Overview of Microgrid Research

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With content from Waterloo's microgrid researchers: Baheej Alghamdi, Mariano Arriaga, Samuel Cordova, Indrajit Das, Mostafa Farrokhabadi, Jose Lara, Fulong Li, William Mendieta, Ehsan Nasr, Daniel Olivares, Mauricio Restrepo, David Romero, Bharat Solanki, Behnam Tamimi, Nils van der Blij, Walter Violante.

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Power & Energy Systems

- One of the largest and broadest Power Groups in Canada and North America with 8 Professors.
- Broad expertise covering practically all areas in power engineering research:
  - Power Systems: optimization, planning, control, stability, modeling, simulation, renewables, etc.
  - Distributions Systems: power quality, automation, reconfiguration, distributed generation, etc.
  - Electricity Markets: auctions, ancillary services, capacity markets, etc.
  - High Voltage: insulation, nano-insulation materials, partial discharge, etc.
  - Power Electronics: converters, controls, FACTS, HVDC, etc.
  - Protections: dc grids, dc breakers, etc.
  - Smart Grids: intelligent loads, ADNs, EVs, microgrids, etc.
- Established international reputation of faculty members and program (5 IEEE Fellows).
- Unique research facilities.
- Outstanding students (multiple awards and scholarships).
- Many grants/contracts from government and industry.
- Multiple international collaborations (e.g. US, Europe, Middle-East) and industrial partners (e.g. Hydro One, ABB, SNC Lavalin).

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Canizares' Group

- Smart grids:
  - The Energy Hub Management System (EHMS):
    - Pilots.
    - Architecture.
    - Residential deployment.
    - Commercial and Industrial EHMS.
    - Local Distribution Company (LDC) EHMS (DMS).
  - Energy hub simulator.
  - Incentive design for voltage optimization programs for industrial loads.
  - Voltage optimization for smart industrial loads.
- Renewable Energy Sources (RES) integration:
  - Power system stability considering power converter interfaces and uncertainties associated with intermittent renewable energy sources.
  - Decision-making and planning tools for investors and planners.
- Electric Vehicles (EVs):
  - Grid impact.
  - Smart charger design, construction, and application.
  - Distribution feeder EV smart charging management.

Canizares' Group

- FACTS:
  - Static and dynamic modeling and control.
  - Hybrid Power Flow Controller (HPFC) modeling and grid applications and studies.
- Energy storage:
  - Compress Air Energy Storage (CAES).
  - Distributed Battery Energy Storage Systems (BESS).
  - Flywheel Energy Storage (FES).
  - Thermal energy storage (TES).
  - Energy Storage System (ESS) services and applications, with focus on Ontario-Canada.
- Microgrids:
  - Canadian remote community microgrids.
  - Deterministic and “uncertain” Energy Management Systems (EMS) .
  - Stability modeling, analysis, definitions, and classifications.
  - Unbalanced Voltage Stabilizer (UVS).
  - Voltage-Frequency Control (VFC).
  - Optimal planning.
  - Testbed facility at Canadian Solar (CANREL).

Microgrid Partners

NSERC
CRSNG

NSERC SMART MICROGRID NETWORK
nsmg-net

hydro one

CanadianSolar

RDC^2 MT
H2020-MSCA-RISE

WWF

KIT
Karlsruhe Institute of Technology

PONTIFICIA
UNIVERSIDAD
CATÓLICA
DE CHILE

HATCH™

Natural Resources Canada
Ressources naturelles Canada

Canada

KASABONIKA LAKE FIRST NATION

INNOVUS
POWER

NSERC
Energy Storage
Technology Network

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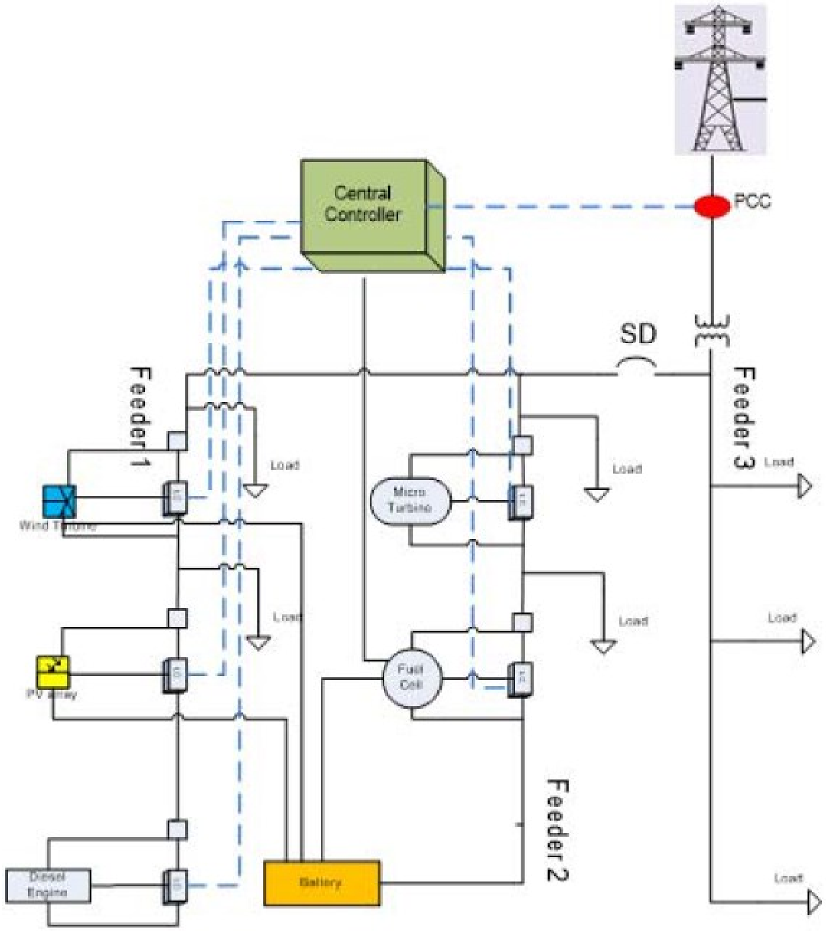
Outline

- Research objectives and definitions
- Energy Management Systems (EMS)
- Stability analysis, modeling and control
- Optimal planning
- Canadian Renewable Energy Laboratory (CANREL)
- DC microgrids

Research Objectives

- Dynamic and static modeling, simulation and analysis of microgrids.
- Design optimal microgrids considering local renewable energy sources (wind, hydro, biomass, geothermal, solar), and most appropriate economically, technically, and socially considering the special conditions of remote communities (climate, location, community).
- Develop dispatch and control technologies for microgrids to properly integrate and control multiple and variable renewable energy sources, storage, and smart loads, considering a connection to the grid.

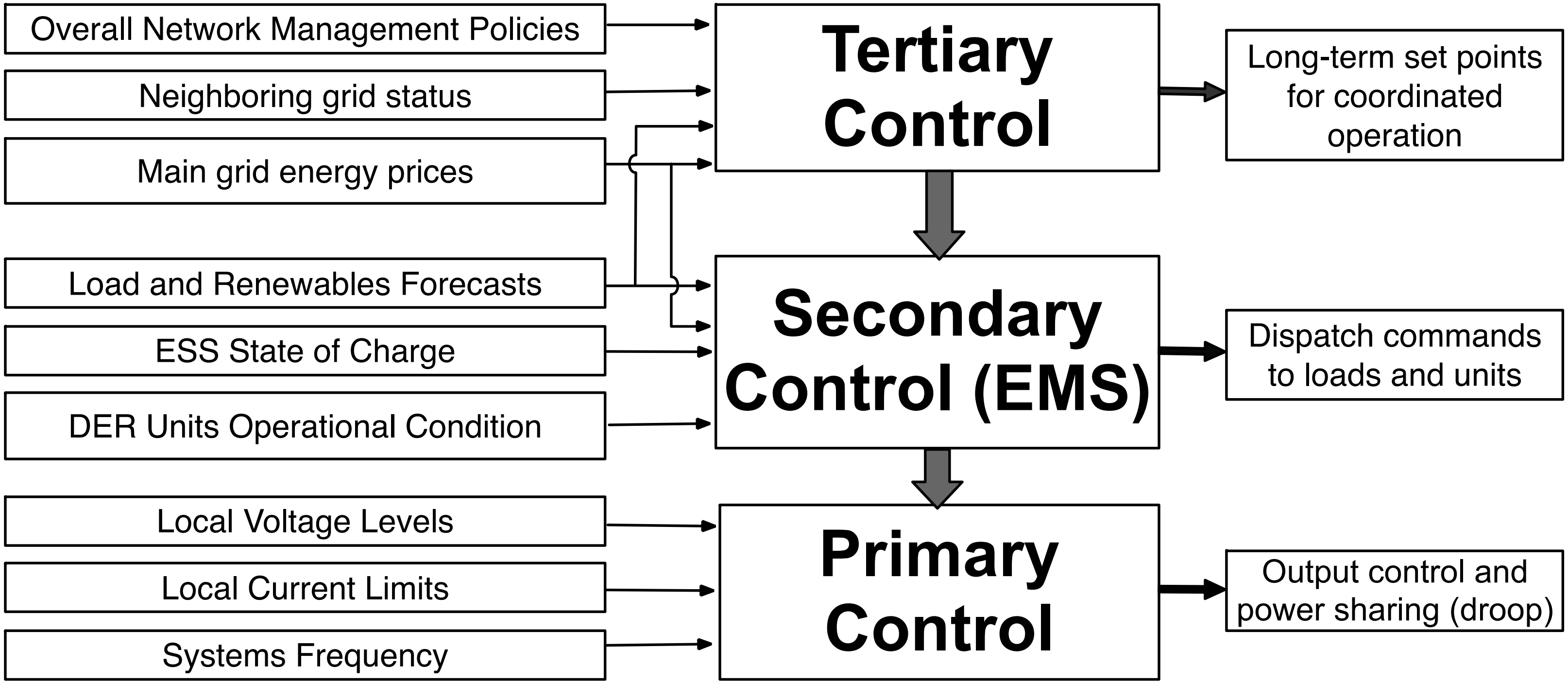
Definitions



- A “small” grid from some kW to a few MW.
- A “local” grid serving a well-identified, “contained” region.
- Operates at distribution system voltage levels, i.e., medium voltage (a few kV).
- Contains “various” DG units and possibly some energy storage.
- Has enough capacity to supply all or at least most of the loads of the local grid.
- Grid connected: has one well-identifiable point of connection to the transmission system or “rest” of the distribution grid (Point of Common Coupling or PCC).
- Isolated (islanded): operates independently of the “large” grid.

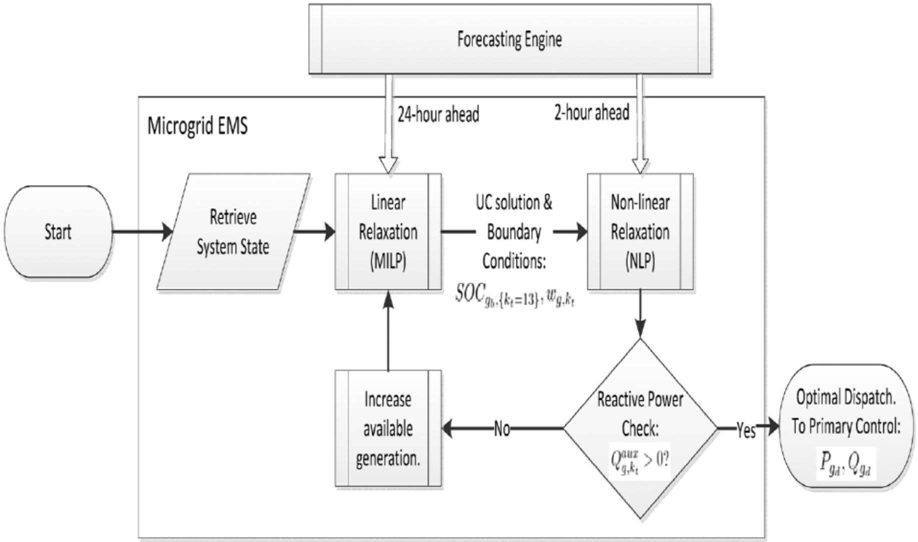
EMS

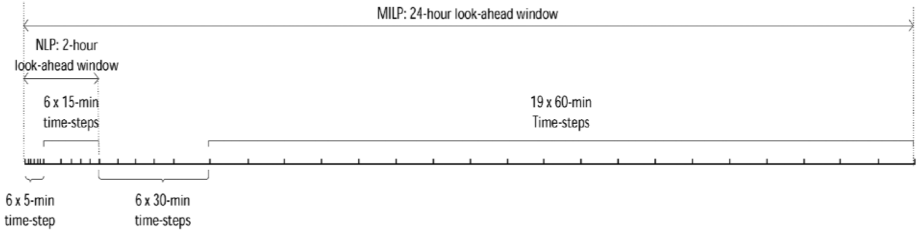
- IEEE PES TF in Microgrid Control, “Trends in Microgrid Control,” *IEEE Transactions on Smart Grid*, vol. 6, no. 4, July 2014, pp. 1905-1919:



Unbalance and Decoupled EMS

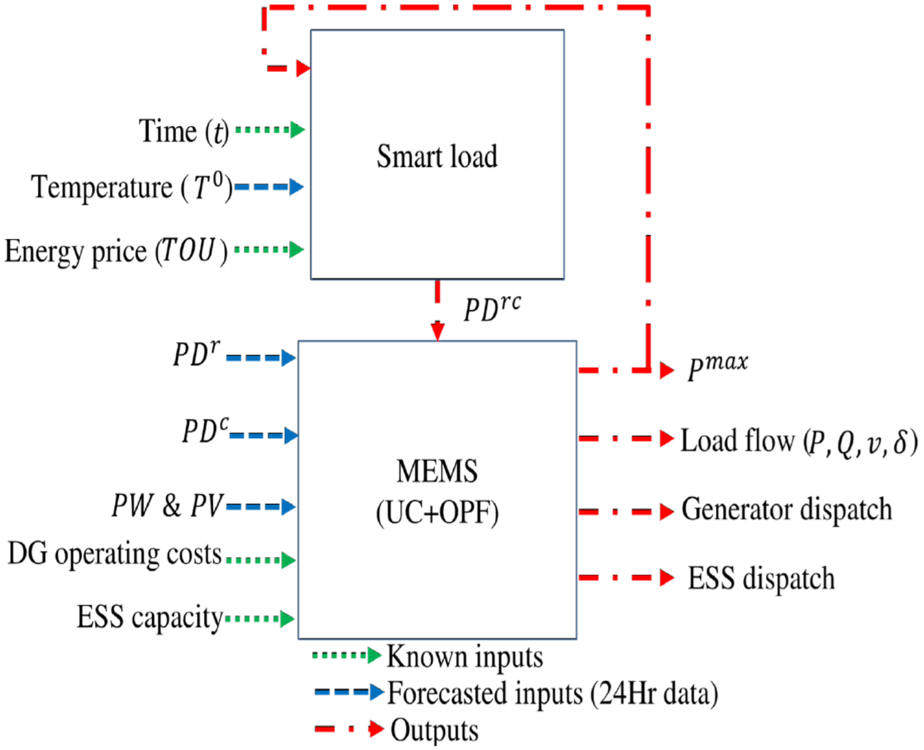
- D. Olivares, C. A. Cañizares, and M. Kazerani, “A Centralized Energy Management System for Isolated Microgrids,” IEEE Transactions on Smart Grid, vol. 6, no. 4, July 2014, pp. 1864-1875.
- Decoupled approach:
    - UC and Economic Load Dispatch (ELD) performed with different update rates.
    - Two different resolutions and horizons of forecast.
    - Multi-stage ELD to optimize ESS operation.
    - Delivers UC decisions and operating points to DERs (power output of DG, output/input of ESS, shiftable/shedable loads commands, etc.). Simplified version integrated into Hatch’s microgrid controller.
    - Detailed 3-phase model to represent unbalanced conditions typical of microgrids (distribution networks).

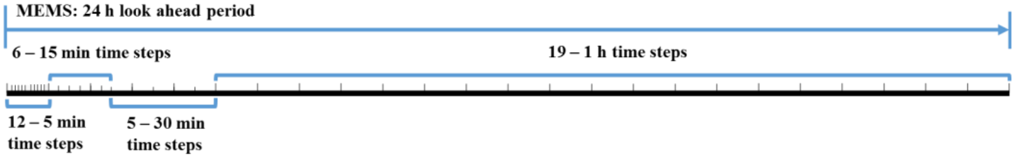




Coupled EMS with Smart Loads

- B. V. Solanki, A. Raghurajan, K. Bhattacharya, and C. A. Cañizares, "Including Smart Loads for Optimal Demand Response in Integrated Energy Management Systems for Isolated Microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 4, July 2017, pp. 1739-1748.
- Microgrid EMS (MEMS) considers:
  - Residential controllable loads.
  - Unit Commitment (UC) for Distributed Energy Resources (DERs) and power flow constraints simultaneously.
- A Neural Network (NN) based Residential Controllable Lod Porfile Estimator (RCLPE) is used to determine smart load models.
- MPC is used to account for uncertainties associated with renewables and electricity demand.





Multi-objective UC EMS

- B. V. Solanki, K. Bhattacharya, and C. A. Cañizares, "A Sustainable Energy Management System for Isolated Microgrids," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, October 2017, pp. 1507-1517.
- Microgrid EMS (MEMS) considers:
  - Residential controllable loads (demand response).
  - Unit Commitment (UC) with MPC and multiple objectives:
    1. Operating cost minimization: J_{op}
    2. Emission cost minimization: J_{em}
    3. Emission and operating costs minimization: $J_{oc} = J_{op} + J_{em}$
    4. Emission and operating costs normalized Pareto-optimal:

$$J_{cp} = \sqrt{\left(\frac{J_{op} - \underline{J}_{op}}{\bar{J}_{op} - \underline{J}_{op}}\right)^2 + \left(\frac{J_{em} - \underline{J}_{em}}{\bar{J}_{em} - \underline{J}_{em}}\right)^2}$$

    5. Emission and operating costs deviation minimization:

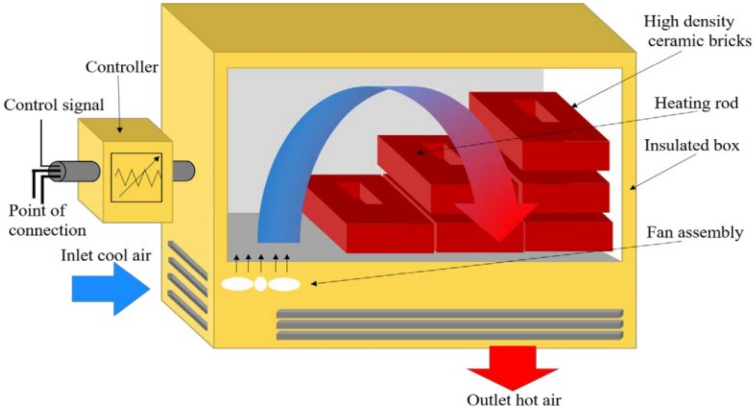
$$J_{gp} = wD_1 + (1 - w)D_2$$

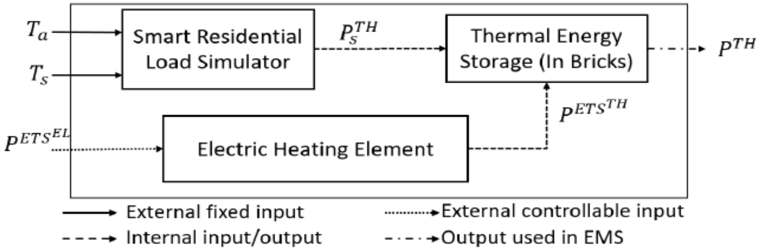
$$D_1 = J_{op} - A_1$$

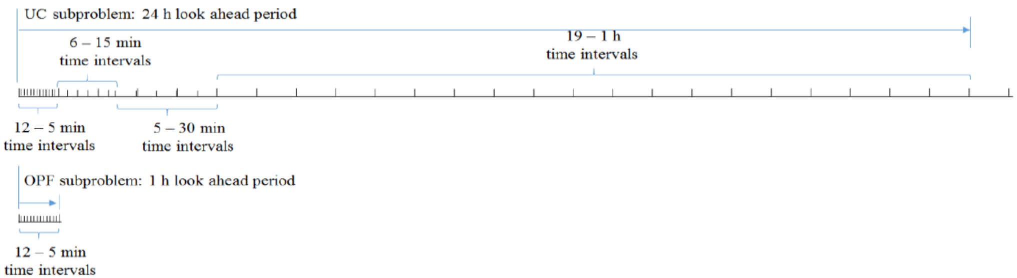
$$D_2 = J_{em} - A_2$$

Decoupled EMS with Thermal Energy Storage (TES)

- P. Sauter, B. V. Solanki, C. A. Cañizares. K. Bhattacharya, and S. Hohmann, “Electric Thermal Storage System Impact on Northern Communities' Microgrids,” *IEEE Transactions on Smart Grid*, vol. 10, no.1, January 2019, pp. 852-863.
- Microgrid EMS (MEMS) considers:
  - Residential controllable energy storage.
  - Decoupled Unit Commitment (UC) and OPF with MPC to manage renewables uncertainty.
- Thermal demand is transformed into electricity demand using a Smart Residential Load Simulator (SRLS).



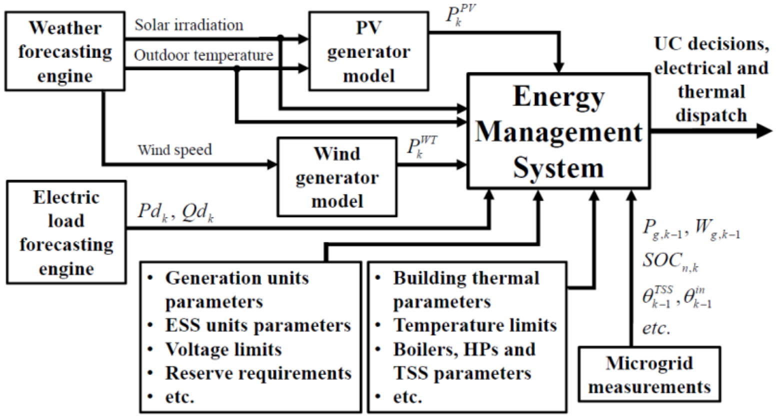




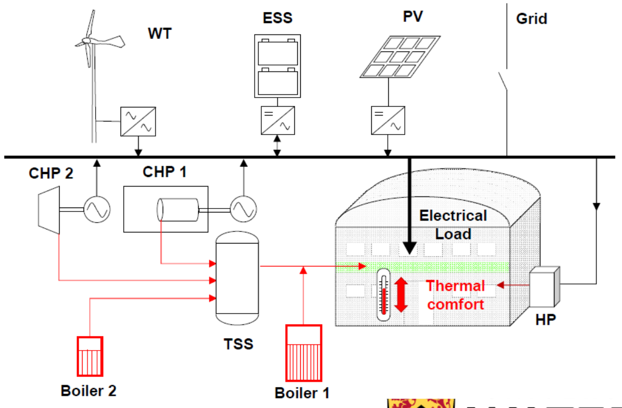
Thermal Energy Resources EMS

- W. Violante, C. A. Cañizares, M. A. Trovato, and G. Forte, “An Energy Management System for Isolated Microgrids with Thermal Energy Resources,” *IEEE Transactions on Smart Grid*, vol. 11, No. 4, July 2020, pp. 2880-2891.
- EMS considering multiple thermal energy resources:
  - Combined Heat and Power (CHP).
  - Boilers.
  - Heat pump.
  - Building.
  - Water tank TES.

- EMS framework based on a UC MILP model:

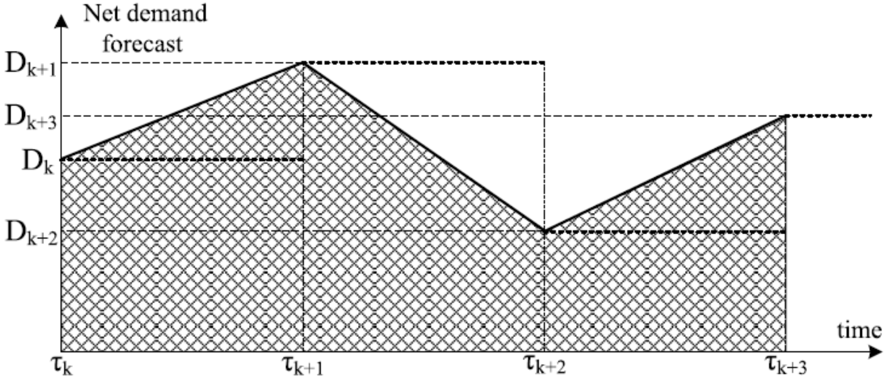


- PrInCE microgrid at the Politecnico di Bari:



UC Considering Frequency Control

- M. Farrokhabadi, C. A. Cañizares, and K. Bhattacharya, “Unit Commitment for Isolated Microgrids Considering Frequency Control,” *IEEE Transactions on Smart Grid*, vol. 9, no.4, July 2018, pp. 3270-3280.
- Frequency control is integrated into the UC problem:
  - Conventional UC formulations assumes fixed generation power output between dispatch periods.
  - In practice, these units participate in frequency control thus changing their output within dispatch intervals.
  - The generation output is assumed to change using a linear model, resulting in a UC mixed integer quadratic programming problem (linear constraints and quadratic objective function).

