in existing or new-built diesel-based systems is a promising approach [7]. A system that comprises renewable energy sources with a fossil fuel generator or other source is called hybrid energy system and is considered to be an economically feasible way of meeting the local power demand [8][9]. However, electricity that is based in renewable energy comes with technical (e.g. intermittent nature of renewable sources of energy) and non-technical challenges (e.g. operation and maintenance) that need to be overcome [10][11].

Among other renewable energy sources, photovoltaic (PV) power generation systems can efficiently complement the energy production of DDGs, especially in regions where the solar irradiation is in abundance [12]. Hybrid PV-DDG systems can be more reliable than standalone DDG systems if they are well designed and carefully operated [13][14][15][16]. In various PV-DDG systems worldwide, the midday energy demand is covered mainly by the PV production. Respecting the minimum load ratio of the DDG at this period can be a challenge. The minimum load ratio of a DDG is typically equal to 30-40% of its nominal power and must be respected in order to prolong the DDG's lifetime and minimize maintenance costs [16]. At these systems the DDG covers the load demand when no PV energy is available during overnight hours. The design of such systems needs to consider several factors, such as the minimum load ratio, adequate spinning reserve etc [18].

The energy management in a PV-DDG system is challenging since the lack of a storage system makes it less flexible and less dispatchable [19]. As a consequence, different methods of balancing the demand and the supply have been proposed in literature [2]. One method is based on

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the PV inverter active power control and aims to serve two conflicting criteria: to achieve the maximization of the PV produced energy without violating the minimum operating limits of the DDG. According to this method the PV inverter must curtail the available PV power output in case the DDG operates at a point lower than the minimum limit. Another method, instead of curtailing the PV power output, activates controllable loads to consume the surplus PV energy and to allow the DDG to operate above the minimum pre-defined point. During the last years, the management and operation of controllable loads has become a new area of research since they serve a multidimensional role in the modern smart grids (e.g. peak shaving, frequency regulation etc) [20]. As stated in [21], controllable loads as well as storage systems, both contribute to higher reliability and controllability of microgrids.

The operation of standalone microgrids becomes more robust with the introduction of a battery energy storage system (BESS), which contributes to the balance of supply and demand [22]. Introduction of a BESS provides more flexibility in respecting the minimum load ratio of the DDG, while avoiding the waste of energy (e.g. via curtail of PV active power or use of dump loads). In literature the control strategies of load following and cycle charge for PV-DDG-BESS systems have been proposed among other [23][24], which provide technical advantages compared to battery-less PV-DDG systems. Nonetheless, the use of batteries is associated with high-cost (including replacement costs after some years) and environmental concerns (recycling of batteries in rural areas in developing countries might be difficult). Introducing only PV generation to existing Diesel-based microgrids is a cost-effective method that could be applied in many different cases (e.g. rural communities, mines, telecommunication stations). Therefore, this study investigates the operation of battery-less PV-DDG systems.

In this paper, the control of battery-less PV-DDG microgrids is addressed. Section II provides real-time simulation results of primary control of the system. Section III deals with HIL simulation of the system applying different secondary control strategies. Section IV concludes the paper.

II. Primary Control of PV-DDG Microgrid

In this section primary control of a PV-DDG microgrid is investigated making use of real-time simulation [25][26]. The Digital Real-Time Simulator (DRTS) operated at the NTUA Electric Energy Systems Lab is the RTDS® [27]. Fig. 1 shows the overview of the simulated system in the software of the DRTS. The DDG is modeled as a synchronous generator (SG) with prime-mover, governor and Automatic Voltage Regulator (AVR). The PV generator and the load are modeled as P-Q sources. The DDG operates with droop control based on (1):

$$f = f_o + R * (f_N / P_N) * P \quad (1)$$

Where f_o is the DDG's frequency without load, R is the droop factor of the DDG, f_N is the nominal frequency and P_N is the nominal power output.

