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Hardware Based Testing of Communication Based Control for DC Microgrid

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Abstract—This paper further describes our work presented in Industry Application Society 2016 Conference, with more details related to the control and operation of the microgrid. The DC microgrid facility was custom designed and implemented at CCNY with minimal off-the-shelf components to enable flexibility and reconfiguration capability. The design steps, requirements, and experimental results of the developed testbed were discussed. As a case study, a central controller for energy management algorithm was developed and tested under several operational scenarios. The experimental results verify the applicability of the developed testbed for validating DC microgrid controllers.

Index Terms—CCNY, control, DC-DC converters, distributed energy resources, inverters, microgrid.

I. NOMENCLATURE

$H_T^{bo}(S)$	General transfer function of the boost converter.
$MPPT(S)$	Maximum power point tracking transfer function.
$H_v^{bo}(S)$	Transfer function of voltage controlled boost converter.
$H_T^{bi}(s)$	General transfer function of the bidirectional converter.
$H_v^{bi}(s)$	Transfer function of voltage controlled bidirectional converter.
$H_c^{bi}(s)$	Transfer function of current controlled bidirectional converter.
$H_T^{inv}(S)$	General transfer function of the inverter.
$H_{pc}^{inv}(S)$	Transfer function of voltage controlled inverter.
$H_c^{inv}(S)$	Transfer function of current controlled inverter.
$H_{iq}^{inv}(S)$	Transfer function of reactive current controlled inverter.
$H_{id}^{inv}(S)$	Transfer function of active current controlled inverter.
m	Small percentage.
P_i	Output power corresponds to the i^{th} DER.
P_L	Load power.
S_g	Signal indicates blackout.
S_{bi}	Signal indicates disconnection of bidirectional converter.
S_{bo}	Signal indicates disconnection of boost converter.
S	Set of all possible signals combination to the converters.
S_{st}	Set of shutdown signals $\{\emptyset, \emptyset, \emptyset\}$.
S_{isl}	Set of signals within the microgrid islanded operational level.
S_{sc1}	Set of signals within the microgrid first critical operational level.
S_{sc2}	Set of signals within the microgrid second critical operational level.
S_{sc}	Set of command signals.
S_{oc}	Set of converter old states.
S_{us}	Set of signals sent by the utility.
V_{DC}^s	Measured DC bus voltage.
V_{DC}^{ref}	Reference for the DC bus voltage.

II. INTRODUCTION

Electrical power systems are encountering drastic changes roused by the global population proliferation, driving greater increase in the electricity demand [1], the governments

carbon pollution standards around the world, and new laws empowered by the white house to reduce carbon dioxide (CO₂) emissions [2-3], the urgent need for more resilient and self-healing grid to confront natural disasters, cyber-attacks and human errors [4], along with other objectives, conclude the imperative transition toward smart grids, with a major role expected to be played by renewable energy based microgrids [5]- [7].

A microgrid can be categorized based on the voltage of its common bus, which links the various resources and loads into AC, DC, or hybrid AC/DC. Also, it can be classified according to the type of control, which can be achieved using one of two approaches: (1) communication-based control and (2) voltage-based droop control. In this paper we will focus on communication based DC microgrid control.

Operation of microgrids proposes several advantages to customers and utilities including improved energy efficiency, facilitated renewable energy and electric vehicle integration, improved voltage control and security of supply [8].

In communication-based control DC microgrid, individual DERs and controllable loads, if any, are controlled via local control agents. The data from local DER and load agents are aggregated in the MG central controller, processed through a predefined control algorithm, then feedback commands are sent back to the local agents through communication links. This allows the design of algorithms that have the potential to achieve high reliable MG performance. However, the main concern about communication-based control is the hypothesis that the reliability of the MG may be affected by the intrinsic drawbacks to ICT networks, e.g. delays and/or packet loss.

Even though research results in the literature have addressed many of the technical challenges that present obstacles against wide-scale deployment of microgrids, there is a wide gap between the research outcomes and their actual implementation. A major reason for this, in our view, is the lack of testing platforms where practical limitations, theories and simulation results can be credibly verified. Microgrid testbeds are essential tools to perform research on microgrids in grid-tied and islanded modes.