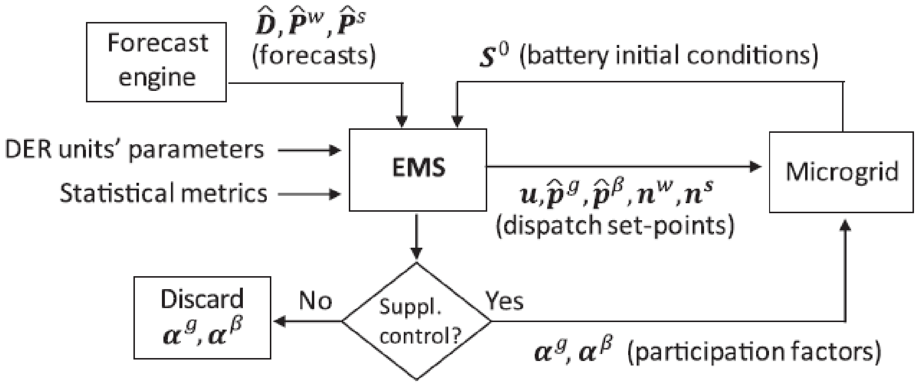


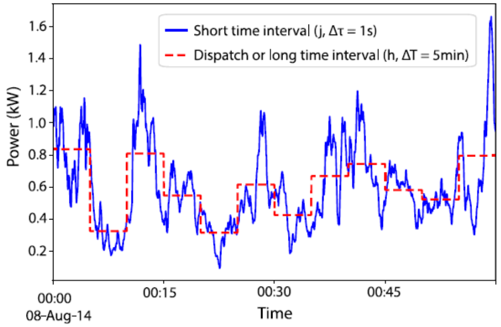
Practical EMS

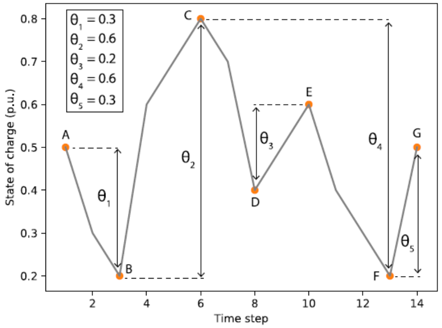
- B. Solanki, C. A. Cañizares, and K. Bhattacharya, "Practical Energy Management Systems for Isolated Microgrids," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, September 2019, pp. 4762-4775.
- Based on a linearization approach considering the fact that network losses and voltage drops across feeders are relatively small in isolated microgrids.
- EMS models are Mixed Integer Quadratic Programming (MIQP) problems.
- Require less computation time and are thus suitable for online applications.

EMS with RES Variability and BESS Degradation

- S. Cordova, C. A. Cañizares, A. Lorca, D. E. Olivares, “An Energy Management System with Short-Term Fluctuation Reserves and Battery Degradation for Isolated Microgrids,” *IEEE Transactions on Smart Grid*, vol. 12, no. 6, November 2021, pp. 4668-4680.
- Model considers:
  - Intra-dispatch fluctuations.
  - Battery degradation.
  - Reserves:
    - Forecast error reserves.
    - Regulation reserves.
    - Operation impact of reserves thru an Expected Reserve Utilization (ERU) concept.
  - Droop frequency control.

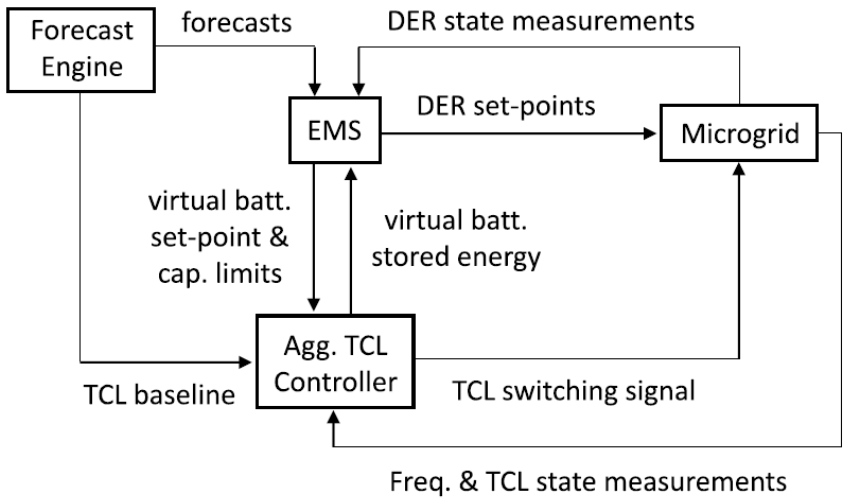






EMS with Thermostatic Virtual Battery

- S. Cordova, C. A. Cañizares, A. Lorca, D. E. Olivares, “Aggregate Modeling of Thermostatically Controlled Loads for Microgrid Energy Management Systems,” *IEEE Transactions on Smart Grid*, submitted July 2022 (under revision), 10 pages.
- Model considers:
  - Aggregated thermostatic flexible loads dispatched as a virtual battery.
  - Dynamic third-order thermal models of homes.
  - Thermostatically Controlled Loads (TCL) with communication delays, uncertainty, and time variability.
  - Frequency control.



Forecast Engine

forecasts

DER state measurements

EMS

DER set-points

Microgrid

virtual batt. set-point & cap. limits

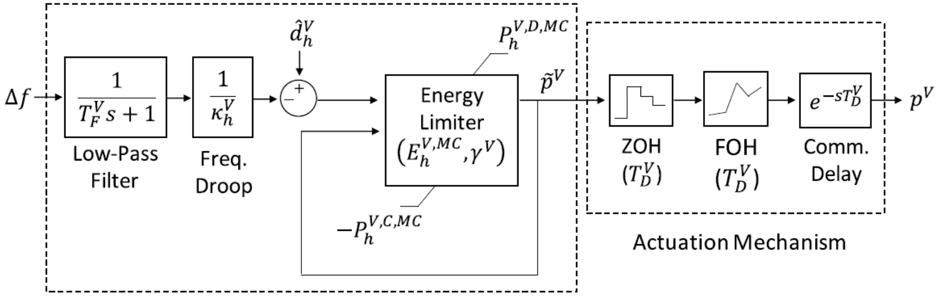
virtual batt. stored energy

Agg. TCL Controller

TCL baseline

TCL switching signal

Freq. & TCL state measurements



Δf

$\frac{1}{T_F^V s + 1}$

Low-Pass Filter

$\frac{1}{\kappa_h^V}$

Freq. Droop

$\hat{d}_h^V$

$+$

$-$

$P_h^{V,D,MC}$

Energy Limiter $(E_h^{V,MC}, \gamma^V)$

$-P_h^{V,C,MC}$

$\tilde{p}^V$

ZOH (T_D^V)

FOH (T_D^V)

$e^{-sT_D^V}$

Comm. Delay

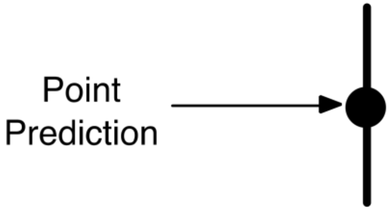
p^V

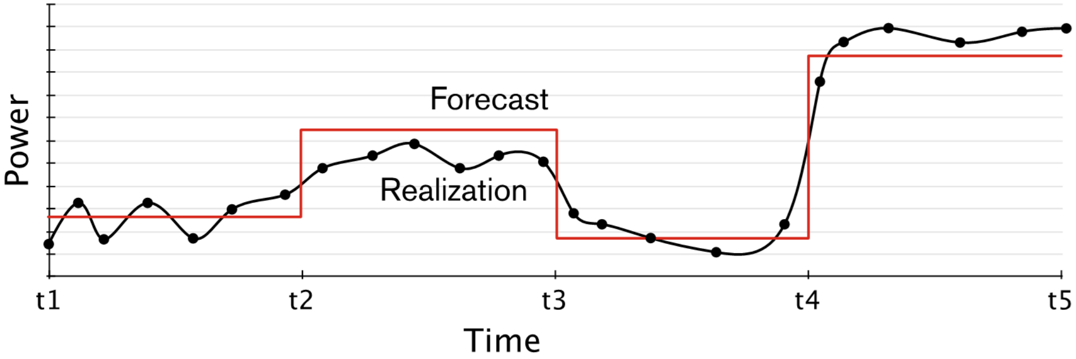
Actuation Mechanism

Virtual Battery Controller

EMS With Uncertainties

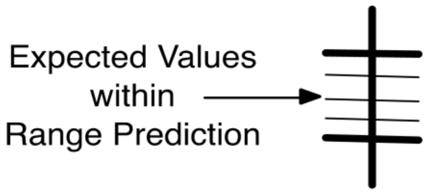
- Uncertainty in the UC can be addressed in three ways:
  1. Wait-and-see (deterministic with MPC/RCH models):
     - Close tracking of the problem with small time steps, solving the dispatch problem using the most current information, and including an explicit reserve requirement.
     - Assumes that point forecasts are accurate and the system natural reserve can handle the mismatches, otherwise shed load.

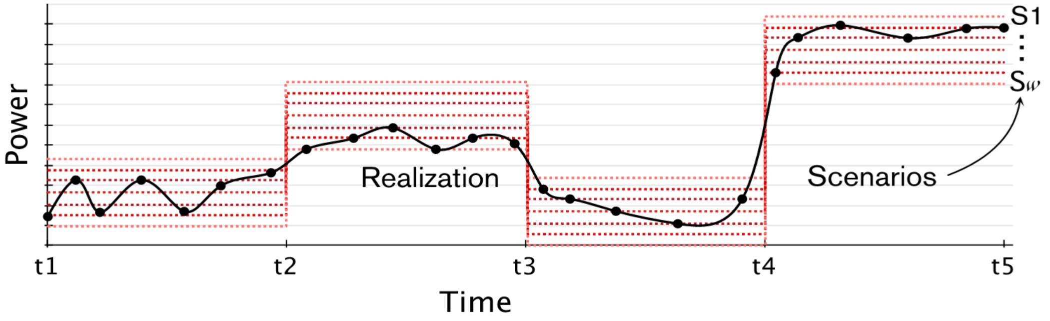




EMS With Uncertainties

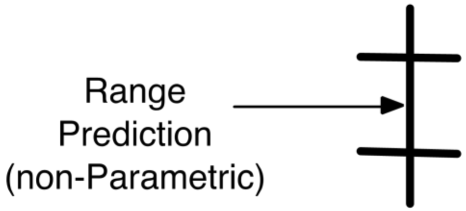
2. Stochastic optimization:
   - Minimize the expected cost over a discrete representation of the uncertainty, leading to large-scale problems.
   - Accounts directly for the stochastic characteristic of wind power, improving the ability of the system to perform corrective actions without load shedding.
   - First stage variables provide probabilistic guarantee on the feasibility of all second stage expected outcomes.
   - D. Olivares, J. D. Lara, C. A. Cañizares, and M. Kazerani, "Stochastic-Predictive Energy Management System for Isolated Microgrids," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, November 2015, pp. 2681- 2693

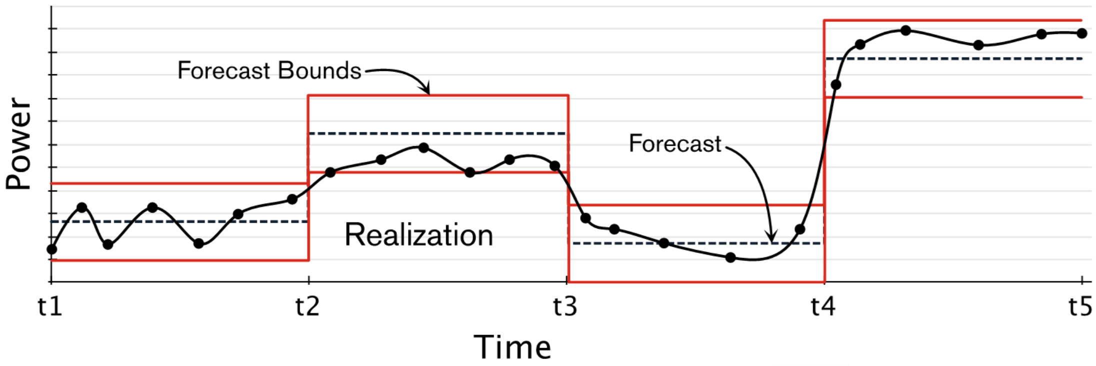




EMS With Uncertainties

3. Intervals:
    - Does not require any probabilistic modeling.
    - Determines a solution that guaranties feasibility for any realization within the bounds of the uncertainty set.
    - Bounds can be given or calculated based on the historical forecast error.
    - Uncertainty sets are able to relate the risk preference of the operator with the choice of the uncertainty set, incorporating probabilistic information if available.
    - Methods:
        - J. Lara, D. Olivares, and C. A. Cañizares, “Robust Energy Management System of Isolated Microgrids,” *IEEE Systems Journal*, vol. 13, No.1, March 2019, pp. 680-691.
        - D. F. Romero and C. A. Cañizares, “An Affine Arithmetic-Based Energy Management System for Isolated Microgrids,” *IEEE Transactions on Smart Grid*, vol. 10, no. 3, May 2019, pp. 2989-2998.