In the past, the PV systems produced its active power based on the local irradiation and temperature. However, according to recent standards [28] the PV inverters should provide ancillary services and adjust their active power according to the grid frequency (applicable also to inverters connected to the low voltage). When the frequency exceeds a threshold the PV inverter should be able to curtail a percentage of its active power output based on (2):

$$P_{PV} = P_{MMPT} - m * (f - f_{thresh}), \text{ for } f > f_{thresh} \quad (2)$$

Where P_{MMPT} is the maximum available power from the PVs, m is the slope factor of the droop curve and f_{thresh} the frequency threshold. The characteristics of the DDG and the PV inverter used in this study can be seen in Table I.

TABLE I: Characteristics of Microgrid's Components

Diesel Generator	
Nominal power	10 kW
Droop factor	R=7%
PV inverter	
Nominal power	3 kW
Frequency threshold	50.2 Hz
Droop curve slope factor	40% of the available power per Hz

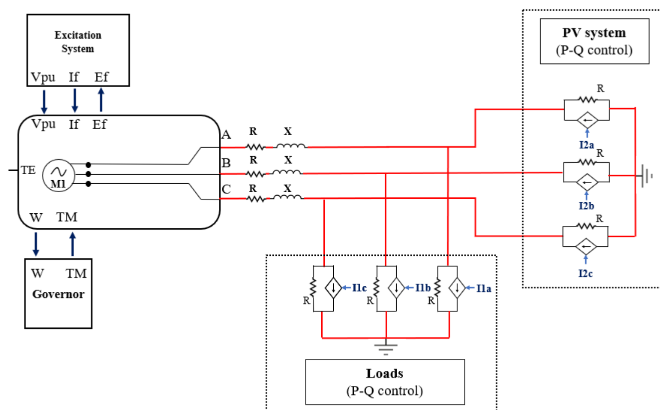

Figure 1. Hybrid DDG-PV microgrid developed in the DRTS software.

Initially the 10-kW load is being served from the DDG and the PV, with each one delivering 7 kW and 3 kW respectively. The load is decreased to 7 kW and the operation of the system is monitored in the case that the PV inverter keeps its active power constant and when operating with droop control. Fig. 2 shows that the droop control of the PV inverter contributes to primary frequency control by improving the frequency in both dynamic and steady-state conditions. In Fig. 3 the distribution of the load among the DDG and the PV is presented. As expected, the DDG operates at higher level, as the PV inverter power is curtailed when operating with droop control. It must be noted that the steady-state values obtained from the simulations coincide with the theroretic calculations. Solving the system of (1) and (2) at the case without droop control results in frequency, PV active power and DDG active power of 51.05 Hz, 3 kW and 4 kW respectively, while with droop control of 50.95 Hz, 2.7 kW and 4.3 kW respectively.

The results show that the active power curtailment of the PVs can contribute to respecting the minimum load ratio of the DDG (Fig. 3), which is one of the main challenges in battery-less PV-DDG systems. Moreover, the standard settings of the droop controller of PV inverters for operation with the main grid (shown in Table I) provided a satisfactory performance also in the case of the islanded microgrid. In the next section a secondary control approach is implemented which relies on communication.

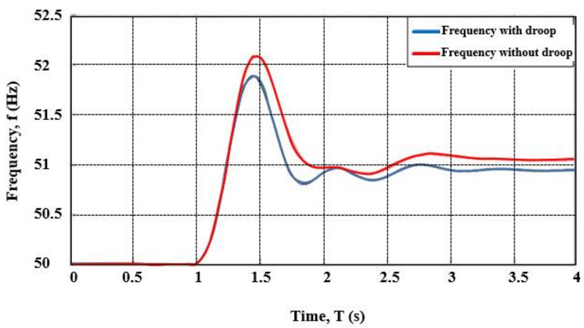

Figure 2. Frequency of a PV-DDG microgrid with and without droop control of the PV inverter.