There are challenges associated with implementing microgrids, e.g. designing an optimal control and monitoring architecture. Some of the research that has been performed to address those challenges was tested on purely software-based simulations [9]- [11]. Other articles have suggested to build a hardware-in-the-loop (HIL) microgrid testbed [12]. This testbed did not depend on hardware, but rather heavily depended on software simulations since, according to the authors of [12], fixed hardware configuration is time consuming and costly to reconfigure. Some researchers designed a hardware-based microgrid testbed, but using off-the-shelf components [13], [14]. Moreover, most of the effort to develop microgrid testbeds in the literature was directed towards AC microgrids.

Fig. 1. Simplified circuit diagram of the CCNY DC Microgrid testbed.

In this paper, we will present a flexible and controllable DC microgrid testbed, which has been designed and implemented at the City College of New York. The developed DC microgrid was custom designed with minimal off-the-shelf components, to give us a high level of flexibility in reconfiguring the hardware setup to test various ideas and concepts. The focus of the paper will be on the design of the testbed, including some case studies that highlight some of the capabilities of the microgrid testbed. We will show communication based testing of the inverter within the MG testbed, along with testing results of controlling and operating the DC microgrid. The purpose of the paper is to share our observations and design considerations with the research community, especially to those who may be interested in reproducing a similar facility.

The rest of the paper will be organized as follows: in section III, the structure of the developed DC microgrid testbed will be presented; in section IV, the system controllers will be described; in section V, experimental results will be presented and discussed; finally, in section VI, the main conclusions of the study will be listed.

III. CCNY DC MICROGRID STRUCTURE AND HARDWARE ARCHITECTURE

Simplified block and circuit diagrams for the developed testbed are illustrated in Figs. 1. The microgrid is connected to the utility grid (i.e. the three-phase 208 V legacy grid) via a Solid-State Relay (SSR), which enables the microgrid to

TABLE I
INDUCTANCES AND CAPACITANCE OF THE CONVERTERS UTILIZED
IN THE DC MG

Converter	Component	Value
Bidirectional converter	L_{BD1}	4.5 mH, 0.25 Ohms
	C_{BD1}	890 μ F
	C_{BD2}	1200 μ F
Boost converter	L_{B1}	4.5 mH, 0.25 Ohms
	C_{B1}	1200 μ F
Inverter	L_{DC}	19m H, 1.4 Ohms
	C_{DC}	1488 μ F
	L_{AC}	3-phase each (19 mH, 1 Ohms)

tie to the grid or island itself when needed. The testbed was structured using the following main components:

- Two 6 kW programmable power supplies, which can be programmed to emulate photovoltaic profiles, or correspond to a pre-defined power-time curve. The power supplies were from Magna-Power, model: XR600-9.9/2008+HS programmable DC power supply-photovoltaic power profile emulator.
- Two dSPACE real-time digital control boards, using RTI 1104 platform.
- Two 12 kW full bridge IGBT modules by SEMIKRON, model: Semistack.
- A custom designed 10 kW DC-DC boost converter, to interface distributed energy resources (DER).
- A custom designed 10 kW DC-DC bidirectional converter, to interface the battery and control its charging and discharging.
- Interface and protection circuits, and filters.
- Several custom designed metering systems utilizing (voltage transducer (VT): LV25-NP by LEM, and current transducer (CT): LA25-NP by LEM).
- A custom designed AC/DC static/dynamic load emulation system that offers a controlled variable load, with a maximum of 6 kVA for AC load, and 10 kW for DC load.
- CCNY-Energy institute 1.4 kW flow batteries composed of 16 cells.

As shown in Fig. 1, the AC load (realized by the developed load emulator) is shared between the utility grid and the CCNY DC microgrid through the AC bus, which is monitored by the implemented metering system (VTs and CTs). The filter is being used to reject harmonics of the inverter current, in the grid-tied mode. The SSR is located at the point of common coupling (PCC) to grid-tie or island the microgrid based on a pre-defined algorithm and islanding detection mechanism. On the DC side, the DC bus links the DC dynamic load, the batteries through the bidirectional DC/DC converter, the photovoltaic emulator through a DC/DC boost converter and the Inverter through an LC filter to reduce the voltage/current ripples. The values for inductances and capacitances used to design and build the converters are shown in Table I.