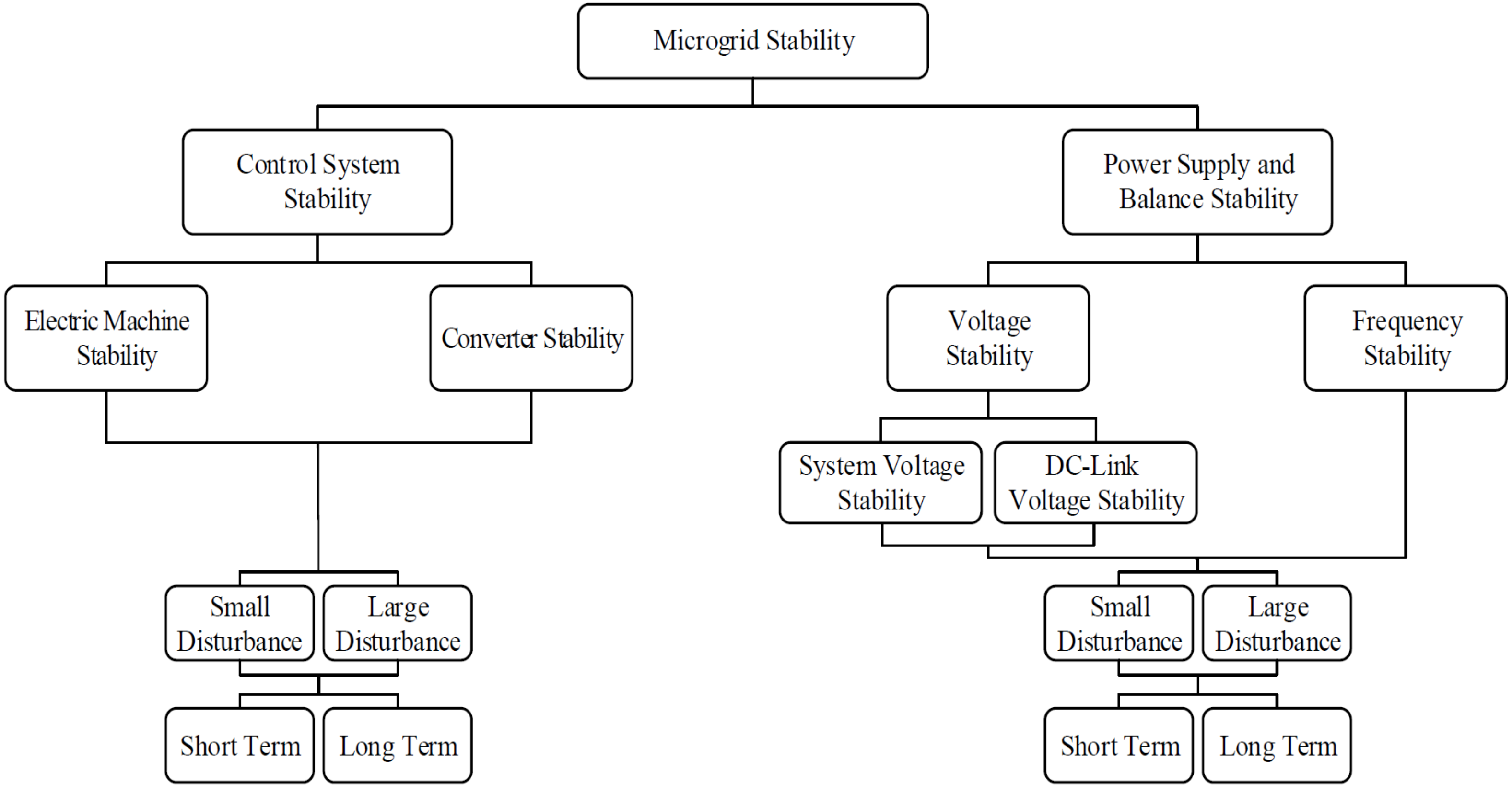


Stability

- References:
  - M. Farrokhabadi, S. König, C. A. Cañizares, K. Bhattacharya, and T. Leibfried, “Energy Storage System Models for Microgrid Stability Analysis and Dynamic Simulation,” *IEEE Transactions on Power Systems*, vol. 33, no. 2, March 2018, pp. 2301-2312.
  - IEEE PES TF Microgrid Stability Analysis and Modeling, “Microgrid Stability Definitions, Analysis, and Examples,” Technical Report PES-TR-66, May 2018, 120 pages.
  - IEEE-PES Task Force on Microgrid Stability Analysis and Modeling, “Microgrid Stability Definitions, Analysis, and Examples,” *IEEE Transactions on Power Systems*, vol. 35, no. 1, January 2020, pp. 13-29.

Stability

- Definitions and classification:

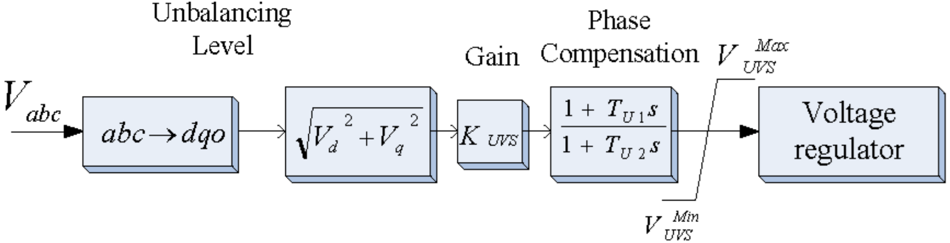


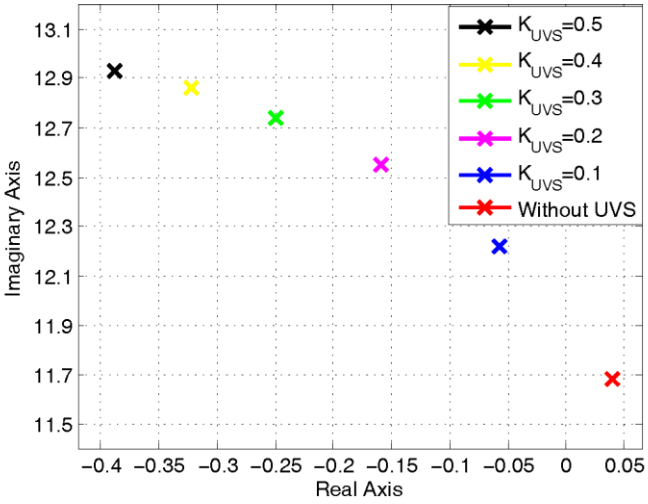
Stability

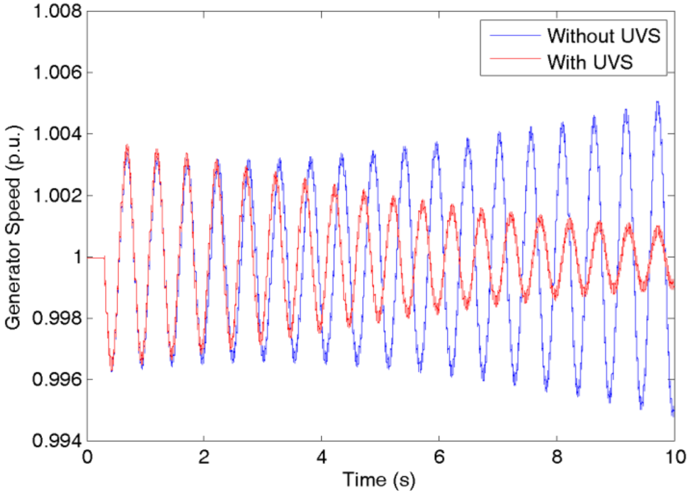
Category	Control System Stability		Power Supply and Balance Stability	
Subcategory	**Electric Machine**	**Converter**	**Voltage**	**Frequency**
Root Cause	Poor controller tuning	Poor controller tuning, PLL bandwidth, PLL synchronization failure, harmonic instability	DERs power limits, inadequate reactive power supply, poor reactive power sharing, load voltage sensitivities, dc-link capacitor	DERs active power limits, inadequate active power supply, poor active power sharing
Manifestation	Undamped oscillations, aperiodic voltage and/or frequency increase or decrease	Undamped oscillations, low steady-state voltages, high-frequency oscillations	Low steady-state voltages, large power swings, high dc-link voltage ripples	High rate of change of frequency, low steady-state frequency, large power and frequency swings

UVS

- Adding an Unbalanced Voltage Stabilizer (UVS) to DER voltage regulators improves microgrid stability:
  - E. Nasr, C. A. Cañizares, and K. Bhattacharya, “Stability Analysis of Unbalanced Distribution Systems With Synchronous Machine and DFIG Based Distributed Generators,” *IEEE Transactions on Smart Grid*, vol. 5, no. 5, September 2014, pp. 2326-2338.







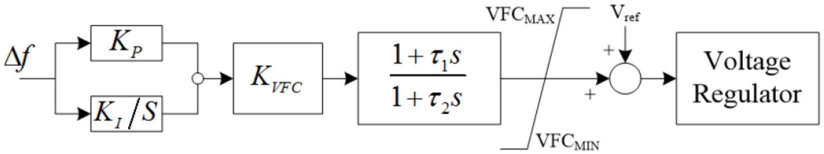
VFC

- M. Farrokhabadi, C. A. Cañizares, and K. Bhattacharya, “Frequency Control in Isolated/Islanded Microgrids Through Voltage Regulation,” *IEEE Transactions on Smart Grid*, vol. 8, no. 3, May 2017, 1185-1194.
- Based on voltage dependency of microgrids loads:

$$P = P_0\left(\frac{V}{V_0}\right)^{n_p} \xrightarrow{n_p=1.5} \Delta P_D = \left((V+\Delta V)^{1.5} - V^{1.5}\right)\frac{P_0}{V_0^{1.5}}$$

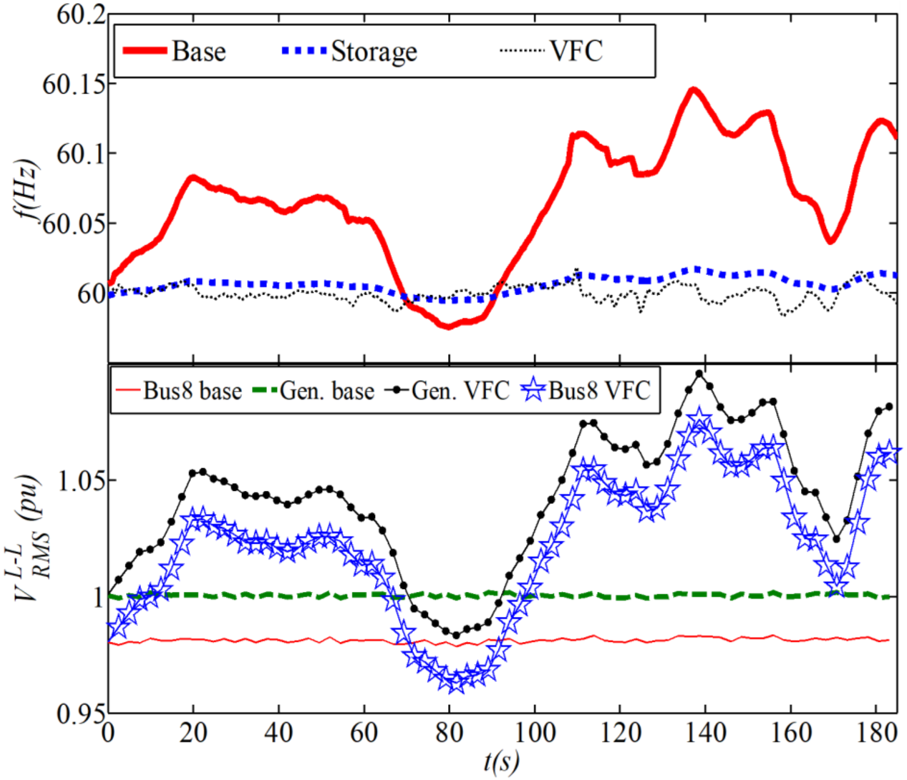
$$\xrightarrow[\Delta V=5\%]{V=V_0=1\text{ pu}} \Delta P_D = \left((1+\Delta V)^{1.5}-1\right)P_0 = 7.6\% P_0$$

- Hence, a controller similar to a PSS can be added to any microgrid voltage regulator:



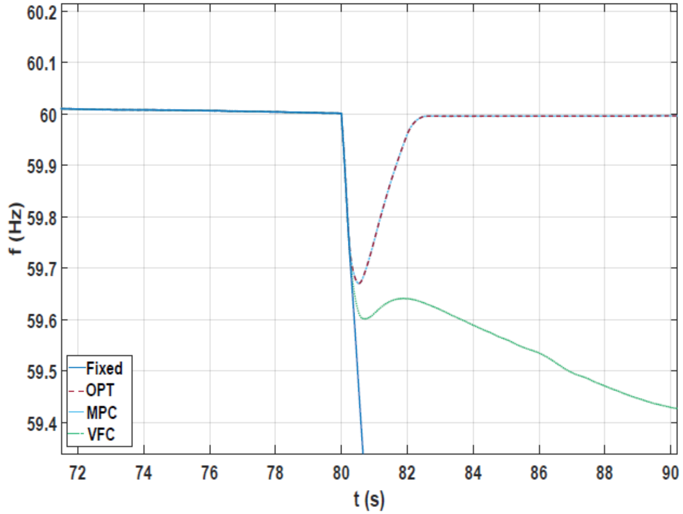
- Integrated into Hatch’s microgrid controller.

