E.ON Energy Research Center

Laboratory Implementation of Automation Functions for Monitoring and Control

Module 7

Control in Automation

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1. Introduction

This module is about role of control system within a power system automation framework. We will consider an exemplary radial DC Microgrid model to explore the role of control and automation in such systems.

Automatic Generation Control (AGC) is a vital system for automatically adjusting the generation or power injection capability so as to meet the load demand in real-time. In conventional AC power system, the power-frequency droop curve is an ideal example of AGC. Based on the grid frequency, the power output is increased or decreased depending on the slope of the droop curve. Droop control is a very essential system for autonomous grids. Even in the case of Microgrids, droop control is essential for automatising power injections by different sources. In AC systems, real or active power and system frequency have a tightly couples relationship and hence droop control was designed based on the power-frequency relationship. Droop curves relate the change in active power for a given change in frequency. Reduction in system frequency than the fundamental 50 Hz denotes an increase in load power and increase in system frequency denotes a decrease in load power. Hence the droop curves are designed such that the generator increases its output power for a drop in frequency and vice-versa. In DC systems however, there is no involvement of frequency nor reactive power. The only

In the theoretical part of the script, the description of the DC Microgrid structure is provided along with the description of control hierarchy. Before the experiment, the student needs to be well read about the theory given in this module and be aware of the experiment to be conducted. The concepts behind the system will be explained in the lab session. A DC Microgrid model in OPAL-RT real-time digital simulator is provided to develop a use-case of a Microgrid management and automation. unit and perform Real-Time simulations. The automation part which consists of droop control and secondary voltage control for AGC which generates the set-points for the secondary controller.

The goal of module will be to understand the interaction between primary and secondary controllers, the design and requirement of virtual impedance droop logic for AGC and perform the provided real-time simulation to understand the role of control system and its interactions with the automation framework.

2. Description of MVDC Microgrid

2.1 Strcuture of the MVDC Microgrid

An exemplary MVDC Microgrid is considered with a radial topology i.e. the grid consists of a central bus where all the sources and loads are connected as shown in 2.1. The MVDC Microgrid consists of 3 distributed energy source based on renewables. Each of the three DC renewable sources (denoted by a constant voltage source of 9kV) is connected to a Line Regulating Converter (LRC). Each LRC consists of 4 Dual Active Bridge (DAB) DC/DC converter submodules of 5MW each, which are connected in input-parallel output-parallel configuration as shown in Figure 2.2. Each LRC is rated at 20MW leading to a total generation capacity of 60MW and the parameters of LRC sis ummarised in Table 2.1. A CLC π-filter is placed at the output of each LRC to prevent circulating currents. The filter parameters are provided in Table III, where C_o denotes the output capacitance of each DAB sub-module and therefore the total output capacitance of LRC is $4C_o$. C_g is the MVDC bus facing capacitance. The filter parameters are summarized in Table 2.2. The operational nominal voltage of the MVDC bus is 6 kV. The loads are lumped into an equivalent tightly regulated Point of Load (POL) converter, which steps down the voltage from 6kV to 3kV and acts as a constant power load (CPL) inside its control bandwidth. There is also a linear resistive load rated at 6kV connected directly at the MVDC bus.

