MICROGRIDS OVERVIEW AND RESEARCH

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OUTLINE

- Definition and motivations
- Distributed generation (DG):
  - » Definition
  - » Technologies
- Optimal planning:
  - » Sizing and site selection
- Microgrid control:
  - » Voltage and frequency control
  - » Energy management problem
- Stability

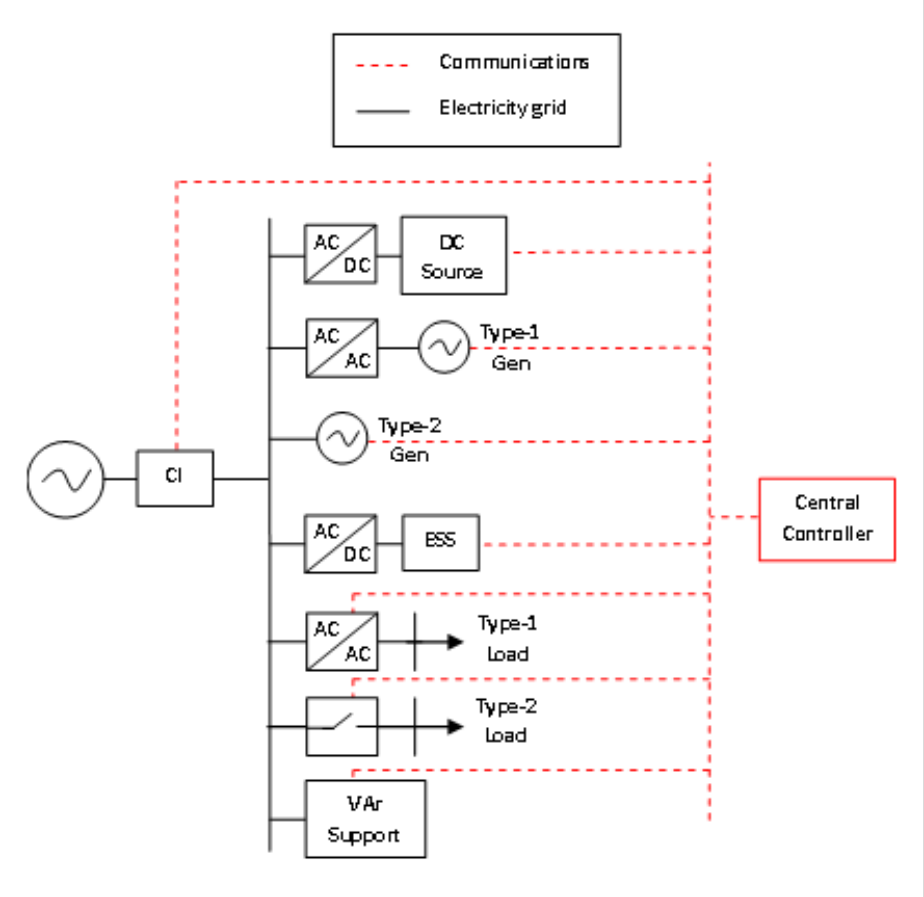
MICROGRID DEFINITION

- There is no “standard” definition, but there is general agreement on what a microgrid is:
  - » 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.

MICROGRID DEFINITION

Microgrid:

- » Cluster of DERs and Loads.
- » Coordinated operation.
- » Grid connected and stand-alone modes.
- » Perceived as a single element by the main grid.
- » Can integrate multiple energy carriers.
- » Facilitates integration of intermittent sources.
- » Challenges: Re-engineering of protection schemes, plug-in feature, control, business models, energy management.



MICROGRID MOTIVATIONS

- Wider deployment of renewables, particularly wind and solar power, at distribution system levels that need to be integrated into the grid.
- Need for increased security and reliability of supply (e.g. storms, military).
- Need for “cleaner” and “cheaper” microgrids (e.g. Canadian remote communities, mining).
- Need for electricity supply in underserved and poor communities (e.g. Canadian indigenous communities, Africa, India, South America).