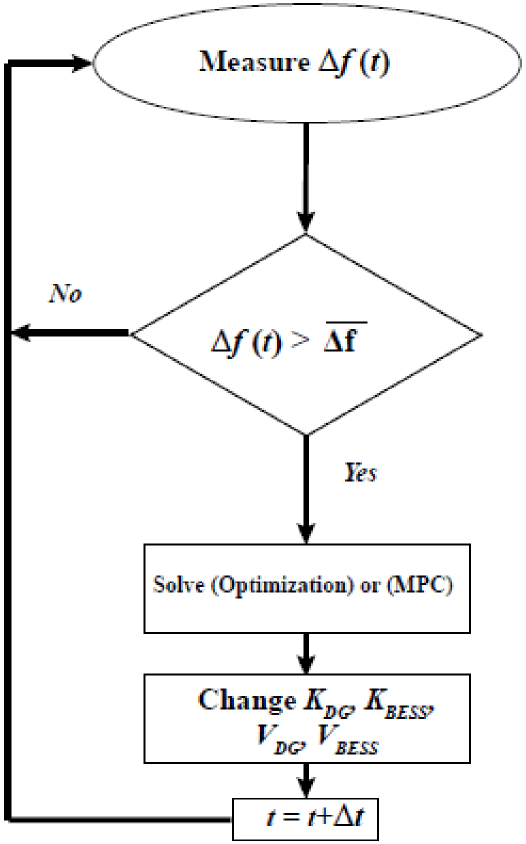
- Application to benchmark test system:



Optimal Frequency Regulation

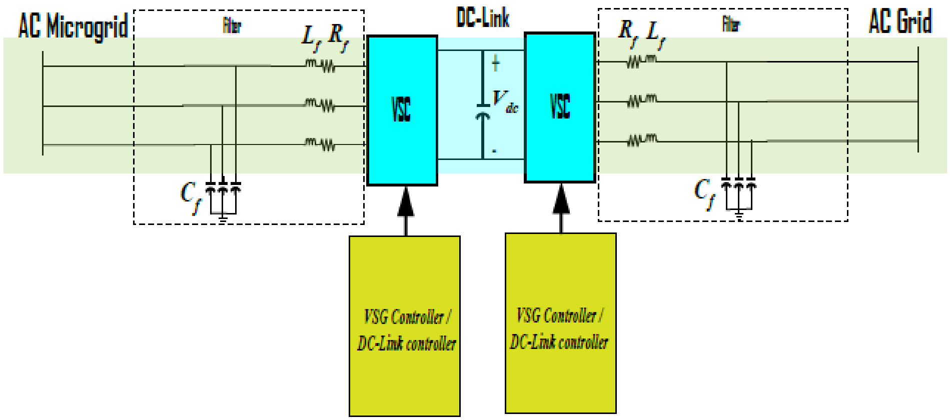
- B. Alghamdi and C. A. Cañizares, “Frequency Regulation in Isolated Microgrids through Optimal Droop Gain and Voltage Control,” *IEEE Transactions on Smart Grid*, September 2020, vol. 12, no. 2, March 2021, pp. 988-998.
- Optimal MPC approach to adjust droop gains and voltage setpoints of DERs to enhance primary frequency regulation in microgrids:

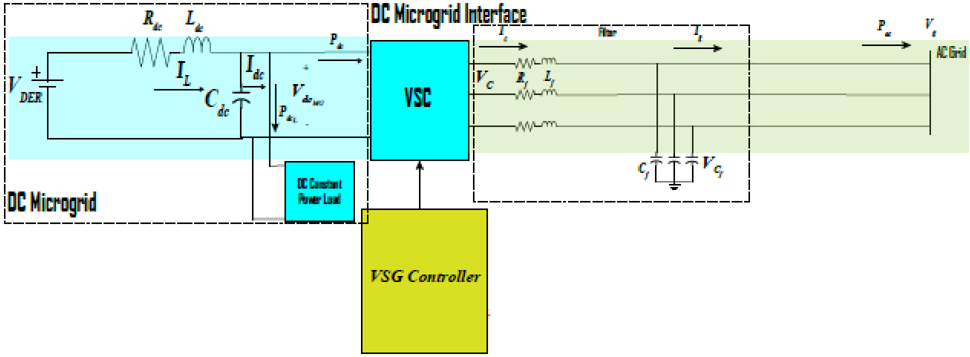


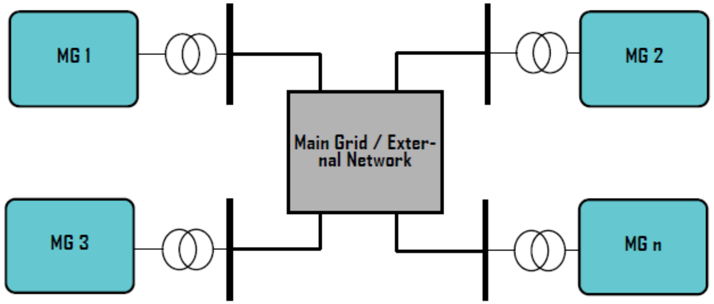


Decentralized AC/DC Microgrid Controls

- B. Alghamdi and C. A. Cañizares, “Stability Enhancement of a Grid of Microgrids through VSG Interfaces,” *Applied Energy*, Microgrids 2021 Special Issue, vol. 310, March 2022, pp 1-15.
- Interfaces based on Virtual Synchronous Generators (VSGs) for ac and dc interconnected microgrids:
  - Frequency support to individual ac microgrids and host ac grid.
  - Voltage support for dc microgrids.

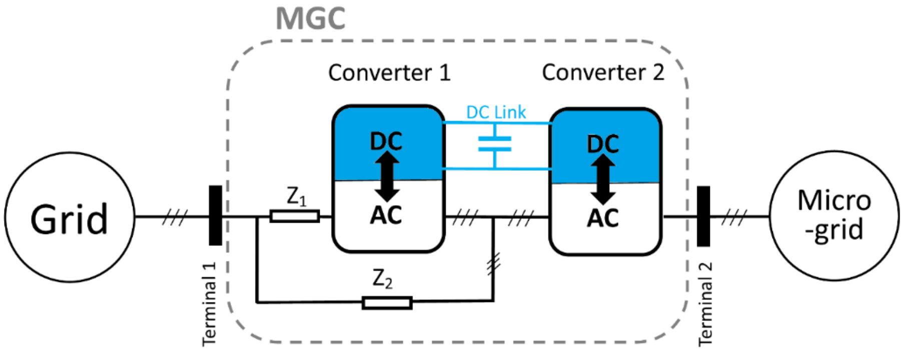


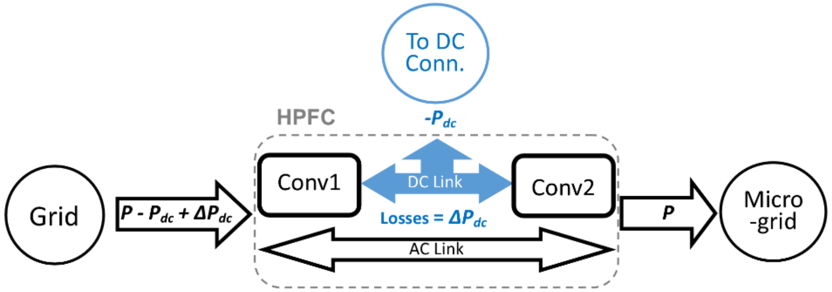




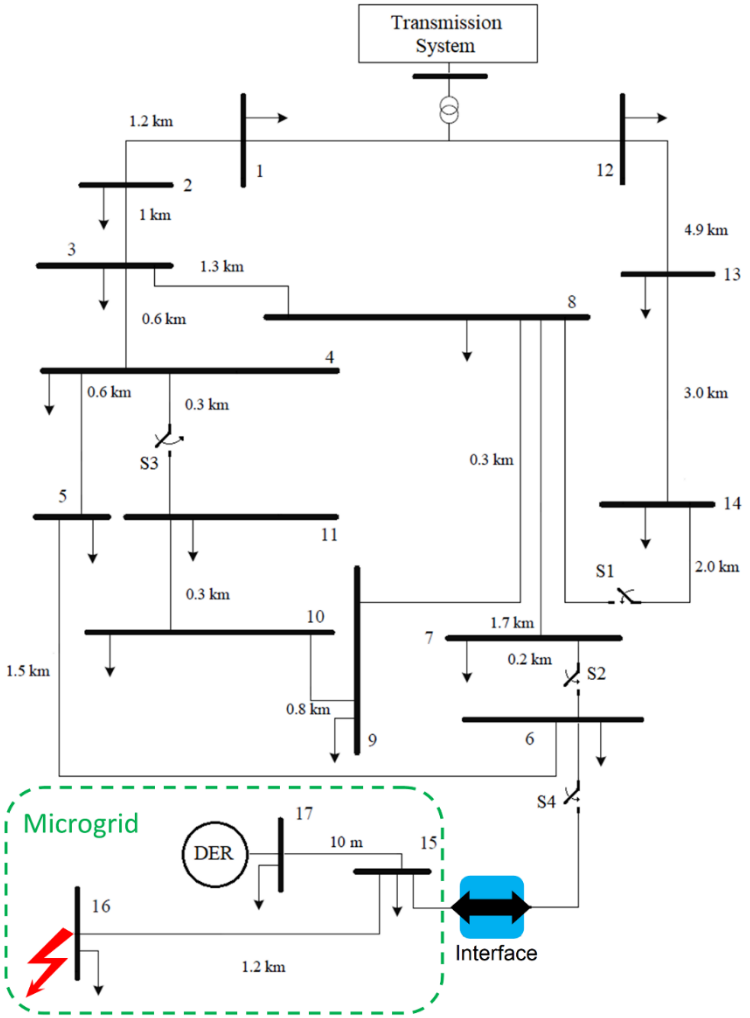
MGC

- B. Tamimi and C. A. Cañizares, “An Effective Controllable Grid Interface for Microgrids,” *IEEE Transactions on Smart Grid*, accepted August 2022, 15 pages.
- Proposed connector:

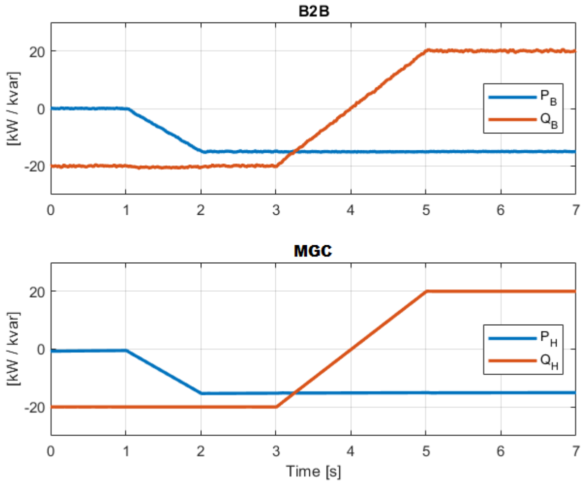




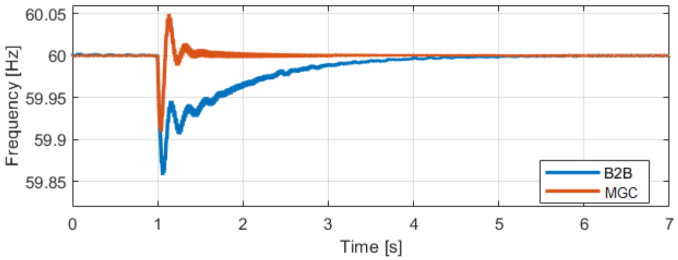
MGC



- Connector comparisons:
  - Power exchange control:



  - MG generation loss:



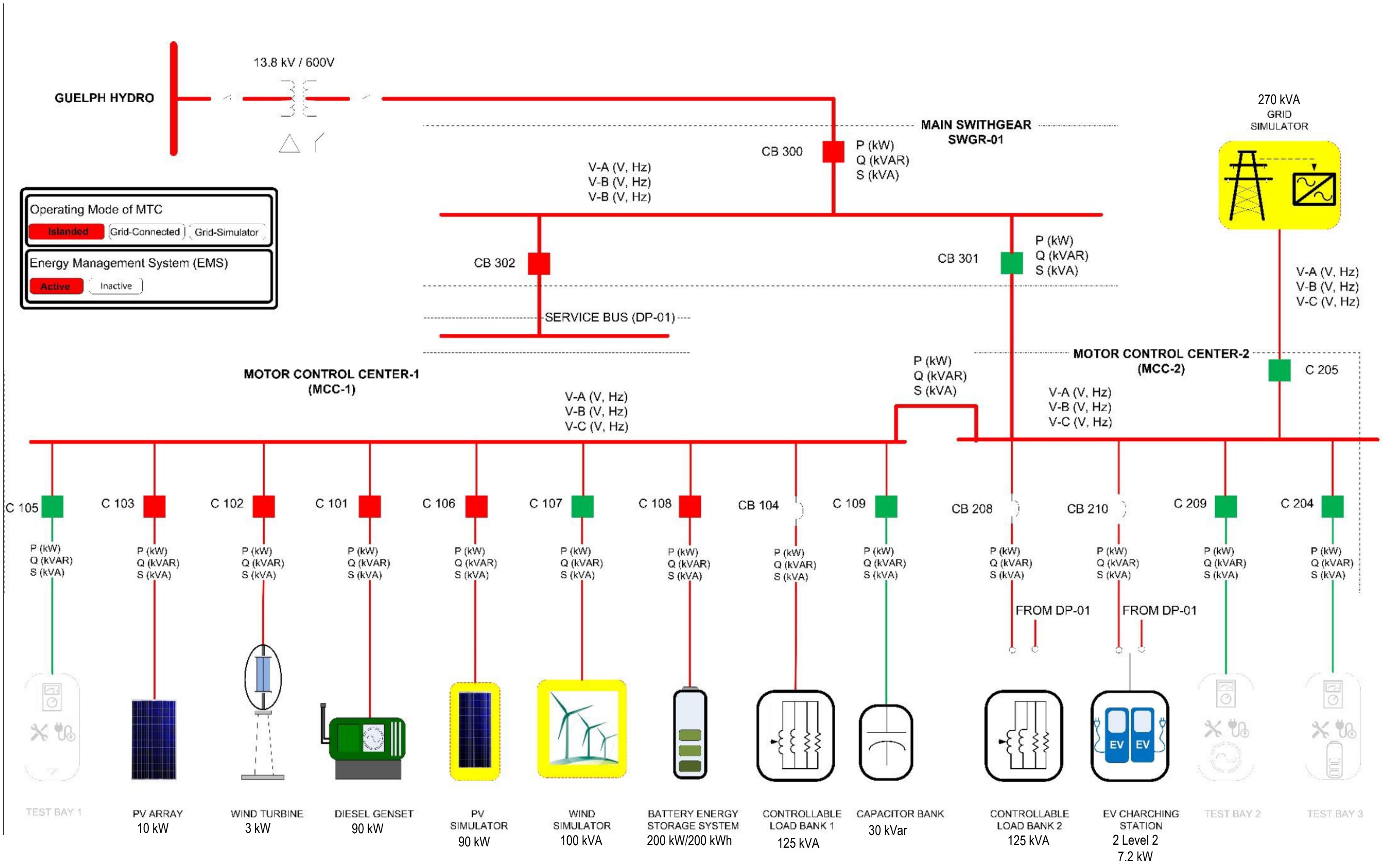
CANREL

- E. Nasr-Azadani, P. Su, W. Zhenga, J. Rajda, C. Cañizares, M. Kazerani, E. Veneman, S. Cress, M. Wittemund, M. Manjunath, and N. Wrathall, “Canadian Renewable Energy Laboratory (CANREL) – A Testbed for Microgrids,” *IEEE Electrification Magazine*, vol. 8, no. 1, March 2020, pp. 49-60.

CanadianSolar KINECTRICS NCC

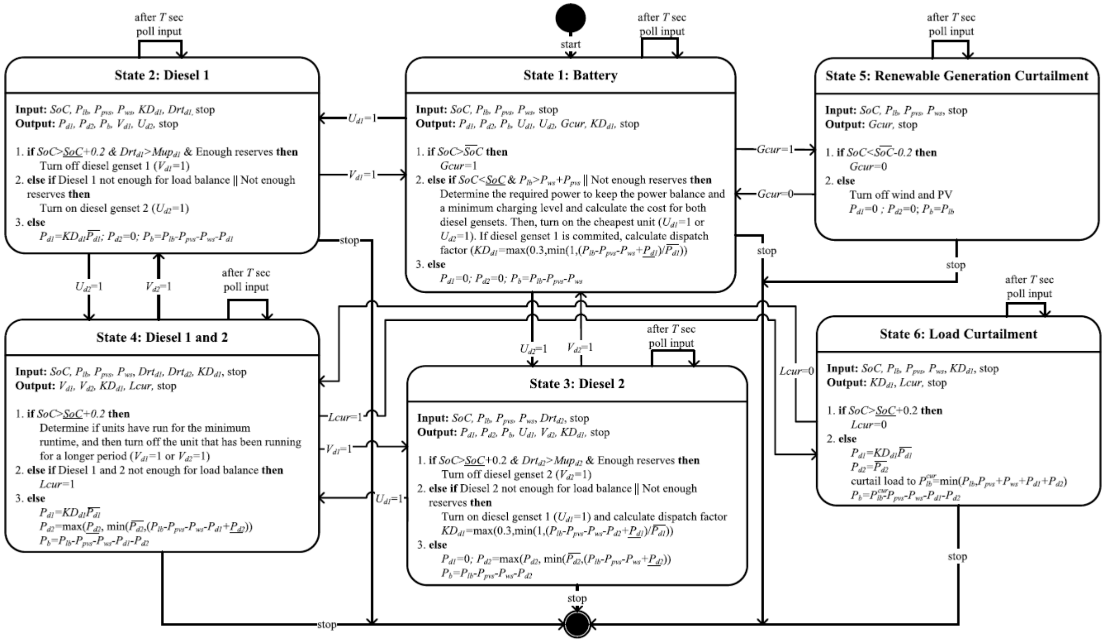
Guelph Hydro Electric Systems Inc. Ontario MINISTRY OF ENERGY UNIVERSITY OF WATERLOO

CANREL


GUELPH HYDRO
13.8 kV / 600V
MAIN SWITHGEAR
SWGR-01
CB 300
P (kW)
Q (kVAR)
S (kVA)
V-A (V, Hz)
V-B (V, Hz)
V-B (V, Hz)
270 kVA
GRID
SIMULATOR
Operating Mode of MTC
Islanded
Grid-Connected
Grid-Simulator
Energy Management System (EMS)
Active
Inactive
CB 302
CB 301
P (kW)
Q (kVAR)
S (kVA)
V-A (V, Hz)
V-B (V, Hz)
V-C (V, Hz)
SERVICE BUS (DP-01)
MOTOR CONTROL CENTER-1
(MCC-1)
V-A (V, Hz)
V-B (V, Hz)
V-C (V, Hz)
P (kW)
Q (kVAR)
S (kVA)
MOTOR CONTROL CENTER-2
(MCC-2)
C 205
V-A (V, Hz)
V-B (V, Hz)
V-C (V, Hz)
C 105
C 103
C 102
C 101
C 106
C 107
C 108
CB 104
C 109
CB 208
CB 210
C 209
C 204
P (kW)
Q (kVAR)
S (kVA)
FROM DP-01
FROM DP-01
EV
EV
TEST BAY 1
PV ARRAY
10 kW
WIND TURBINE
3 kW
DIESEL GENSET
90 kW
PV
SIMULATOR
90 kW
WIND
SIMULATOR
100 kVA
BATTERY ENERGY
STORAGE SYSTEM
200 kW/200 kWh
CONTROLLABLE
LOAD BANK 1
125 kVA
CAPACITOR BANK
30 kVar
CONTROLLABLE
LOAD BANK 2
125 kVA
EV CHARCHING
STATION
2 Level 2
7.2 kW
TEST BAY 2
TEST BAY 3

CANREL EMS

- M. Restrepo, C. A. Cañizares, J. Simpson-Porco, P. Su, and J. Taruc, “Optimization- and Rule-Based Energy Management Systems at the Canadian Renewable Energy Laboratory Microgrid Facility,” *Applied Energy*, vol. 290, May 2021, pp. 1-14.
- Rule-based EMS (RBEMS) :



State 1: Battery

```
Input: $SoC, P_{lb}, P_{pvs}, P_{ws}$, stop
Output: $P_{d1}, P_{d2}, P_b, U_{d1}, U_{d2}, Gcur, KD_{d1}$, stop

1. if $SoC>\overline{SoC}$ then
       $Gcur=1$
2. else if $SoC<\underline{SoC}$ & $P_{lb}>P_{ws}+P_{pvs}$ || Not enough reserves then
       Determine the required power to keep the power balance and
       a minimum charging level and calculate the cost for both
       diesel gensets. Then, turn on the cheapest unit ($U_{d1}=1$ or
       $U_{d2}=1$). If diesel genset 1 is commited, calculate dispatch
       factor ($KD_{d1}=\max(0.3,\min(1,(P_{lb}-P_{pvs}-P_{ws}+\underline{P_{d1}})/\overline{P_{d1}}))$
3. else
       $P_{d1}=0; P_{d2}=0; P_b=P_{lb}-P_{pvs}-P_{ws}$
```

State 2: Diesel 1

```
Input: $SoC, P_{lb}, P_{pvs}, P_{ws}, KD_{d1}, Drt_{d1},$ stop
Output: $P_{d1}, P_{d2}, P_b, V_{d1}, U_{d2}$, stop

1. if $SoC>\underline{SoC}+0.2$ & $Drt_{d1}>Mup_{d1}$ & Enough reserves then
       Turn off diesel genset 1 ($V_{d1}=1$)
2. else if Diesel 1 not enough for load balance || Not enough
   reserves then
       Turn on diesel genset 2 ($U_{d2}=1$)
3. else
       $P_{d1}=KD_{d1}\overline{P_{d1}}; P_{d2}=0; P_b=P_{lb}-P_{pvs}-P_{ws}-P_{d1}$
```

State 3: Diesel 2

```
Input: $SoC, P_{lb}, P_{pvs}, P_{ws}, Drt_{d2}$, stop
Output: $P_{d1}, P_{d2}, P_b, U_{d1}, V_{d2}, KD_{d1}$, stop

1. if $SoC>\underline{SoC}+0.2$ & $Drt_{d2}>Mup_{d2}$ & Enough reserves then
       Turn off diesel genset 2 ($V_{d2}=1$)
2. else if Diesel 2 not enough for load balance || Not enough
   reserves then
       Turn on diesel genset 1 ($U_{d1}=1$) and calculate dispatch factor
       $KD_{d1}=\max(0.3,\min(1,(P_{lb}-P_{pvs}-P_{ws}-P_{d2}+\underline{P_{d1}})/\overline{P_{d1}}))$
3. else
       $P_{d1}=0; P_{d2}=\max(P_{d2}, \min(\overline{P_{d2}},(P_{lb}-P_{pvs}-P_{ws}+\underline{P_{d2}}))$
       $P_b=P_{lb}-P_{pvs}-P_{ws}-P_{d2}$
```

State 4: Diesel 1 and 2

```
Input: $SoC, P_{lb}, P_{pvs}, P_{ws}, Drt_{d1}, Drt_{d2}, KD_{d1}$, stop
Output: $V_{d1}, V_{d2}, KD_{d1}, Lcur$, stop

1. if $SoC>\underline{SoC}+0.2$ then
       Determine if units have run for the minimum
       runtime, and then turn off the unit that has been running
       for a longer period ($V_{d1}=1$ or $V_{d2}=1$)
2. else if Diesel 1 and 2 not enough for load balance then
       $Lcur=1$
3. else
       $P_{d1}=KD_{d1}\overline{P_{d1}}$
       $P_{d2}=\max(\underline{P_{d2}}, \min(\overline{P_{d2}},(P_{lb}-P_{pvs}-P_{ws}-P_{d1}+\underline{P_{d2}}))$
       $P_b=P_{lb}-P_{pvs}-P_{ws}-P_{d1}-P_{d2}$
```

State 5: Renewable Generation Curtailment

```
Input: $SoC, P_{lb}, P_{pvs}, P_{ws}$, stop
Output: $Gcur$, stop

1. if $SoC<\overline{SoC}-0.2$ then
       $Gcur=0$
2. else
       Turn off wind and PV
       $P_{d1}=0$ ; $P_{d2}=0; P_b=P_{lb}$
```

State 6: Load Curtailment

```
Input: $SoC, P_{lb}, P_{pvs}, P_{ws}, KD_{d1}$, stop
Output: $KD_{d1}, Lcur$, stop

1. if $SoC>\underline{SoC}+0.2$ then
       $Lcur=0$
2. else
       $P_{d1}=KD_{d1}\overline{P_{d1}}$
       $P_{d2}=\overline{P_{d2}}$
       curtail load to $P_{lb}^{cur}=\min(P_{lb},P_{pvs}+P_{ws}+P_{d1}+P_{d2})$
       $P_b=P_{lb}^{cur}-P_{pvs}-P_{ws}-P_{d1}-P_{d2}$
```

