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Frequency Decoupled Energy Management System for Storage Units of DC Microgrids

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Introduction

- Microgrid is the concept of renewable resources and energy storage systems (ESS) integration into a controllable grid.

Islanded or grid-connected modes

- DC Microgrid applications: All Electric Shipboard, More Electric Aircraft (MEA): ESS operate in an islanded DC voltage.

- DC microgrids offer direct connection of the generation side to the consumption side with lower conversion stages.
- DC microgrids: decentralized and flexible control platform.

→ The control platform manages power flow

Introduction

- The design of ESS is a key role in MEA applications to make them optimally operate and protect the electrical generator.

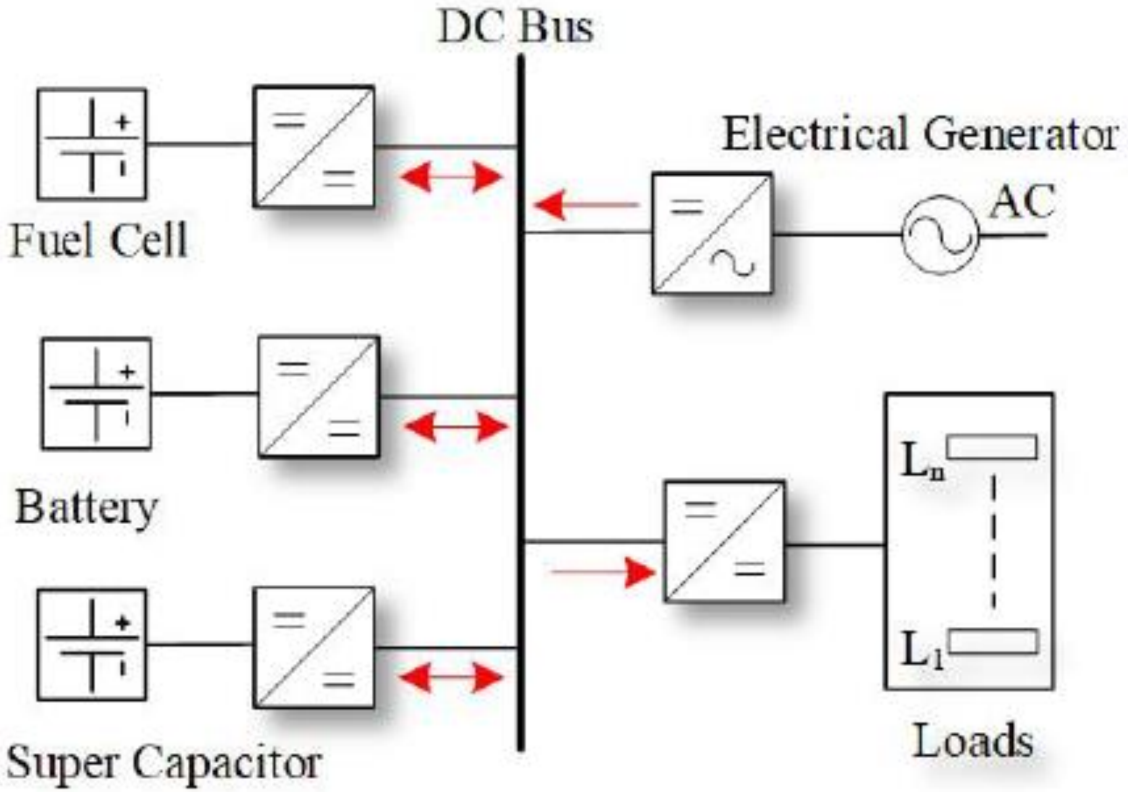
- Different ESS technologies with regard to their response time, capacity, power, and cost:
  - Li-ion batteries
  - Fuel cells (FC)
  - Super capacitors (SC)

- Different ESS should be implemented in DC microgrids to satisfy all demanded energies with different requirements.

DC Microgrid

All generation sources are connected to the DC bus through bidirectional DC-DC buck converters.

An AC-DC inverter interfaces the DC microgrid with the AC system containing the electric generators.



EMS Concept

- Electrical generators have slower dynamics with respect to ESS .
- The intermittency in the renewable resources and load variations are detrimental to the operation of the electrical generator.
- ESS provide uninterruptible power supply and compensate for the electrical generators.
- The variations in the demanded loads introduce high-frequency transients that can last minutes or seconds.
- These variations should be avoided from the electrical generators.

EMS Concept

1. Quick load variations affect FC's lifetimes.

2. Li-ion batteries are exposed to temperature increase, decreasing efficiency and lifetime, if they provide fast changing currents.