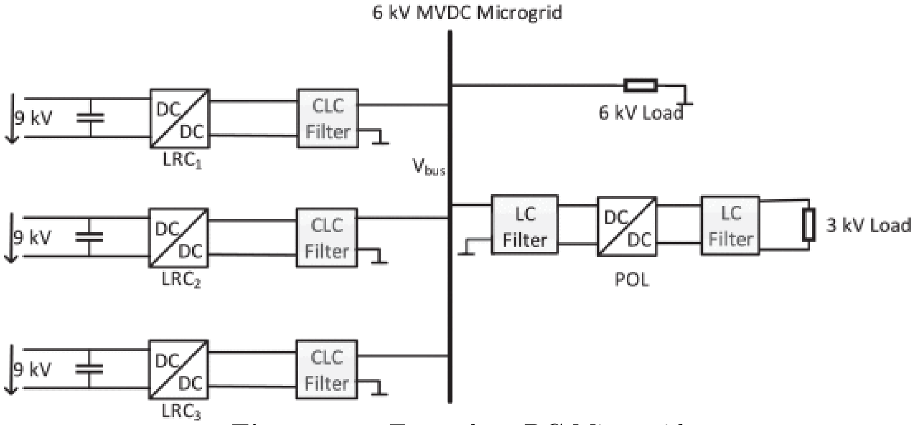

Figure 2.1: Exemplary DC Microgrid

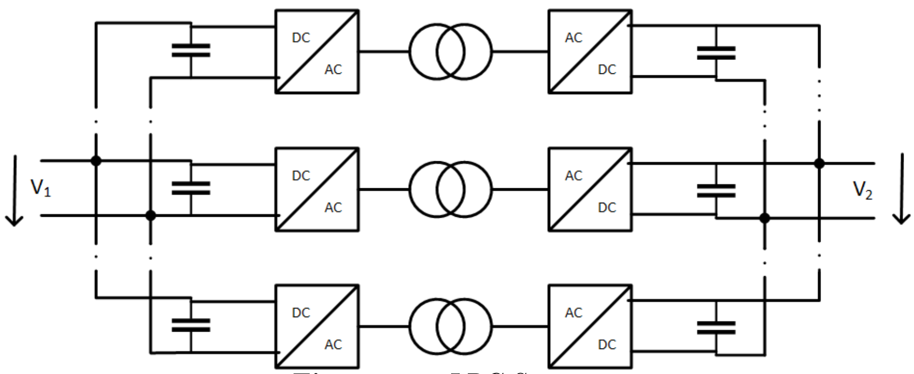

Figure 2.2: LRC Structure

DC/DC Power Converter	Capacity (MW)	Number of DABs
LRC_1	20	4
LRC_2	20	4
LRC_3	20	4

Table 2.1: Power Capacity (in MW) of each LRC

Filter Parameter	Capacity (MW)
$4C_o$	4 × 500 µF
L_f	500 µH
C_g	262 µF

Table 2.2: CLC π Section Filter Parameters

2.2 DC/DC Converter - Dual Active Bridge

The single-phase DAB topology consists of two H-bridges and a medium frequency AC link transformer as shown in Figure 2.3.

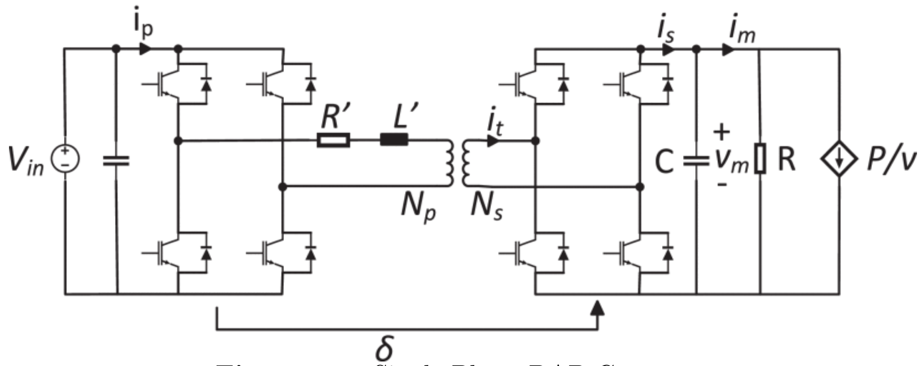

Figure 2.3: Single Phase DAB Converter

The primary and secondary bridges act as inverter and rectifier respectively. In high power applications Phase Shift Modulation (PSM) technique is applied for the synthesis of the gate signals which results in a phase shifted square wave voltage waveform across the two terminals of the medium frequency transformer. Power flow in the AC link takes place through the leakage inductance of the transformer and it can be controlled by the phase shift angle δ between the primary and secondary bridges. If the secondary lags the primary, then the power flows from the primary to secondary side and vice versa. Therefore the topology is capable of bidirectional power flow. Typically the duty cycle of the PWM for both primary and secondary bridges are constantly maintained at 0.5. However recently many researchers have also utilized the duty cycles of primary and secondary bridges as additional control variables apart from the conventional phase shift variable. The DAB converter is inherently a soft switching topology and therefore the switching losses are low. Furthermore, the topology utilises a medium frequency transformer in its AC link, thanks to the kHz range of switching frequency used in the AC/DC and DC/AC conversation stages of the H-bridges. So the weight of the transformer is much lower compared to the conventional 50 Hz transformer of the same power rating. So the DAB converter has very high power density.