- Optimization-based EMS (OEMS):

min. Costs

s.t. Load balance

Thermal generator constraints including UC

Battery constraints

Load and RES curtailment

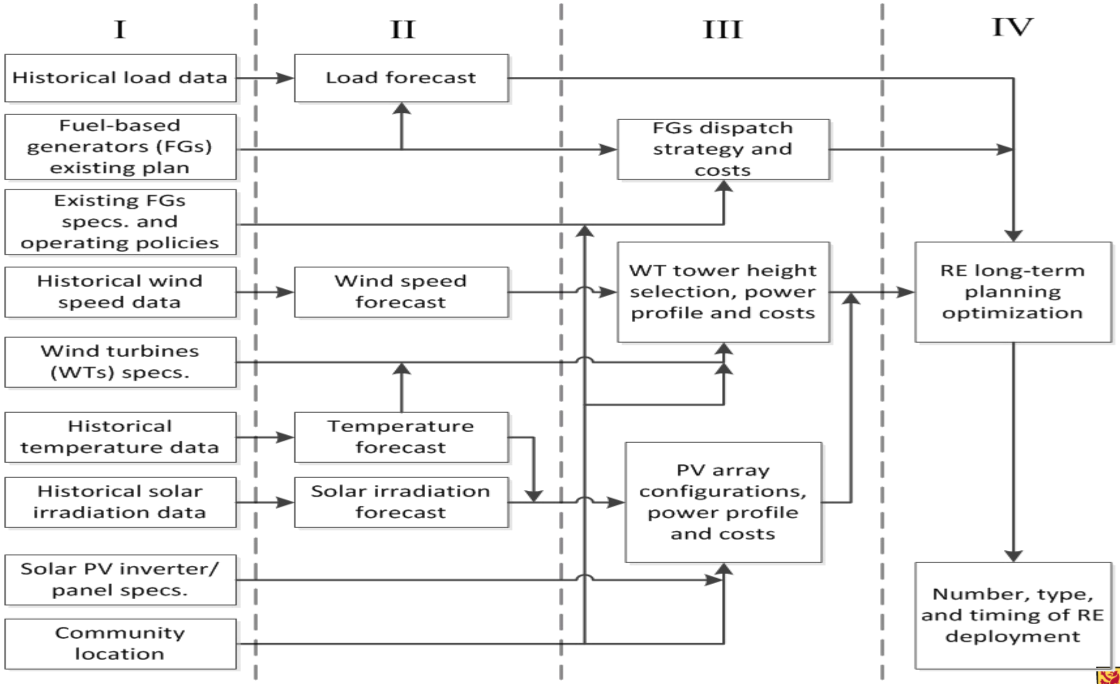
Reserves

Optimal Planning

- Determine best microgrid design technically and economically considering:
  - Local resources.
  - Type of equipment.
  - Sizes.
  - Costs: purchase, installation, operation and maintenance.
  - Social and community issues.
- Feasibility of installing RE capacity:
  - Decide most appropriate location(s).
    - Start with the location(s) with high wind/solar energy resources (high capacity factors).
    - Move then to sites with "less" RE resources.
  - Optimize for overall project and O&M costs.
  - Constraints:
    - Sites with capacity factor above certain level.
    - Maximum allowed RE penetration level.

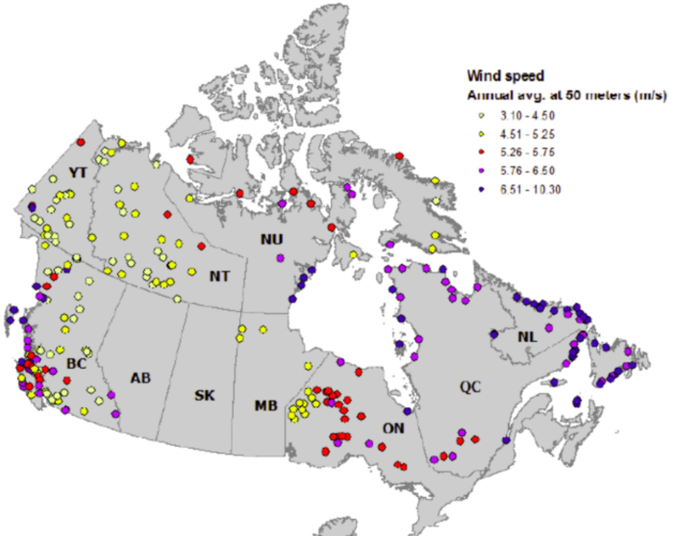
Optimal Planning

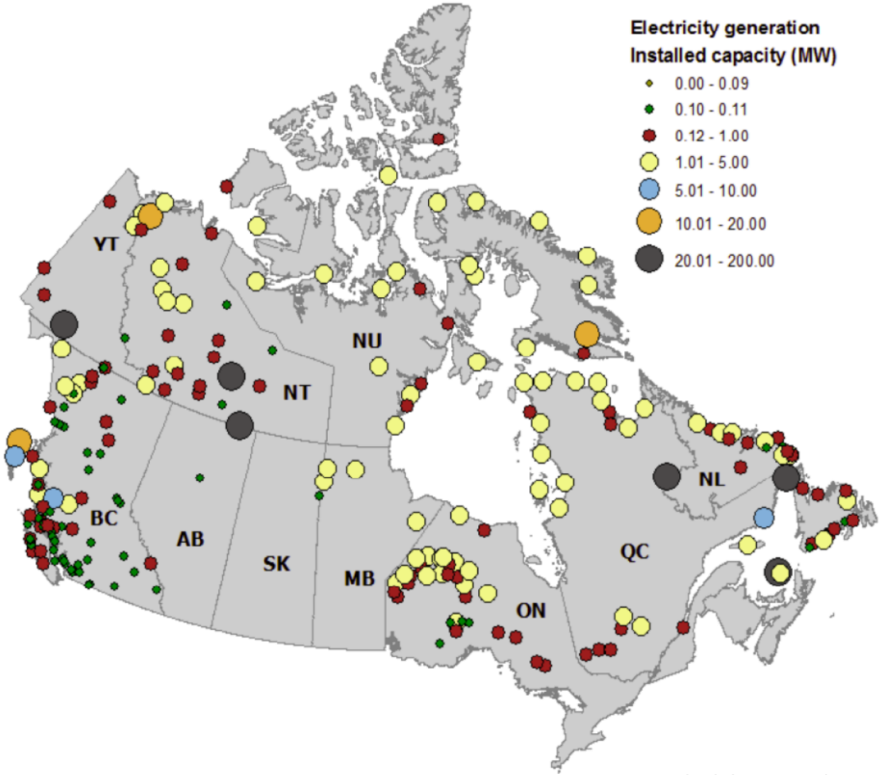
- Long-term renewable energy planning:
  - M. Arriaga, C. A. Cañizares, and M. Kazerani, “Long-Term Renewable Energy Planning Model for Remote Communities,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, January 2016, pp. 221-231.
  - I. Das and C. A. Cañizares, “Renewable Energy Integration in Diesel-based Microgrids at the Canadian Arctic,” IEEE Proceedings, Special Issue “Electricity for All: Access to Electricity Issues and Solutions for Energy-disadvantaged Communities,” invited paper, vol. 107, no. 9, September 2019, pp. 1838-1856.

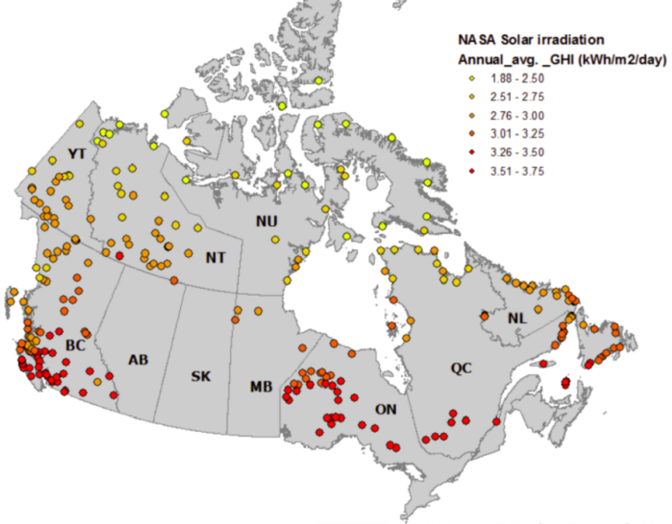


Optimal Planning Examples

- Canadian microgrid survey:
  - M. Arriaga, C. A. Cañizares, and M. Kazerani, “Northern Lights,” *IEEE Power and Energy Magazine*, invited paper, vol. 12, no. 4, July-August 2014, pp. 50-59.







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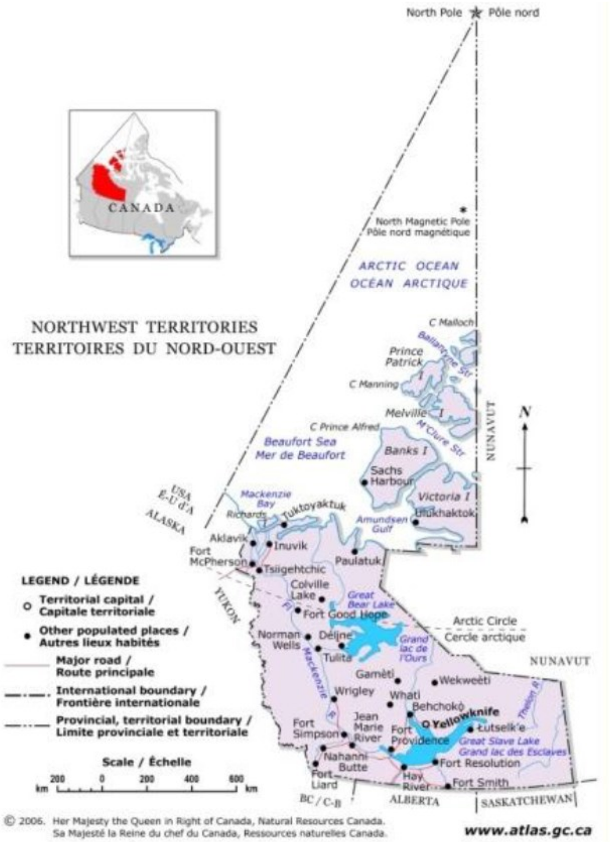
Optimal Planning Examples

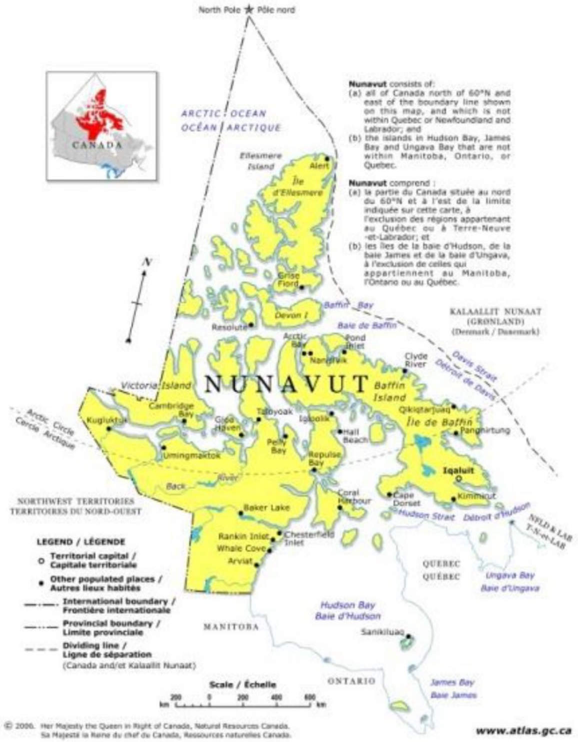
© 2002. Her Majesty the Queen in Right of Canada, Natural Resources Canada.
Sa Majesté la Reine du chef du Canada, Ressources naturelles Canada.

- M. Arriaga, C. A. Cañizares, and M. Kazerani, "Renewable Energy Alternatives for Remote Communities in Northern Ontario, Canada," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 3, July 2013, pp. 661-670.
- KLFN Community:
  - 914 people.
  - 500 km north of Thunder Bay.
  - Winter-road access.
- Electricity generation:
  - 0.4 MW, 0.6MW, and 1 MW diesel generator in operation.
  - 1.5 MW diesel generator replacing 0.4 MW generator is being installed.
  - 3x10 kW Bergey WTs.
  - 1x30 kW Wenvor WT.
  - 10 kW solar PV array.