3. SC compared to battery and FC, has medium power density. It can supply surge power without influence on its lifetime.

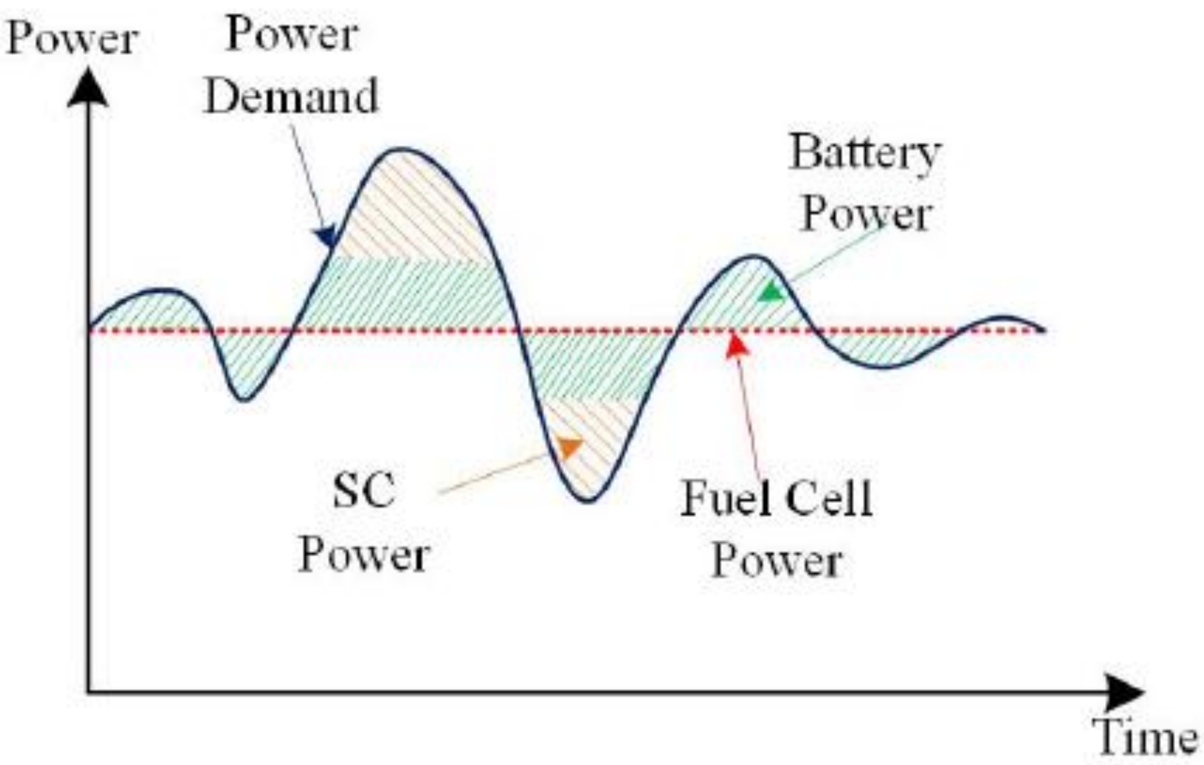
This ability of SC makes it capable of providing fast transient loads.

SC is considered as an ancillary surge power supply in a DC microgrid with sensitive slow dynamic resources.

Load Variations

DC microgrid topology provides a decentralized control platform, where all generation sources have their own controllers.

The droop control is such decentralized method.



Frequency Decoupling

A frequency decoupled algorithm is needed to protect sensitive resources from supplying burst power:
electrical generators and FC.

Electrical generators are protected and FCs lifetimes are extended.

Frequency decoupled energy management system (EMS): the required energy is decoupled <u>in the frequency point of view.</u>

The dynamic performance of ESS was neglected in most of EMS methods.

Contribution

- Propose a droop-based control algorithm that decouples the current into different frequency components and assigns them to different ESS.

- Address plug ”n” play by introducing adaptive droop controllers that can be assigned to any number of ESS in the DC microgrid.

- The EMS is required to prioritize ESS according to their characteristics.

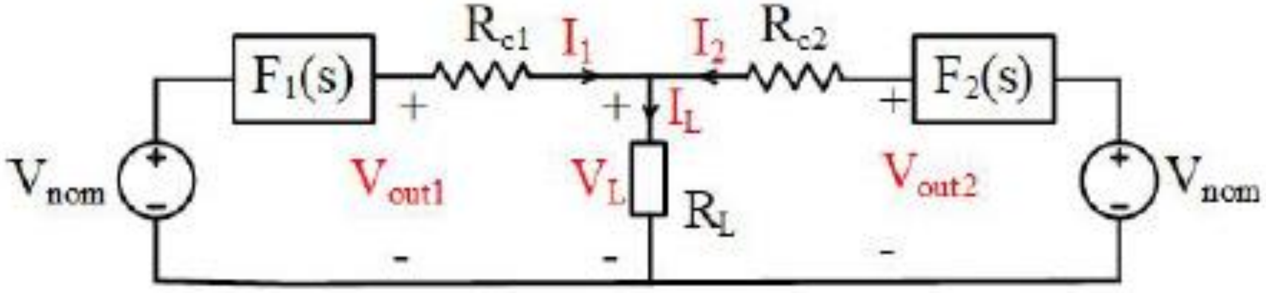
- It is desired to keep FC power constant, while SC compensates for the fast changing fluctuations. Battery provides power with lower fluctuations.