As explained earlier the power flow from the primary to secondary side is dependant on the leakage inductance of the transformer L' where L' is the primary referred leakage inductance and the phase shift angle δ. The power-angle relationship is given by equation (2.1).

$$P_{DAB1} = \frac{V_{in} v \delta}{n_t \omega L'} \left(1 - \frac{\delta}{\pi}\right) \tag{2.1}$$

The parameters of the the DAB are summarised Table 2.3.

Filter Parameter	Capacity (MW)
V_{in}	9 kV
v	6 kV
f	1 kHz
ω	2π f rad/s
L'	1.518 mH
C_o	500 µF

Table 2.3: DAB Parameters

3. Hierarchical Control of DC Microgrid

A clear hierarchy in system level voltage control is availed through the CLC filter structure as shown in Figure 3.1. The secondary (PI) control regulates the bus voltage and provides voltage reference for primary control. The power sharing is implemented through virtual resistance droop logic. For any given load change, the power is shared among converters depending on the droop curve of every converter. The droop controller sends the voltage set-points to the primary controllers and the primary controller controls the individual converters to produce the requested output voltage.

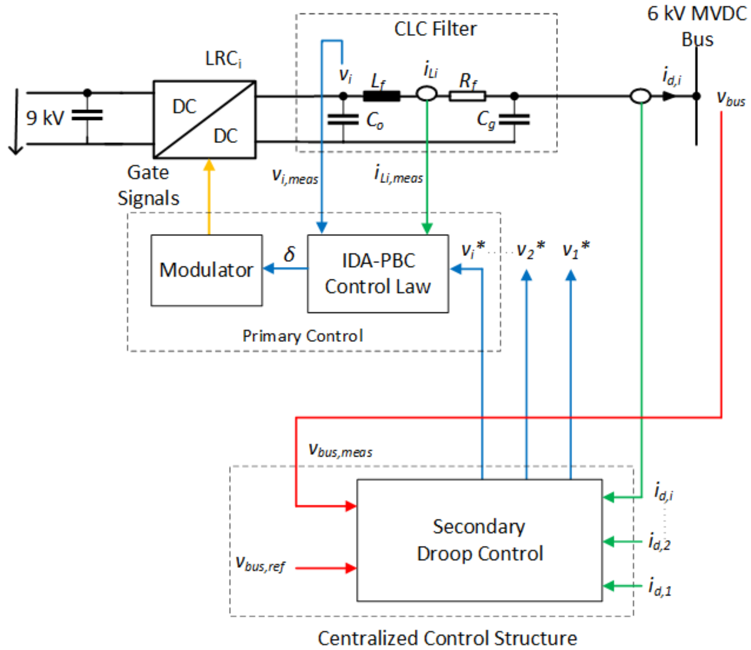

Figure 3.1: Control hierarchy of DC Microgrid

3.1 Primary Control - Control of DAB DC/DC converter

Port Controlled Hamiltonian (PCH) modelling is an energy based modelling approach, where the conventional state variables are represented through an equivalent energy variables. The Hamiltonian represents the total energy in the system. In the case of power converters, it represents the amount of energy stored in the energy storage elements such as inductors and capacitors. The control of power converters through the control variables such as δ in the case of DAB converter is basically changing the energy function of the system. This energy shaping can be done in such a way that there is positive damping in the system or positive damping energy in the system such that the system changes its energy states in a damped and stable manner.

Based on the power flow equations of the converter, the PCH equivalent model can be derived as a first step. Then PCH controlled needs to be designed which is an energy shaping control. Interconnection and Damping Asssignment Passivity Based Control (IDAPBC) is an algebraic approach/method to design such an energy shaping PCH control. The tedious derivations are explained in [1]. The final control law is given by equation (3.1).

$$\delta = \frac{\pi}{2} - \sqrt{\frac{\pi}{2}^2 - \Big(\frac{\pi n_t \omega L' i_m v^*}{V_{in} v_m}\Big) + \Big(\frac{\pi n_t \omega L'}{V_{in}}\Big) r_1 (v_m - v^*)} \tag{3.1}$$

Here r_1 is the injected damping parameter. However, the actual damping resistor injected is equivalent to $R_{damp} = 1/r_1$. The equivalent circuit representation is shown in Figure 3.2.