The MATLAB/SIMULIK based state machine control was implemented on two dSPACE units to act as an Energy

TABLE .II
 K_p AND K_i OF THE CONVERTERS CONTROL TECHNIQUES USED IN THE
 DC MICRGRID

DC MICROGRID							
Converter	Control technique	Outer Loop		Inner Loop			
				Charge		Discharge	
		K_p	K_i	K_p	K_i	K_p	K_i
Bidirectional converter	Current control	N/A	N/A	0.002	10	0.02	3
	Voltage control	3	1	0.002	10	0.02	3
		Outer Loop		I_d		I_q	
Inverter	Current control	N/A	N/A	192.1	97671	192.1	97671
	DC voltage control	0.1	10	192.1	97671	192.1	97671
Boost converter	Voltage control	0.02	0.2	N/A	N/A	N/A	N/A

Management System (EMS). The main dSPACE was utilized to perform as a Microgrid Central Controller (MGCC), which manages the power exchange with the main grid in a grid-tied mode, among other functions. For instance, it relays set points to the various converters within the microgrid. A second dSPACE acts as a local controller for the DERs connected to the DC bus. To isolate the dSPACE (i.e. control circuit) from the power circuit, an isolation circuit shown in Fig. 2 was used. The circuit in Fig. 2 has an optocoupler to isolate the dSPACE from the power circuit. The IGBT modules by SEMIKRON are forward biased by 15 V and the dSPACE analogue to digital channel generates 10 V only, therefore, a power supply was used to generate the 15 V. A DC/DC isolation converter was used to isolate the power supply from the power circuit as shown in Fig. 2.

IV. SYSTEM CONTROLLERS

A. DC-DC boost converter controller

DERs output is typically intermittent by nature, e.g. due to cloud variations in the case of photovoltaic systems. Therefore, a controlled DC-DC boost converter is required to regulate the output voltage and/or track the maximum power point. A PI controller was used with K_p and K_i values of 0.002 and 0.2, respectively.

One of the main features of the developed DC microgrid is flexibility. The controller parameters can be easily changed, e.g. the value of K_i can be changed to decrease the rise time and give a quick response to operating point variations, on the expense of introducing higher overshoot. Boost converter controller can be in voltage or MPPT control state. The

Fig. 2. Isolation circuit.

Fig. 3. Bidirectional converter local controller: a) voltage control mode, b) current control mode.

Fig. 4. Control diagram of active and reactive current control of the inverter.

transfer function varies with the state of the MG, which can be represented as follows:

$$H_T^{bo}(S) = \bar{S}_S^{-1} * MPPT(S) + S_S^1 * H_v^{bo}(S) \quad (1)$$

B. DC-DC bidirectional converter controller

Stationary storage devices require bidirectional DC-DC interface to control their charging and discharging processes. We developed a converter that operates between two fixed voltages, the DC bus voltage and the battery system voltage. Two PI controllers were implemented to achieve a desired reference current signal, with K_p and K_i equal to 0.02 and 110, respectively, in the charging mode, and K_p and K_i of 0.02 and 3, respectively, in case of discharging. The battery charger controller can correspond to a power/current reference signal for charging and discharging, or can regulate the DC bus voltage if needed, in case of an islanded microgrid as shown in Fig. 3. The bidirectional converter controller model can be found in [15] and the transfer function can be demonstrated by (2):

$$H_T^{bi}(s) = \bar{S}_S^{-2} * H_v^{bi}(s) + S_S^2 * H_c^{bi}(s) \quad (2)$$

C. Inverter controller

A bidirectional AC/DC converter was used to control the amount of active and reactive power exchanged with the main grid. A robust controller was implemented to synchronize with the utility grid and seamlessly send or receive active or reactive power when demanded.

Fig. 4 presents a block diagram for the control system of the converter. v_{abc} is measured from the utility grid side to acquire the phase and frequency using a phase locked loop (PLL), to enable synchronization with the grid. The inverter output currents in the abc frame of references are converted to dqo frame of references, and regulated through PI controllers to generate the dq voltages, which are used to generate the modulation signals [16]. In order to maintain the DC bus voltage using the inverter another PI is utilized to regulate I_d , which has an input of $(V_{DC}^{ref} - V_{DC}^*)$ as shown in Fig. 4.