Droop Controller

Conventional droop controller: a virtual resistor

This virtual resistor can be extended to a transfer function that decouples the load current between ESS.

$$V_{\text{out1}} = V_{\text{nom}} - F_1(s)I_1 \quad , \quad V_{\text{out2}} = V_{\text{nom}} - F_2(s)I_2$$



Frequency decoupling method

A first order low pass filter is considered for each ESS:

$$\text{z domain:} \quad F(z) = \frac{\alpha z}{z - (1 - \alpha)}$$

$$\text{s domain:} \quad F(s) = \frac{\alpha s + \alpha T}{s + \alpha T}$$

α is the filter parameter defining the cut off frequency.

This parameter is used as a variable to assign each ESS the corresponding components of the load current.

Frequency decoupling method

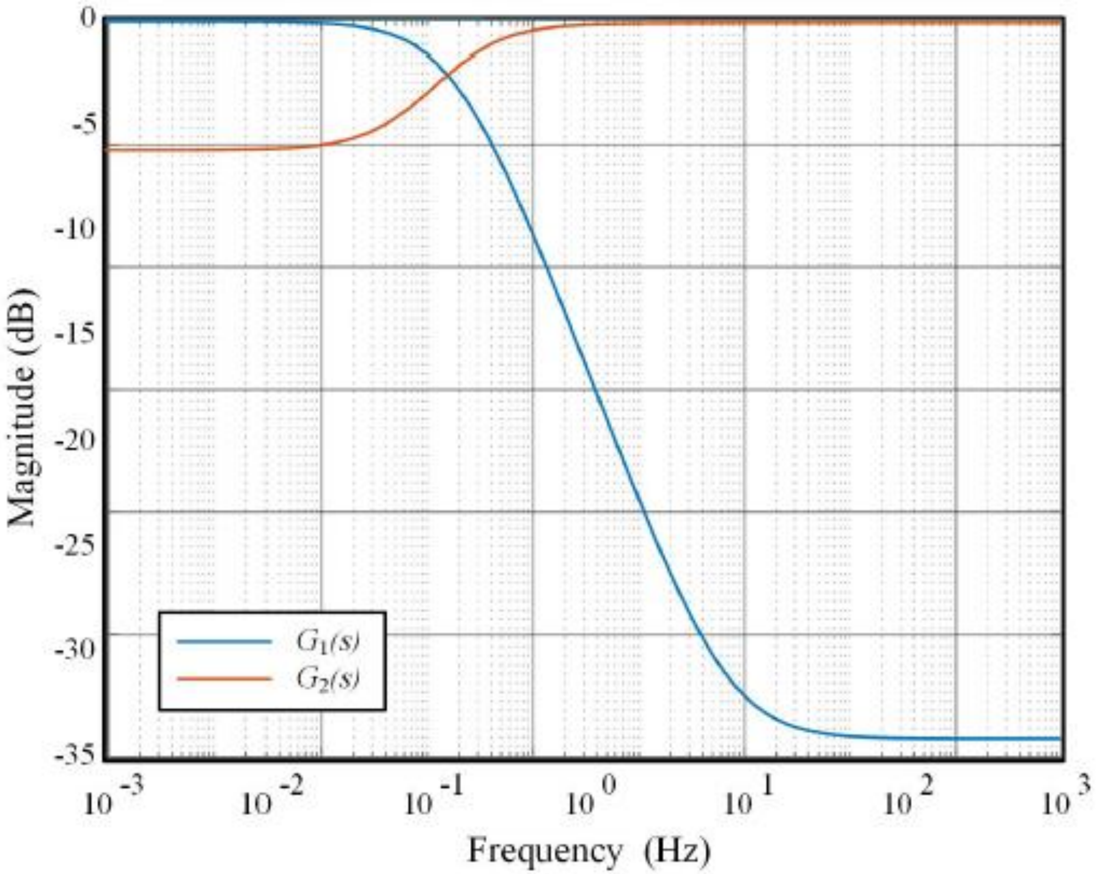
The load current is decoupled through G1(s) and G2(s):

$$I_1 = \frac{F_2(s)}{F_1(s) + F_2(s)} I_{\mathrm{load}} = G_1(s) I_{\mathrm{load}}$$

$$I_2 = \frac{F_1(s)}{F_1(s) + F_2(s)} I_{\mathrm{load}} = G_2(s) I_{\mathrm{load}}$$

Low-frequency components pass through one ESS

High frequency components pass the other ESS.