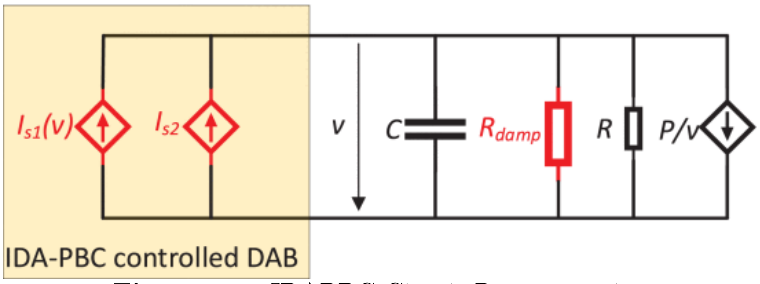

Figure 3.2: IDAPBC Circuit Representation

It can be noted that the control law does not require the load power knowledge beforehand. Only the output voltage and load current needs to be sensed for implementing this control law. It is worth remembering that the product of output converter voltage and load current need not necessarily be the demanded load power, this product only represents the supplied converter power.

From the PCH theory, the closed loop pole introduced by such an IDAPBC control is given by equation (3.2). Here R represents the resistive load and P represents constant power load and C is the output capacitance of DAB C_o.

$$\lambda_{pri} = -\left(\frac{r_1 + \frac{1}{R}}{C_o} + \frac{PC_o}{v_{bus,ref}^2}\right) \tag{3.2}$$

This concludes the design of primary control since the only design parameter is the damping parameter r_1.

3.2 Automatic Generation Control - Droop Logic

The AGC of the DC Microgrid is shown in Figure 3.3. Firstly the design of secondary PI control

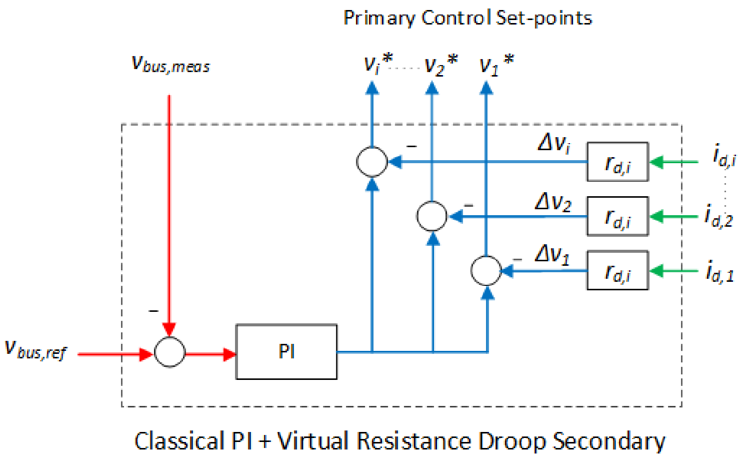

Figure 3.3: Automatic Generation Control - Droop Logic

is explained followed by the power sharing logic.

3.2.1 Secondary PI Control Design

For the design of secondary PI control, we consider the simplified representation of the multi-converter system in the primary loop as shown in Figure . An aggregated first order model is

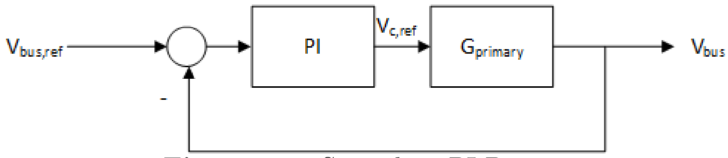

Figure 3.4: Secondary PI Design

considered of the form:

$$G_{primary} = \frac{V_{bus,nom}}{1 + sT_{pri}} \tag{3.3}$$

Here, $V_{bus,nom}$ represents the nominal bus voltage of 6 kV and T_{pri} represents the time constant. The output can be expressed as:

$$V_{bus} = G_{primary} V_{c,ref} \tag{3.4}$$

Here $V_{c,ref}$ is the converter reference voltage from the secondary PI and therefore the relation for the PI controller can be expressed as follows:

$$V_{c,ref} = (V_{bus}^{*} - V_{bus})(K_p + K_i s) \tag{3.5}$$

Using the above two equations, the closed loop transfer function relating the bus voltage reference $V_{bus,ref}$ and the output bus voltage V_{bus} can be obtained by eliminating $V_{c,ref}$ as follows:

$$\frac{V_{bus}}{V_{bus,ref}} = \frac{V_{bus,nom}}{T_{pri}} \frac{K_p s + K_i}{s^2 + s\left(\frac{1+K_p V_{bus,nom}}{T_{pri}}\right) + \frac{K_i V_{bus,nom}}{T_{pri}}} \tag{3.6}$$