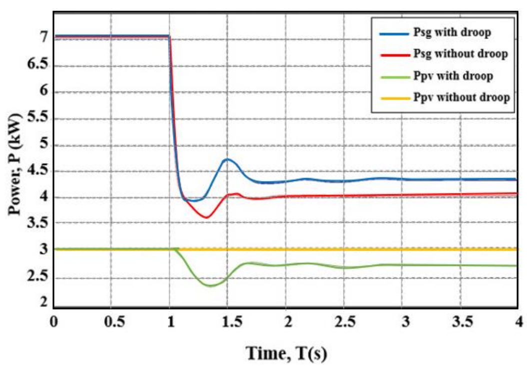

Figure 3. Active power of the DDG and PV inverter with and without droop control of the PV inverter.

III. SECONDARY CONTROL OF PV-DDG MICROGRID

A. Application of a Testing Chain for Smart Grid Controllers

A smart grid testing chain is a sequence of steps that need to be followed in order to validate effectively a control algorithm of a smart grid. Such a testing chain has been proposed in [29][30]. At first a pure software simulation of the control algorithm and the power system is performed. The power system and control algorithm operation are tested under different conditions with the use of the same simulation tool [31][32]. This kind of simulation offers an initial validation of the proposed algorithm, but it does not provide more information regarding the system's interface. The next step in the testing chain is called Software in the Loop (SIL) and is considered to be a co-simulation technique [33][34]. The power system and control algorithm are simulated in different software tools. According to SIL these two systems are connected and can exchange information while being in a closed loop configuration. Afterwards, a Controller Hardware in the Loop (CHIL) technique is proposed [35][36][37]. At this case the power system is real-time simulated in a DRTS, while a hardware controller executes the control algorithm. CHIL simulation takes into account different kind of weaknesses in the system such as noise, time delays etc. The last stage of the testing chain, prior to field deployment, is the combination of CHIL with Power Hardware in the Loop (PHIL) simulation. PHIL simulation integrates actual power hardware to a real-time simulated system in the DRTS [38][39]. Combining CHIL and PHIL simulation can result in even more realistic operation as it will be demonstrated in this paper. The testing chain is depicted in Fig. 4 and is suggested as an efficient way to validate smart grid controllers safely in the laboratory, before field deployment.

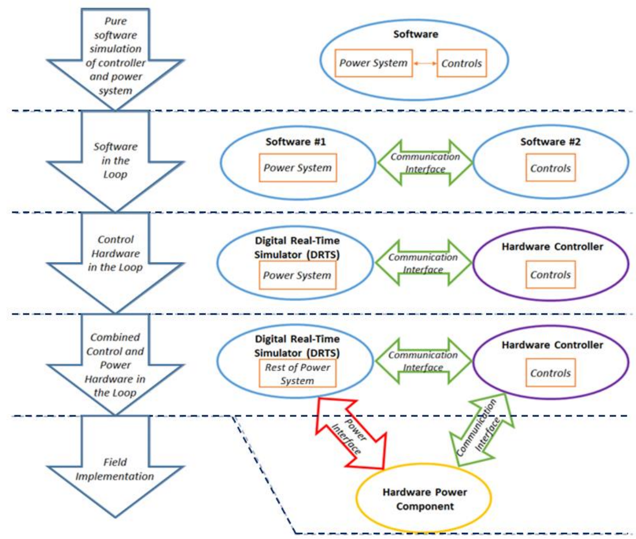

Figure 4. Testing chain for smart grid controllers [29][30].

B. Hardware in the Loop system configuration

A PV-DDG microgrid is simulated in the software of the DRTS. It includes a 5.4 kW DDG with synchronous generator (SG), a 3.6 kW PV system and a load with maximum demand of 4.5 kW. The microgrid controller adjusts the active power demand of the system by activating controllable loads in order to respect the minimum load ratio of the DDG (i.e. 30% of its nominal power at this study). The controller receives measurements of the demand and the PV production. If the minimum load ratio of the DDG is violated, the controller sends a set-point to the controllable loads in order to restore the operation marginally above the minimum load ratio. During midday, when the PV power production is significant, the production of the DDG can be reduced below its minimum acceptable load ratio. At this case the controllable loads are activated, the demand increases and the system balances again under new conditions.