Frequency decoupling method

Having three ESS:

$$F_1(z) = \frac{5e^{-6}z}{z-(1-5e^{-6})z} \Rightarrow F_1(s) = \frac{5e^{-6}s+0.05}{s+0.05}$$

$$F_2(z) = \frac{5e^{-5}z}{z-(1-5e^{-5})z} \Rightarrow F_2(s) = \frac{5e^{-5}s+0.5}{s+0.5}$$

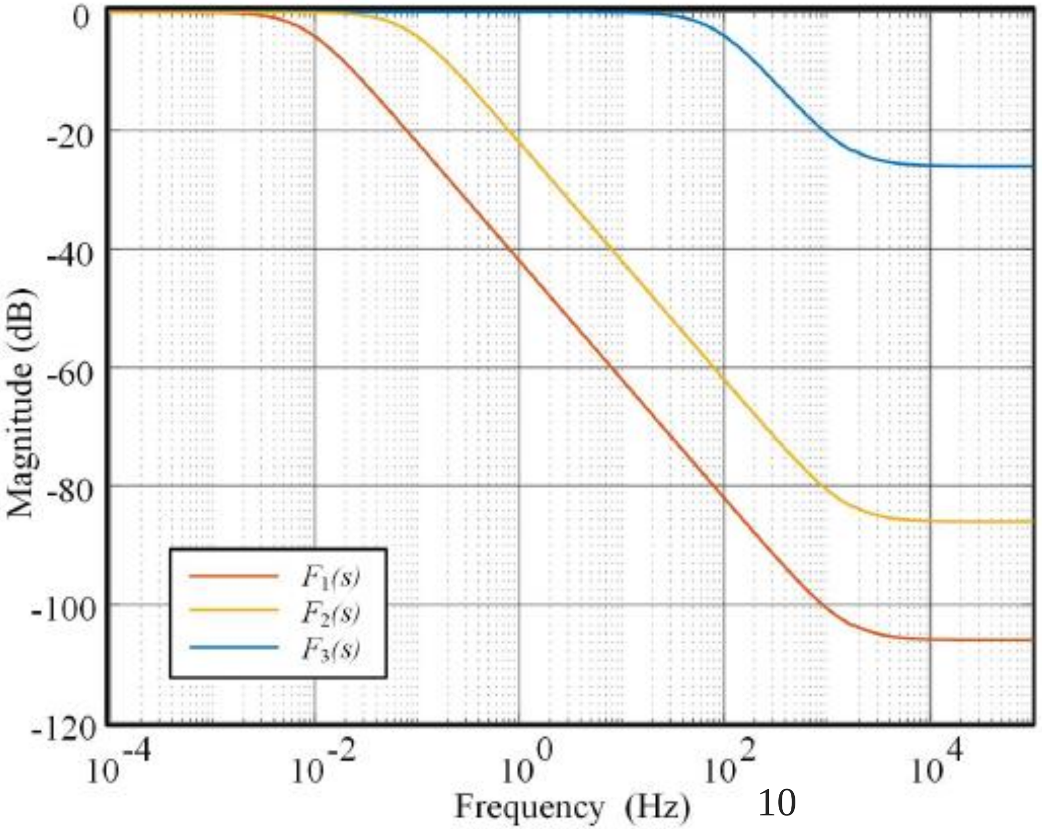
$$F_3(z) = \frac{5e^{-2}z}{z-(1-5e^{-2})z} \Rightarrow F_3(s) = \frac{5e^{-2}s+500}{s+500}$$

- ✓ F1(s) is assigned to FC, due to its lower filter parameter.
- ✓ F2(s) is assigned to the battery.
- ✓ F3(s) is assigned to SC for passing high-frequency components due to its higher filter parameter.

Frequency decoupling method

The cutoff frequencies depend on the filters parameter.

F1(s): The filter with lowest α, passes only very low-frequency components: is assigned to FC.
F2(s): is assigned to the battery
F3(s): is assigned to SC.



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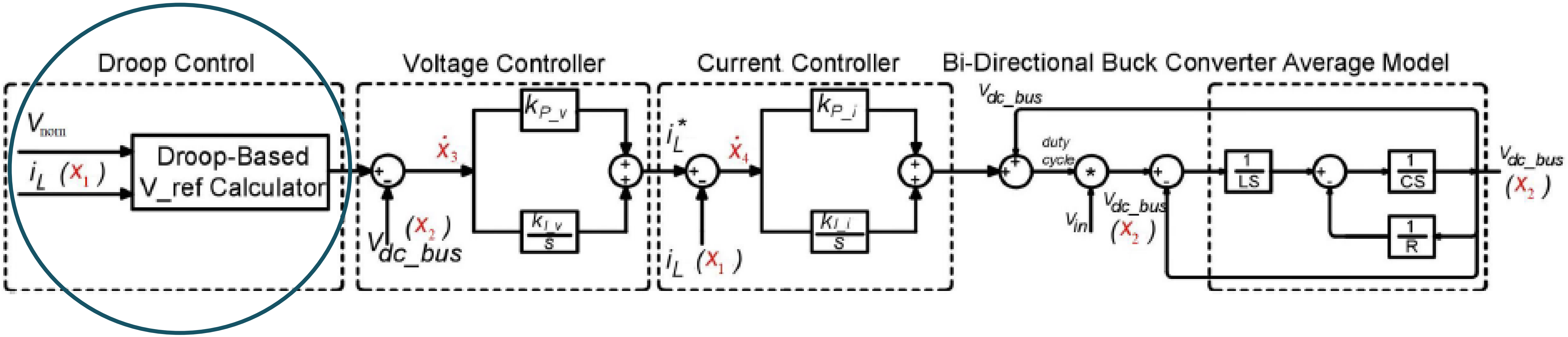
Droop Controller