The general transfer function of the inverter during various states of the microgrid could be represented as in (3):

$$H_T^{inv}(S) = \bar{S}_S^{-3} * H_{DC}^{inv}(S) + S_S^3 * H_c^{inv}(S) \quad (3)$$

Where:

$$H_c^{inv}(S) = A * H_{id}^{inv}(S) + B * H_{iq}^{inv}(S) \quad (4)$$

Such that:

$$\neg \forall i((A \leq 1 \rightarrow \exists \mathbb{R}(A \in \mathbb{N}^0)) \wedge (B \leq 1 \rightarrow \exists \mathbb{R}(B \in \mathbb{N}^0))) \quad (5)$$

D. DC microgrid central controller

For a centralized communication based controlled DC microgrid to maintain reliable operation, a predefined control can be applied. The control logic could be designed based on

the events that may encounter the DC microgrid and set up control schemes that modifies the microgrid operation accordingly. Algorithm I illustrates the operation of the DC microgrid during various conditions (e.g. grid-tied, islanded mode). The transition between different control schemes is event driven. It should be noted that:

$$S_s^i = \begin{cases} 1 & \exists i(i \neq 0 \rightarrow S_s^i \in S) \\ 0 & \exists i(i \neq 0 \rightarrow S_s^i \in S) \end{cases} \quad (6)$$

$$\{S_{os}, S_{cs}, S_{us}, S_{isl}, S_{sc1}, S_{sc2}, S_{st}\} \subseteq S \quad (7)$$

The values for all the Kp and Ki used to control the converters within the microgrid are shown in Table II.

V. RESULTS AND DISCUSSION

The fully controlled inverter used, was operated at a switching frequency of 6.06 kHz and a sampling time of 0.1 ms for the digital controller, which allows quick responses when the desired values for P and Q are changed through I_d and I_q . Fig. 5(a) shows the inverter testing in the current control mode ($S_s^3 = 1$). It is operated at a unity power factor, then commanded to send active power to the utility grid by setting I_d to 3 A ($S_s^3 = 1, A = 1$). Suddenly reversing the direction of the current by setting I_d to -3 A. It can be noticed that i_a and v_a were in phase, and then when the current reverse its direction, i_a and v_a became 180° phase shifted. Moreover, sending and receiving Q was tested ($S_s^3 = 1, B = 1$). In Fig. 5(b), the inverter controller was commanded to change I_q from 3 A to -1 A, it can be noticed that i_a was leading v_a by 90° then lagged by 90°. These results show the ability of the inverter to instantly reverse the mode of sending or receiving active/reactive power, which might be used to enhance the voltage level of the PCC.

Two experiments were performed, hardware experiment to examine the performance of the microgrid and simulation experiment to test the validity of the algorithm.

A. Experiment result

In this case, the inverter is commanded to send active power to the utility grid to simulate peak shaving during demand response events. Analogues to $S_u=1$ and $S_{us}=\{S_s^1, S_s^2, S_s^3\}$. In this experiment, the DC bus voltage was regulated via the boost converter ($S_s^1=1$) while the battery charger and the grid inverter are free to send or receive power ($S_s^2 = 1, S_s^3=1$). Fig. 6 illustrates the results of this case. Two events were tested within the same experiment: 1) the grid inverter draws 0.9 kW to the utility grid while the DER is fixing the DC bus voltage at 300 V through the DC-DC boost converter. When I_d is set to 3 A ($A=1$ and $B=0$), the DC-DC boost converter, which acts here as a slack bus, reacts and increase its output current to maintain the voltage. 2) The bidirectional converter starts to discharge the batteries by setting $I_{bidirectional}$ to inject 4 A reducing the stress on the DER while maintaining the power delivered to the utility grid.

B. Simulation results

A case is presented by a set of four subplots. Each subplot has five sections, each section reflects a new event or a set of events taking place. The (a) subplot of each figure represents DC currents for the inverter, boost converter, bidirectional converter and DC load. Subplots (b), (c) and (d), demonstrate the DC bus voltage, AC current from the inverter to the grid, and AC voltage, respectively.