The zeros of the above transfer function is at:

$$z = -\frac{K_i}{K_p} \tag{3.7}$$

The poles of closed loop transfer function are at:

$$p = -\left(\frac{1 + K_p V_{bus,nom}}{2T_{pri}}\right) \pm \frac{1}{2}\sqrt{\left(\frac{1 + K_p V_{bus,nom}}{2T_{pri}}\right)^2 - 4\frac{K_i V_{bus,nom}}{T_{pri}}} \tag{3.8}$$

In order to avoid overshoots or ringing, it is best to eliminate the term within the square root. Therefore, a relationship between the proportional and integral gains are developed of the form:

$$K_i = \frac{(1 + K_p V_{bus,nom})^2}{4T_{pri} V_{bus,nom}} \tag{3.9}$$

Thus the two poles lies only at the location:

$$p = -\left(\frac{1 + K_p V_{bus,nom}}{2T_{pri}}\right) \tag{3.10}$$

Thus knowing the desired location of the pole, the proportional gain can be calculated from which the integral gain can be calculated.

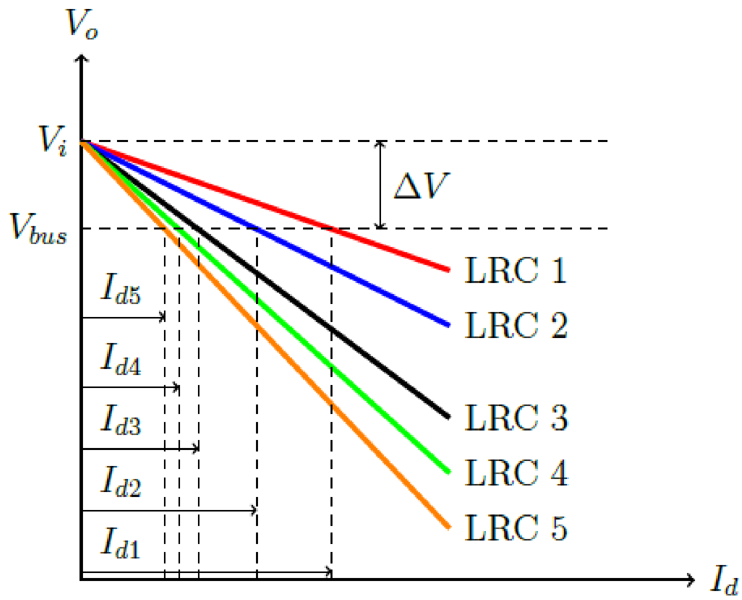

Figure 3.5: Droop Design

3.2.2 Virtual Resistance Droop Design

The droop concept in DC Microgrids is based on the amount of voltage drop of a given increase in power. Thus a virtual resistance is introduced to mimic the voltage drop across the terminals of the converter for a given increase in output power. Figure 3.5 illustrates the virtual resistance droop concept.

Let the nominal power be P_tot. Then the total current $I_{d,tot}$ drawn by the load at operating voltage V_{bus} is P_{tot}/V_{bus} and let p_1,p_2,…,p_n be the power contribution of each LRC in percentages.

$$\sum_{i=1}^{n} p_i = 100 \tag{3.11}$$

Therefore the individual converter currents I_{di} are

$$I_{di} = \frac{p_i I_{d,tot}}{100} \tag{3.12}$$

The virtual droop resistance is computed as the slope of the droop curve.

$$R_{di} = -\frac{V_i - V_{bus}}{I_{di}} = -\frac{\Delta V}{I_{di}} \tag{3.13}$$

The voltage drop factor ΔV should be chosen appropriately, choosing a high value implies that the voltage reference of the primary will be high and therefore problem arises when the reference voltage is higher than the converter's maximum output voltage, since it enters a saturation stage. For very small values of ΔV, errors in current sharing occur. A nominal ΔV of around 30 to 35 percent of the rated bus voltage is recommended.

This droop logic is only suited for Radial microgrids. For Multi Terminal DC (MTDC) Grids, this logic is not suitable since different buses in the MTDC grid have different permissible voltage ranges and the power flow is not straightforward due to the meshed nature of MTDC grids.