Conventional droop controller: a virtual resistor.

Adaptive droop controller: a transfer function.



Mathematical Model

Quantitative examinations are needed for each ESS and the associated controllers.

The goal is to create a mathematical model

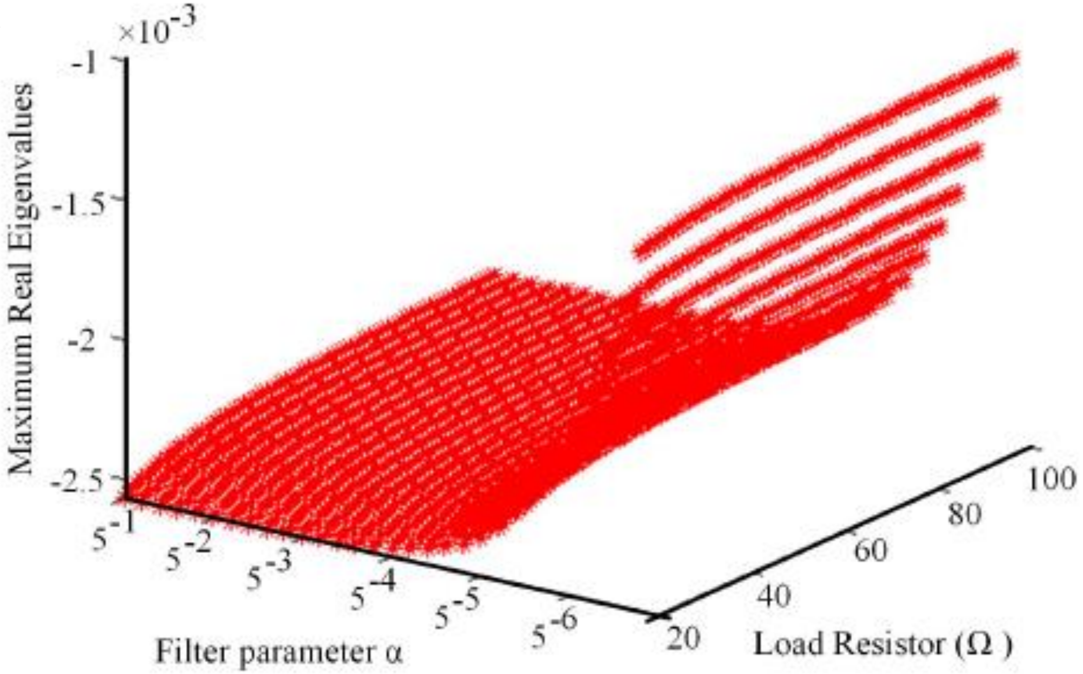
→ State space model

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \frac{-k_{P_i}V_{in}}{L} & \frac{-k_{P_i}k_{P_v}V_{in}}{L} & \frac{k_{P_i}k_{I_v}V_{in}}{L} & \frac{k_{I_i}V_{in}}{L} & \frac{-k_{P_i}k_{P_v}V_{in}}{L} \\ \frac{1}{C} & \frac{-1}{RC} & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & -1 \\ -1 & -k_{P_v} & k_{I_v} & 0 & -k_{P_v} \\ \frac{n_2}{d_1} - \frac{n_1 k_{P_i}V_{in}}{d_1 L} & -\frac{n_1 k_{P_i}k_{P_v}V_{in}}{d_1 L} & \frac{n_1 k_{P_i}k_{I_v}V_{in}}{d_1 L} & \frac{n_1 k_{I_i}V_{in}}{d_1 L} & -\frac{d_2}{d_1} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ y \end{bmatrix} + \begin{bmatrix} \frac{k_{P_i}k_{P_v}V_{in}}{L} \\ 0 \\ 1 \\ k_{P_v} \\ \frac{k_{P_i}k_{P_v}V_{in}n_1}{Ld_1} \end{bmatrix} V_{nom}$$

Mathematical Model

By observing eigenvalue of matrix A from the state space model: System stability for different filter parameters can be assessed.