Optimal Planning Examples

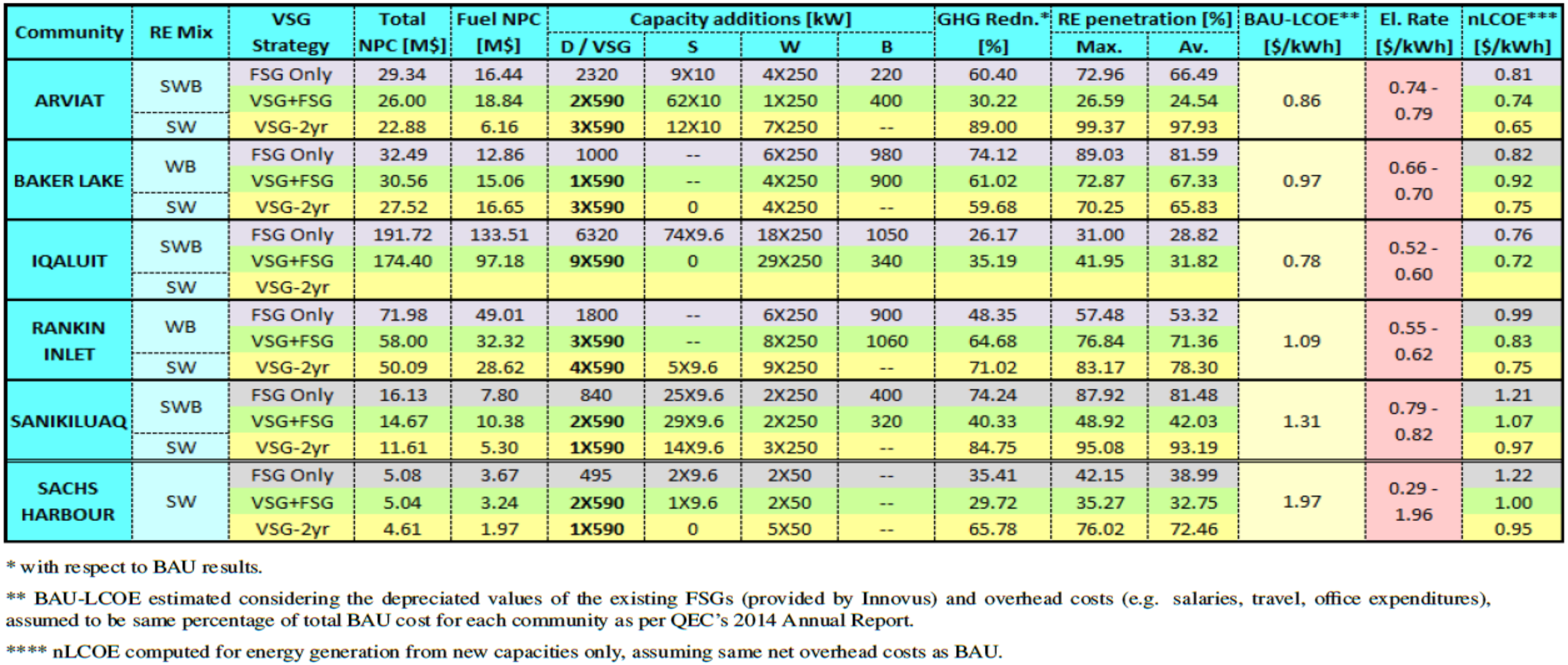
- Determine optimal RE penetration in Nunavut and NWT community microgrids considering Variable Speed Generator (VSG):





Optimal Planning Example

- Results:



Community	RE Mix	VSG Strategy	Total NPC [M$]	Fuel NPC [M$]	Capacity additions [kW]				GHG Redn.* [%]	RE penetration [%]		BAU-LCOE** [$/kWh]	El. Rate [$/kWh]	nLCOE*** [$/kWh]
					D / VSG	S	W	B		Max.	Av.			
ARVIAT	SWB	FSG Only	29.34	16.44	2320	9X10	4X250	220	60.40	72.96	66.49	0.86	0.74 - 0.79	0.81
		VSG+FSG	26.00	18.84	**2X590**	62X10	1X250	400	30.22	26.59	24.54			0.74
	SW	VSG-2yr	22.88	6.16	**3X590**	12X10	7X250	--	89.00	99.37	97.93			0.65
BAKER LAKE	WB	FSG Only	32.49	12.86	1000	--	6X250	980	74.12	89.03	81.59	0.97	0.66 - 0.70	0.82
		VSG+FSG	30.56	15.06	**1X590**	--	4X250	900	61.02	72.87	67.33			0.92
	SW	VSG-2yr	27.52	16.65	**3X590**	0	4X250	--	59.68	70.25	65.83			0.75
IQALUIT	SWB	FSG Only	191.72	133.51	6320	74X9.6	18X250	1050	26.17	31.00	28.82	0.78	0.52 - 0.60	0.76
		VSG+FSG	174.40	97.18	**9X590**	0	29X250	340	35.19	41.95	31.82			0.72
	SW	VSG-2yr												
RANKIN INLET	WB	FSG Only	71.98	49.01	1800	--	6X250	900	48.35	57.48	53.32	1.09	0.55 - 0.62	0.99
		VSG+FSG	58.00	32.32	**3X590**	--	8X250	1060	64.68	76.84	71.36			0.83
	SW	VSG-2yr	50.09	28.62	**4X590**	5X9.6	9X250	--	71.02	83.17	78.30			0.75
SANIKILUAQ	SWB	FSG Only	16.13	7.80	840	25X9.6	2X250	400	74.24	87.92	81.48	1.31	0.79 - 0.82	1.21
		VSG+FSG	14.67	10.38	**2X590**	29X9.6	2X250	320	40.33	48.92	42.03			1.07
	SW	VSG-2yr	11.61	5.30	**1X590**	14X9.6	3X250	--	84.75	95.08	93.19			0.97
SACHS HARBOUR	SW	FSG Only	5.08	3.67	495	2X9.6	2X50	--	35.41	42.15	38.99	1.97	0.29 - 1.96	1.22
		VSG+FSG	5.04	3.24	**2X590**	1X9.6	2X50	--	29.72	35.27	32.75			1.00
		VSG-2yr	4.61	1.97	**1X590**	0	5X50	--	65.78	76.02	72.46			0.95

* with respect to BAU results.

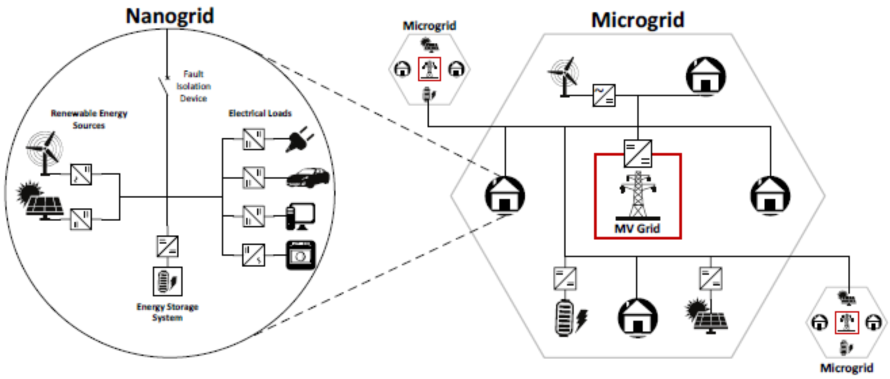
** BAU-LCOE estimated considering the depreciated values of the existing FSGs (provided by Innovus) and overhead costs (e.g. salaries, travel, office expenditures), assumed to be same percentage of total BAU cost for each community as per QEC's 2014 Annual Report.

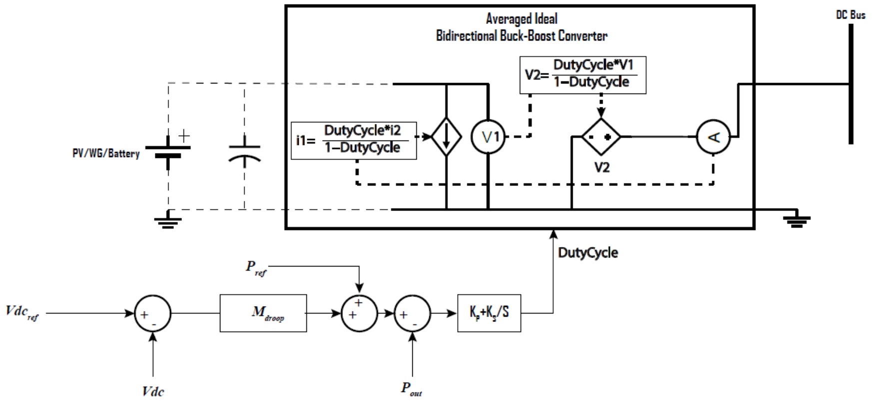
**** nLCOE computed for energy generation from new capacities only, assuming same net overhead costs as BAU.

  - VSG-FSG: Old generators remain fixe speed (FSGs) and new generators are all VSGs.
  - VSG-2yr: All FSGs are replaced with VSGs.

DC Microgrid EMS

- F. Li, C. Cañizares, and Z. Lin, "Energy Management System for DC Microgrids Considering Battery Degradation," *Proc. IEEE-PES General Meeting*, Montreal, August 2019, 5 pages.
- Evolved from dc generation (solar, batteries) and loads (LEDs, electronic equipment, EVs).
- Characteristics:
  - Based on controlled dc voltage sources through dc-dc buck-boost converters and dc-ac VSCs.
  - Voltage is regulated to control power (current) flows.
  - Less losses.
  - No I_{dc} zero crossing, which is a challenge for protections (breakers).
  - Currently found within buildings mostly.





DC Microgrid EMS

- EMS:

Grid cost

BESS degrad. cost

$$C_{total} = \alpha C_g + (1-\alpha) C_{dg}$$

$$= \sum_{\Delta t} \left[\alpha \cdot \xi_{g,t}^{dc} P_{g,t}^{dc} + (1-\alpha) \cdot \varphi\left(P_{bat,t}^{dc} + P_{bat,t}^{c} \right) \right] \Delta t$$

$s.t.$

$$SoC_{bat,t} = SoC_{bat,t-1} + \left(P_{bat,t-1}^{c} \eta_c - \frac{P_{bat,t-1}^{dc}}{\eta_d} \right) \Delta t$$

$$P_{bat,min}^{c} \le P_{bat,t}^{c} \le P_{bat,max}^{c}$$

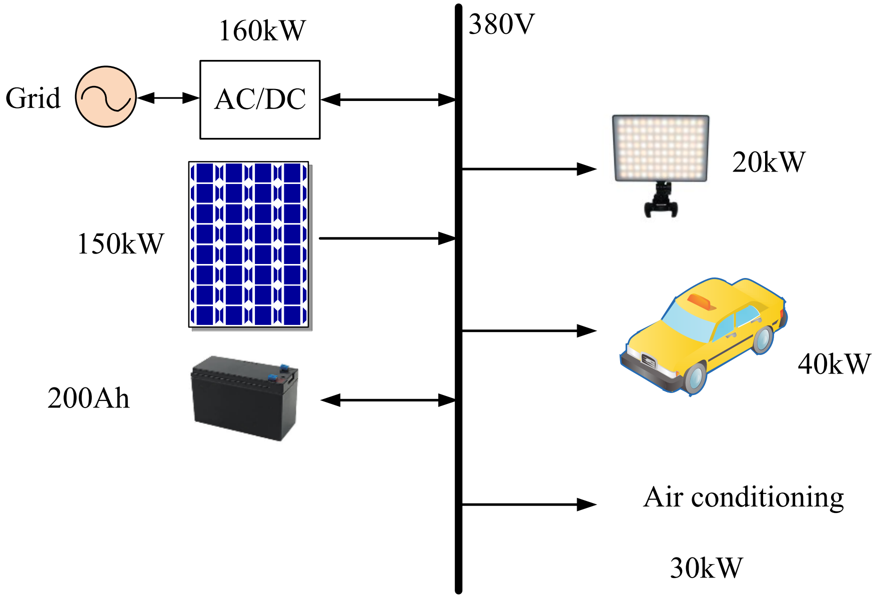
$$P_{bat,min}^{dc} \le P_{bat,t}^{dc} \le P_{bat,max}^{dc}$$

$$SoC_{bat,min} \le SoC_{bat,t} \le SoC_{bat,max}$$

$$P_{g,min}^{c} \le P_{g,t}^{c} \le P_{g,max}^{c}$$

$$P_{g,min}^{dc} \le P_{g,t}^{dc} \le P_{g,max}^{dc}$$

$$P_{bat,t}^{dc} + P_{g,t}^{dc} + P_{PV,t} = P_{EV,t} + P_{AC,t} + P_{LED,t} + P_{bat,t}^{c} + P_{g,t}^{c}$$



DC Microgrid Power Flow

- N. H. van der Blij, D. Chaifouroosh, C. A. Cañizares, T. B. Soeiro, L. M. Ramirez-Elizondo, M. T. J. Spaan, and P. Bauer, "Novel Power Flow Methods for DC Grids," *Proc. International Symposium on Industrial Electronics (ISIE)*, Delft, Netherlands, June 2020, 6 pages.
- Power flow solution methods:
  - Quadratic Solver (QS): Solve quadratic power equation P_N with Newton methods.
  - Optimization Problem (OP): Solve power flow problem as an optimization problem.
  - Gauss-Seidel (GS) accelerated: Solve voltage equations iteratively from previous solutions.
  - Newton Raphson (NR): Solve nonlinear power equations using Jacobian.
  - Backward-Forward (BF): For radial or weakly meshed networks, sequentially solving voltages from previous nodes.
  - New Direct Matrix-Current Approximation (DM-CA): Based on unknown currents that depend on known voltages.
  - New Direct Matrix-Impedance Approximation (DM-IA): Based on a linearization of on a current equations.