After performing a pure simulation of the system, the control algorithm was implemented on a hardware controller in order to perform CHIL tests. The controller obtained measurements and sent set-points to the real-time simulated microgrid in the DRTS. Next, the combination of CHIL and PHIL simulation was applied to achieve more realistic conditions, according to the aforementioned testing chain. Instead of using a simulation model of the controllable loads, the physical hardware loads of the laboratory were connected to the real-time simulated microgrid (making use of a power amplifier and sensor [38]). In this way the physical constraints of the hardware loads were taken into account, as well as communication delays between the hardware controller and hardware loads, similar to conditions in the field. The laboratory setup of the combined CHIL/PHIL simulation is depicted in Fig. 5.

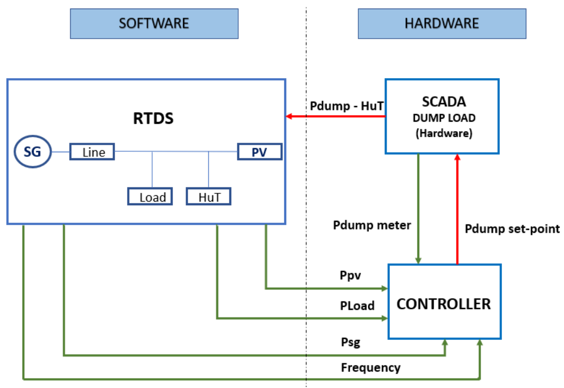

Figure 5. Combined CHIL and PHIL laboratory setup.

The communication between the hardware controller and the controllable loads was performed via the laboratory SCADA and a Programmable Logic Controller (PLC) that activates relays that connect the loads. In real life applications heat pumps could be used as controllable loads [20], however at the experiment resistive loads were employed based on the availability at the laboratory. Fig. 6 shows the relays that connect/disconnect the controllable loads. An algorithm that selects appropriately the connection of the loads was developed based on two principles. First, the set-points are rounded to the nearest available load. Second, the control method indicates that the controllable load set-point must be served by using the minimum number of loads possibly in order to reduce the fatigue of the used loads.

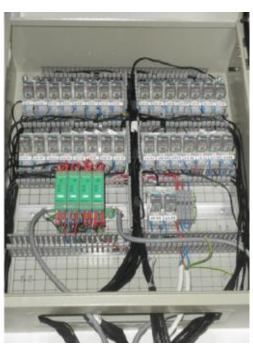

Figure 6. Relays connecting/disconnecting the controllable loads.

C. *CHIL/PHIL simulation results using hardware controllable loads*

Before applying the combined CHIL/PHIL simulation, the closed-loop stability of the PHIL configuration had to be ensured in order to avoid damage of equipment. Next the CHIL/PHIL test was initiated. Fig. 7 shows the active power of the DDG in a 24-hour experiment. It is shown that the use of the controllable loads manages to respect the minimum load ratio of the DDG at most times. It should be noted that the active power of the DDG does not coincide exactly with the minimum load ratio because the desired set-points (Fig. 8) are not always fully available due to constraints of the actual physical loads (i.e. only specific steps of power are available without high precision). This non-ideal behavior was shown at the combined CHIL/PHIL test revealing its advantage compared to CHIL or pure simulation.

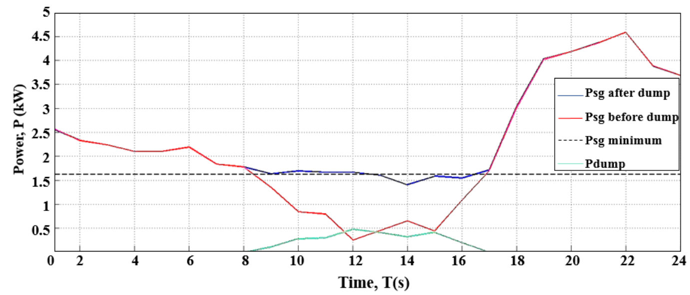

Figure 7. Active power of DDG and hardware controllable loads during daily operation at the CHIL/PHIL test.