All negative eigenvalues: System is stable for all loading condition and possible filter parameters

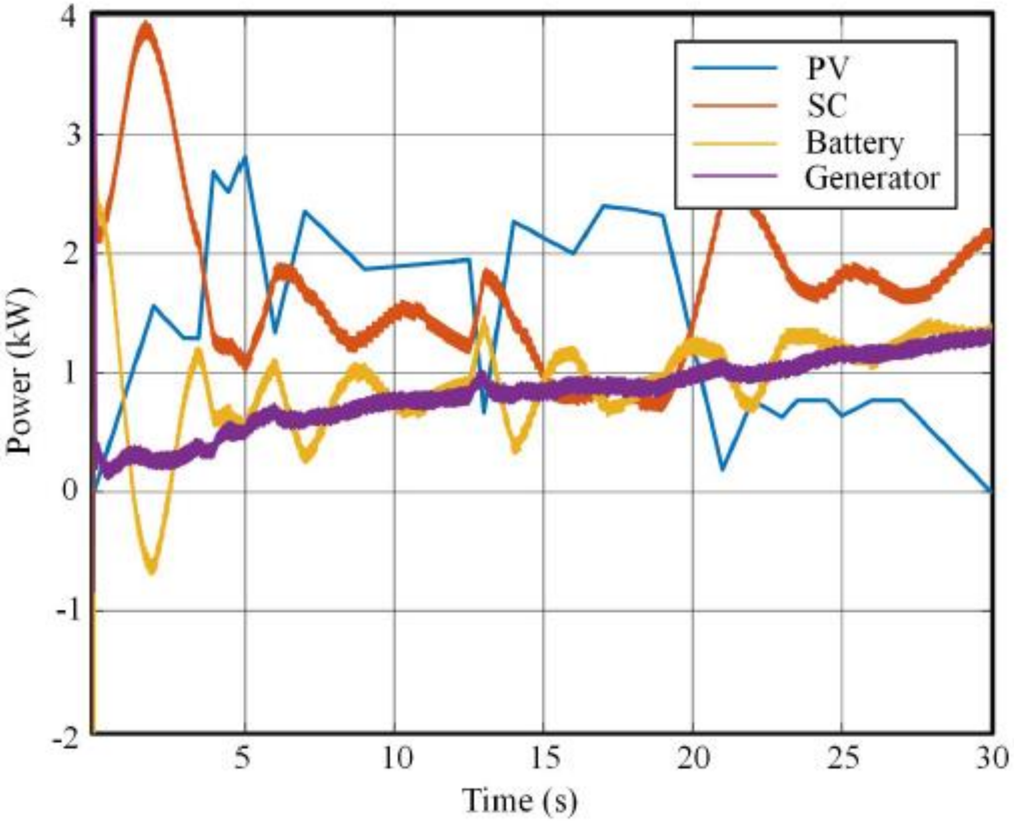


Simulation Results

Effectiveness of proposed method in decoupling the load current:

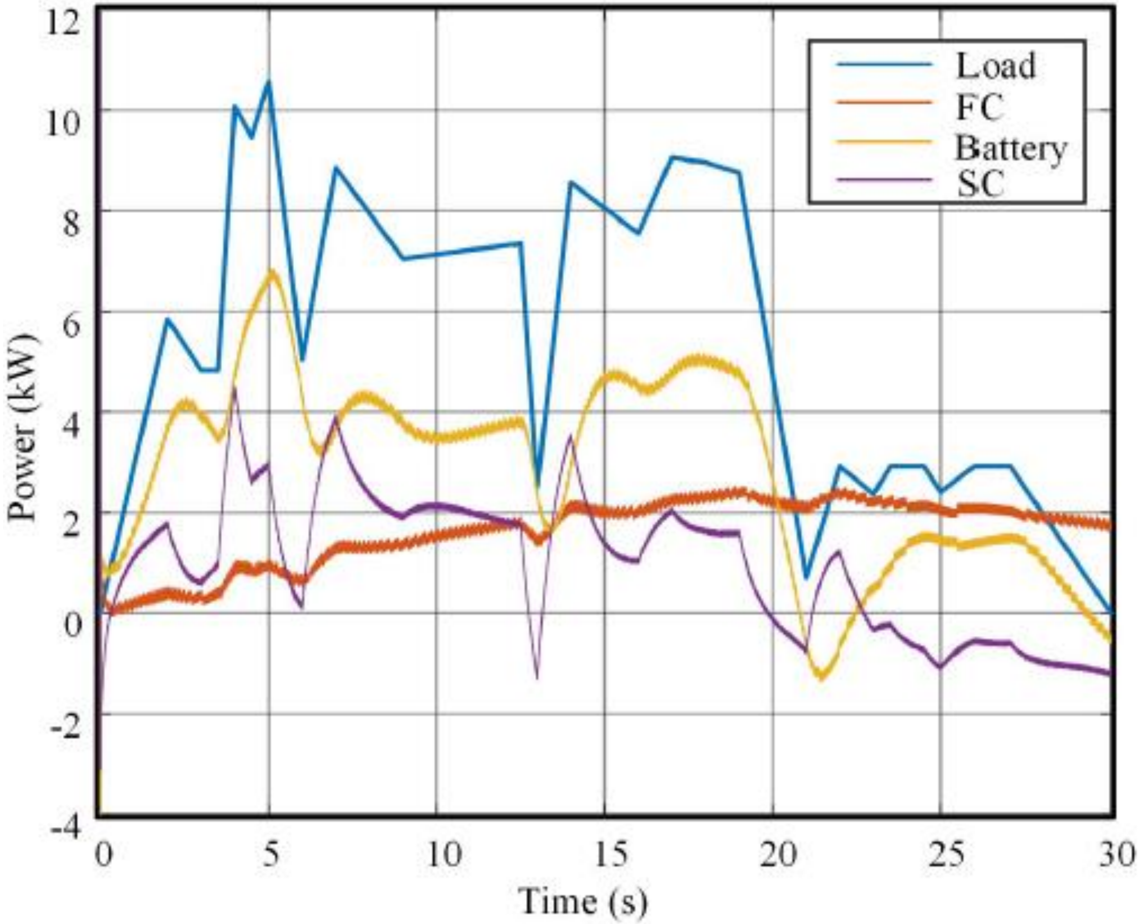
Objective: make electrical generator or FC produce power as smooth as possible, while other ESS compensate for the load power variations.