This case shows the operation of the microgrid central controller, during the grid-tied where energy saving is the

Algorithm I	
DC Microgrid Central Control Algorithm	
Input:	$S_{os} \mid \forall i (S_s^i \in S_{os} \rightarrow S_s^i \in S)$
Output:	$S_{cs} \mid \forall i (S_s^i \in S_{cs} \rightarrow S_s^i \in S)$
<pre> if $S_g \leftarrow 0$ then if $S_u \leftarrow 0$ then $S_{cs} \leftarrow S_{os}$ else $S_{cs} \leftarrow S_{us}$ end else if $S_{bi} \leftarrow 0$ && $S_{bo} \leftarrow 0$ then execute load shedding such that $\exists i(i \neq 3 \rightarrow \exists P(\sum P_i > P_L))$ $S_{cs} \leftarrow S_{isl}$ else if $S_{bi} \leftarrow 0$ && $S_{bo} \leftarrow 1$ then execute load shedding such that $\exists i(i < 2 \rightarrow \exists P(\sum P_i > P_L))$ $S_{cs} \leftarrow S_{sc1}$ else if $S_{bi} \leftarrow 1$ && $S_{bo} \leftarrow 0$ then execute load shedding such that $\exists i(i=1 \rightarrow \exists P((m*\sum P_i) > P_L))$ $S_{cs} \leftarrow S_{sc2}$ else $S_{cs} \leftarrow S_{st}$ end if end if Return S_{cs} </pre>	

objective function. Throughout section (1), the energy price signal is assumed to indicate low price. The MGCC checks if $S_{bi} = 0$ assuring normal operation, which leads the MGCC to command the inverter maintains the DC bus voltage to 300 V ($S_s^3=0$), and boost converter controller to operates as MPPT ($S_s^1=0$). Bidirectional controller is commanded to initiates maximum charging ($I_{ref} = 5A$) ($S_s^2=1$), using current control as can be noticed in Fig. 7(a), where the bidirectional converter current becomes -5 A, i.e. charging with 5 A. Therefore, the inverter DC current increases to 5 A to maintain the dc bus voltage to 300 V as shown in Fig. 7(b). The AC current increases as well from the grid to the inverter, as shown in Fig. 7(c). For the interval of section (2), the battery system signals it is fully charged and the bidirectional change $I_{ref} = 0$, where the bidirectional converter output current drops to zero, as shown in Fig 7(a). The current of the inverter drops to zero as well since the inverter regulates the DC bus voltage and the DC MG can self-sustain its DC loads at that interval. It can be seen in Fig 7(b) that the voltage is maintained at 300 V.

During section (3), some solar power fluctuations start causing the boost converter output current to decrease gradually. The inverter DC/AC current increases in order to maintain the DC bus voltage, which can be noticed in Figs. 7(a), 7(b) and 7(c), respectively.

Fig. 5. (a) and (b) show sending/receiving P and Q respectively to the utility grid.

Fig. 6. Experiment results.

Fig. 7. A case showing operation during grid-tie mode.

During section (4), the irradiance goes back to its value of section (1), and the boost converter output current as well. This results in dropping the inverter DC/AC current to almost zero, maintaining the DC bus voltage, as shown in Figs. 7(a), 7(b) and 7(c), respectively.

During the last segment, the energy price is assumed to go high. The MGCC confirms the availability of the bidirectional converter, by checking the last status report it got $S_{bi} = 0$. If there was no fault, the bidirectional controller switches to current control and starts discharging at the rated current with 5 A. The inverter DC current drops to -5 A to maintain the DC bus voltage to 300 V, i.e. sending 5 A to the grid, as shown in Figs. 7(a) and 7(b), respectively.

VI. CONCLUSION

To successfully operate, maintain, and upgrade the future smart grid, it is crucial to validate research ideas experimentally along with the common simulation-based studies. This paper presented the development and implementation of a DC microgrid testbed. As a case study, a central controller for energy management algorithm was developed and implemented. Results showed that the implemented microgrid can be flexibly used to test various

ideas related to microgrid operation and control. As a future step, the authors are currently in the process of integrating the developed hardware-based microgrid setup with a Real Time Digital Simulation system, to test and further update the energy management algorithm.

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