4. Experimental set-up

4.1 Real-Time Simulation of DC Microgrid

In this Module, we will be using the OPAL-RT real time simulator, a picture of the real-time simulatior is shown in . This simulator allows time steps as low as 10 microseconds and with the

Figure 4.1: Picture of OP5707 from OPAL-RT

use of eFPGA , time steps of hundreds of nanoseconds can also be achieved. Thus the OPAL-RT simulator enables switched simulations of kHz range of power electronic converters. On the other hand, the other very famous real-time simulator is the Real Time Digital Simulator (RTDS), which has a time step around 50 microseconds and thus it suits power sstem simulations with synchronous generators, long transmission lines , protection systems etc.

4.2 Description of OPAL-RT Simulator and RT-Lab Software

The RT-Lab environment of OPAL-RT system provides the link to MATLAB Simulink. This allows detailed switched models of power converters built in MATLAB Simulink to be transferred to the RT-LAB environment, where the complex system can be simulated in a real-time manner with feasibility of real-time multiple inputs and outputs. The eMEGAsim open real-time software component of the RT-Lab runs on the OP5707 hardware, which consists of two six core Intel CPUs and a Xilinx Virtex 6 FPGA board. This advanced feature allows complex simulations to be run on real time. This allows the MATLAB models of DC Power System from MATLAB Simulink to be loaded into RT-LAB for real time simulations.

4.3 Tasks

The students will be introduced to working with RT-Lab software and about the experimental setup. The students will be provided with converter models and control structure as building blocks. The students will then perform thier first task, which is building the MVDC microgrid model.

Time-domain real-time simulations will be performed to test and validate the closed loop system performance of the DC Microgrid and validate the automation process. These include:

1. Design of damping parameter for primary controller
2. Design of virtual impedance droop for accurate power sharing at both low and high load conditions
3. Analysis of sudden load increase step increase or decrease
4. Analysis of sudden generation disconnection

5. Analysis of sudden input voltage fluctuation in one converter

5. Home Work

5.1 Task 1 - Secondary Control Design

Consider the theory from Section . Let us consider that the aggregate of the primary control system has a closed loop response with time $T_pri = 1.5s$. Then design a PI control gains of secondary such that the closed loop poles does not have any imaginary part. The two poles should only lie on the real axis and the value of the two poles are -900 rad/s. Also calculate the location of zeros.

5.2 Task 2 - Droop Control Design

Consider the nominal load in the system to be 40 MW and the nominal bus voltage as 6 kV. Considering a 35 percent drop in converter output voltage for nominal load of 40 MW, design the virtual droop resistance R_d parameters for the following cases:

- Power sharing ratio of three converters to be equal
- Power sharing ratio of Converter 1 to be 40 percent, Converters 2 and 3 share power equally with 30 percent.

5.3 Task 3 - Primary Control Design

Consider the parameters of the converter from Table which is controlled using the IDAPBC control as explained in Section . Calculate the location of closed loop pole, if infinite damping is injected from the IDAPBC control. Calculate the damping parameter r_1 if the closed loop pole is located at -755 rad/s. Consider the load resistor $R = 3.6\Omega$ and the constant power load of $P = 40MW$.

6. Results and discussion

The following experimental tasks will be performed during the lab session after building the model.

6.1 Data Monitoring and Acquisition

After building the simulation model, it can be first built and loaded using RT-Lab software, after which the model can be executed in real-time. The Op-Write block in RT-Lab is used to write the desired simulation data into a Matlab file (.mat) format that could be used to plot at a later stage.

6.2 Setting up damping for primary controllers

Design of damping for primary control based on Homework Task 3.

6.3 Automatic Generation Control - Virtual Resistance based Droop Logic for Power Sharing

Design of damping for AGC based on Homework Task 1 and Task 2.

6.4 Bus-Voltage Set-point Variation

In this example, the DC bus voltage set point is varied and the performance should be tracked in the real-time console.

6.5 Load Changes and Converter Disconnection

The point of load (POL) converter is designed to perform step increase/decrease of load power, such that the performance of the closed loop system can be tested.

6.6 Input Voltage Fluctuation

In this task, the input DC voltage would be reduced by a step of 10 percent to emulate a sudden drop in power generation from a volatile RES source.

7. Conclusion and Remarks

Bibliography

[1] Marco Cupelli, Sriram K Gurumurthy, Siddharth K Bhanderi, Zhiqing Yang, Philipp Joebges, Antonello Monti, and Rik W De Doncker. Port controlled hamiltonian modeling and ida-pbc control of dual active bridge converters for dc microgrids. *IEEE Transactions on Industrial Electronics*, 66(11):9065–9075, 2019. 5