First case study:
Generation side has variations.
Load is 5 kW and constant.



Simulation Results

Second case study: no electrical generator.
Three ESS are responsible for producing the required load power. FC, battery, and SC are the existing ESS.



SC is the backup source and is responsible for all excess required power.

Objective: smooth current passes through FC. The remaining variations pass through battery or SC.

HIL Results

A HIL real-time simulator is used to show the operation of the proposed method in decoupling the variations.

PV arrays, ESS, the electrical generator and all buck converters are modeled in Typhoon HIL 602.

Texas Instruments DSP boards are used for implementing the control method.

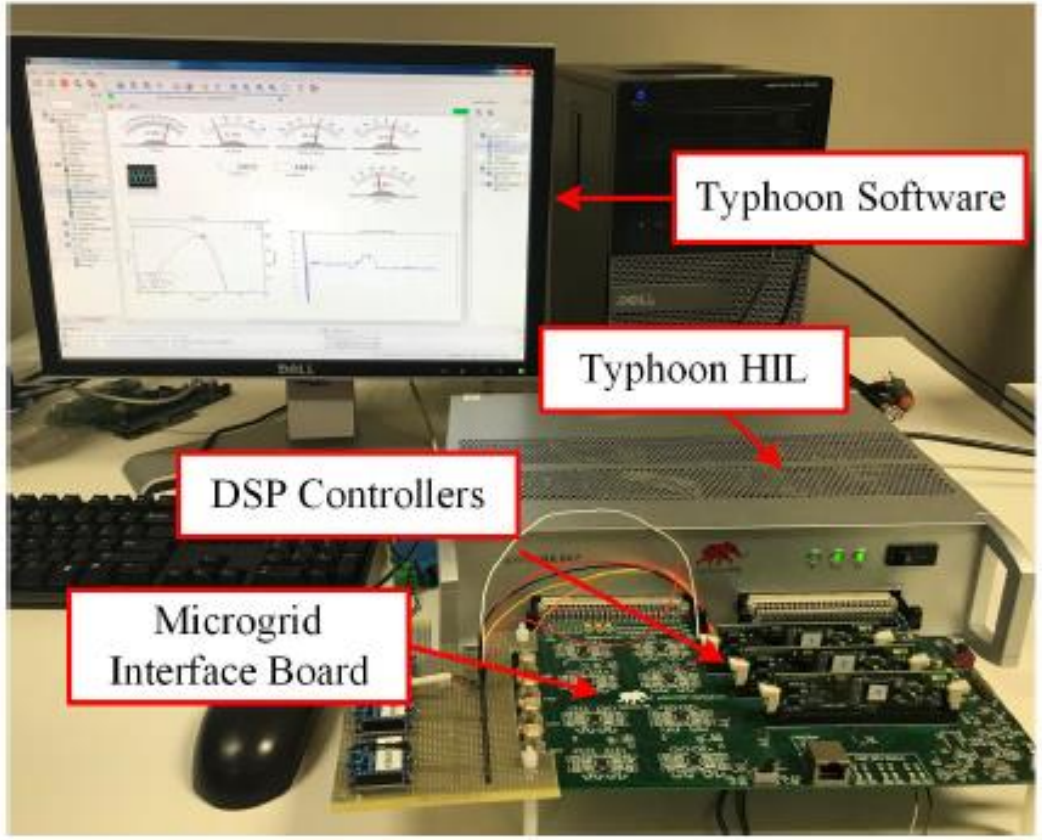


Fig. 13: HIL setup.