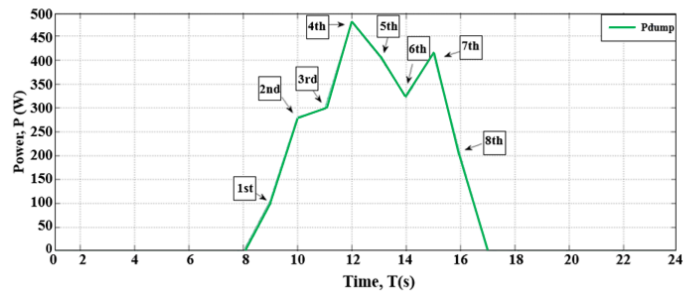

Figure 8. Active power of the hardware controllable loads during daily operation at the CHIL/PHIL test.

The CHIL/PHIL configuration was used at a fast increase in the PV power output. The active power of the DDG and the frequency are illustrated in Fig. 9 and Fig. 10 respectively. It is clear that the physical controllable loads, when activated by the controller, maintain the active power of the DDG above the minimum load ratio. The combined CHIL/PHIL approach provides insights on the communication time-delays between the hardware controller and hardware controllable loads, which would not be possible at a simple CHIL test. The total time-delay is about 1 second (Fig. 9) which is acceptable for this application. Moreover, Fig. 10 shows that the activation of the controllable loads by the controller leads to improved steady-state frequency after the operation of the primary frequency control.

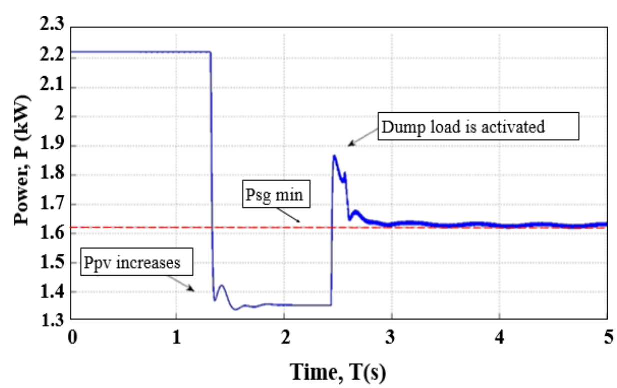

Figure 9. Active power of the DDG at the CHIL/PHIL test: use of hardware controllable loads.

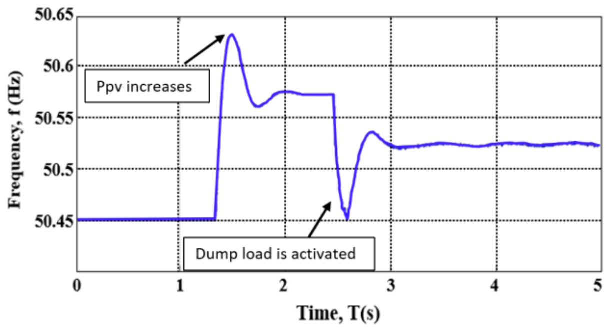

Figure 10. Frequency at CHIL/PHIL test: use of hardware controllable loads.

D. *CHIL/PHIL simulation results of active power curtailment of hardware PV inverter*

Next a similar configuration is considered, where instead of the use of controllable loads, a PV inverter with advanced capabilities is considered. The PV inverter is able to curtail its active power by receiving a set-point from an external controller. A hardware PV inverter with this capability was used at a combined CHIL/PHIL test. Therefore a similar setup to Fig. 5 was implemented, where the PV inverter was the hardware device and there were no controllable loads. Fig. 11 shows that the active power curtailment of the hardware PV inverter, instructed by the hardware controller, manages to maintain the power of the DDG above the minimum load ratio. The improved frequency after the end of the primary frequency control is shown at Fig. 12, while the initial increase of the PV active power (due to irradiation increase) and its active power curtailment is shown in Fig. 13. The figures also show that the communication delay between the hardware controller and hardware PV inverter is much larger than the case with the controllable loads, leading to a violation of the minimum load ratio for a longer duration (around 10 seconds). The additional delay is due to the slow communication capabilities of the specific commercial PV inverter.