HIL Results

DC microgrid with a constant load of 3 kW is modeled with variations in the generation side, PV arrays.

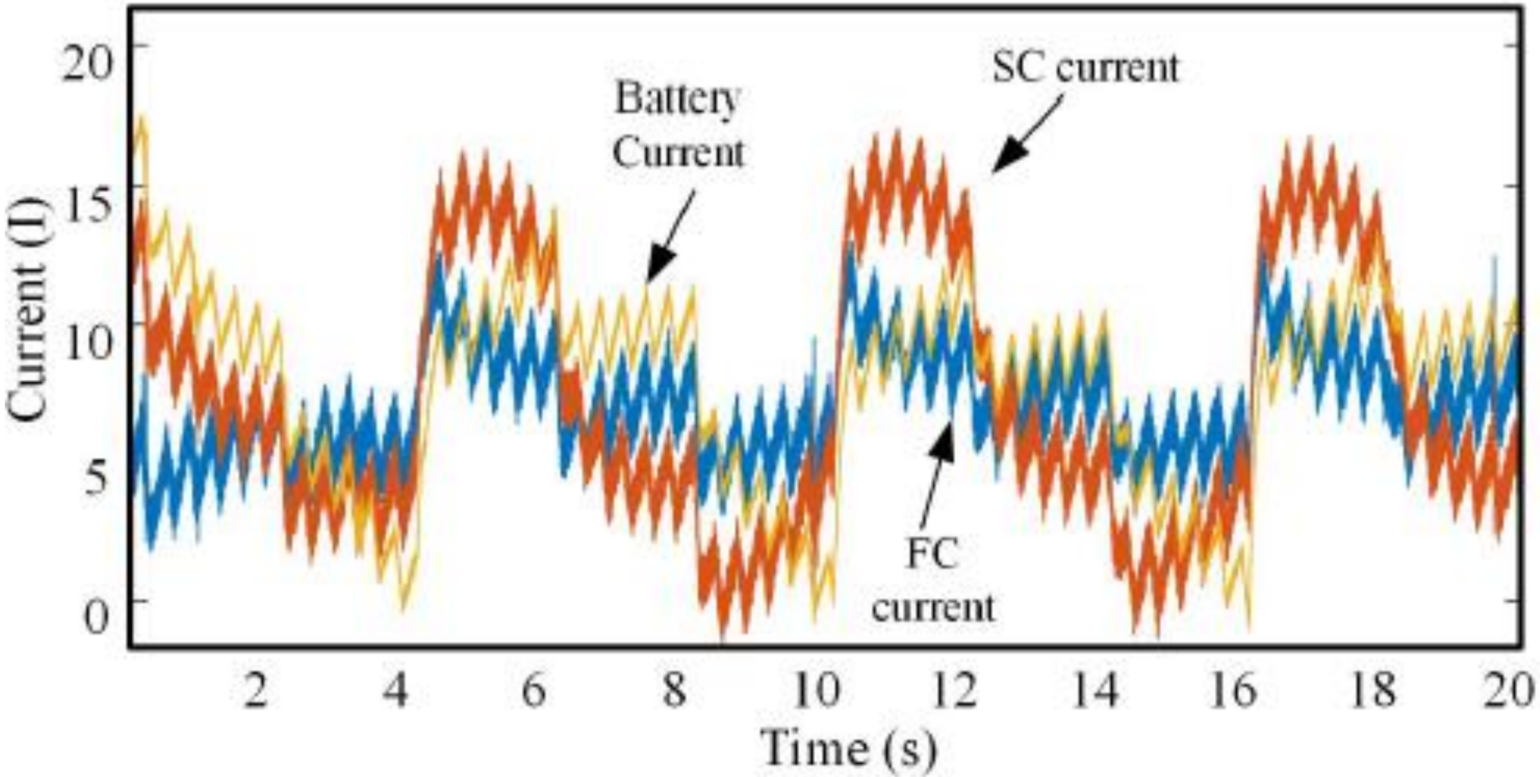
PV arrays are considered to produce:
A constant current of 60 A for 2 seconds.
A constant current of 70 A for 2 seconds.
A constant current of 80 A for 2 seconds.

Three ESS to supply the load and absorb the variations produced by the PV arrays.

HIL Results

It is seen that all ESS currents are different from each other.

FC has the smoothest current.
SC is responsible for producing the variations.



Conclusion

- ✓ A DC microgrid with different kinds of ESS is considered.
- ✓ An adaptive droop control method is proposed to decouple any variations exist in the generation or load side.
- ✓ The method splits the demanded currents into low and high-frequency components.
- ✓ Each component of the required power is assigned to different ESS, according to their intrinsic characteristics.
- ✓ The proposed method addresses redundancy by providing the ability to assign the controllers to any sources of the system.

Questions