It is clear that the use of the active power curtailment of the PV inverter allows more precise control than the use of a set of controllable loads. Moreover, it does not require the use of additional devices (e.g. dump loads). However, an advanced PV inverter is necessary. The combination of PV active power curtailment and flexibility of the existing loads making use of demand response seems the most promising option for battery-less PV-DDG systems.

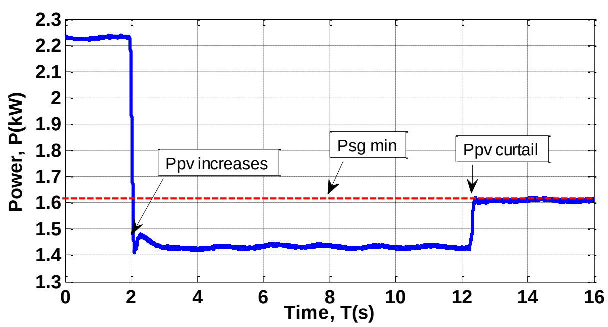

Figure 11. Active power of the DDG at the CHIL/PHIL test: applying active power curtailment of the hardware PV inverter.

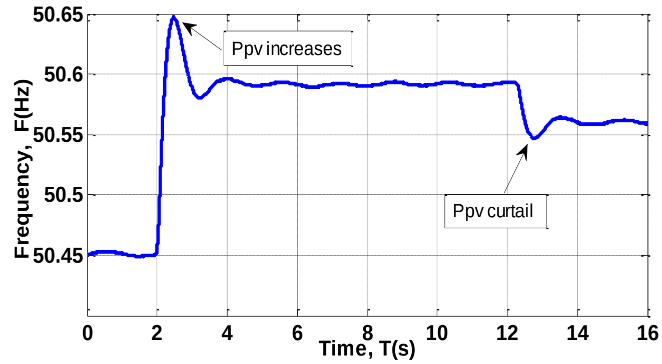

Figure 12. Frequency at the CHIL/PHIL test: applying active power curtailment of the hardware PV inverter.

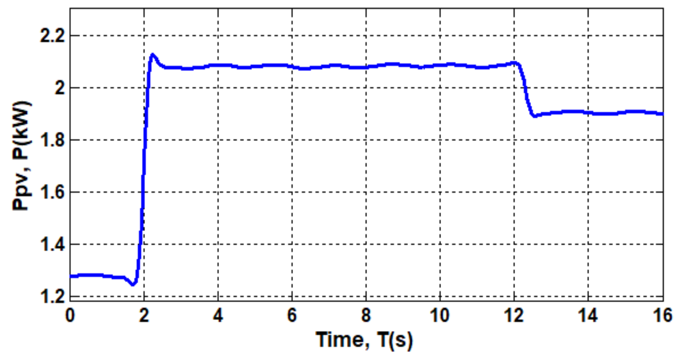

Figure 13. Active power of the hardware PV inverter at the CHIL/PHIL test: irradiation increase and active power curtailment.

IV. CONCLUSION

This paper deals with the control of battery-less PV-DDG microgrids. At first primary control was investigated, where the PVs curtail active power based on droop control in order to respect the minimum load ratio of the DDG and contribute to frequency control. A combined CHIL/PHIL setup was implemented, as part of a testing chain, in order to investigate secondary control of such systems. Two different control approaches were implemented on a hardware controller. The first method makes use of hardware controllable loads and the latter curtails active power of a hardware PV inverter. It can be concluded that both examined methods contributed to the efficient operation of the system in terms of frequency deviation and DDG's minimum power output. The PV active power curtailment method provided more accurate active power control and is simpler to implement. Combining PV active power curtailment and demand response seems to be the most promising option for battery-less PV-DDG microgrids. Moreover, the combination of CHIL/PHIL testing presented more realistic operation than CHIL testing, as insights on the particularities of the hardware components were provided (i.e. constraints of the controllable loads), as well as on the communication between the hardware controller and the hardware power components. Therefore CHIL/PHIL simulation is suggested as an efficient lab testing approach, prior to field deployment.

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