DG DEFINITION

- A generation plant connected to the grid at distribution level voltage or on the customer's side of the meter.
- Integral part of Distributed Energy Resources (DERs).
- No generally accepted definition regarding DG capacity:
  - » DoE: less than a kW to tens of MW.
  - » IEEE: less than 10 MW.
  - » CIGRE: less than 100 MW.
  - » EPRI: a few kW to 50 MW.

DG TECHNOLOGIES: RENEWABLE

No emissions:

- » Solar:
  - PV.
  - Thermal.
- » Wind.
- » Small hydro.
- » Bio-fuels from bio-waste.
- » Geothermal.
- » Ocean.

DG TECHNOLOGIES: NONRENEWABLE

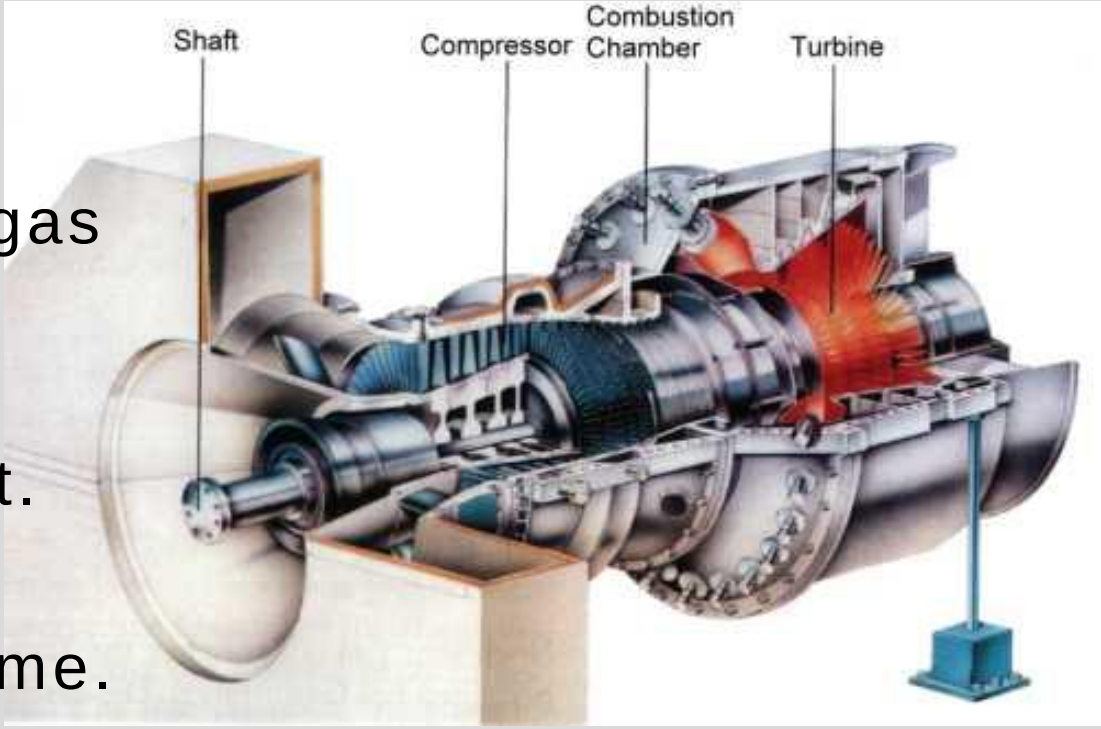
Engines (gas-diesel):

- » Mature industry.
- » At the core of most existing microgrids
- » Low costs.
- » High efficiency.
- » High emissions.
- » Peak shaving.
- » Load following.
- » Reserve support.
- » CHP capability.

DG TECHNOLOGIES: NONRENEWABLE

Gas turbine (GT):

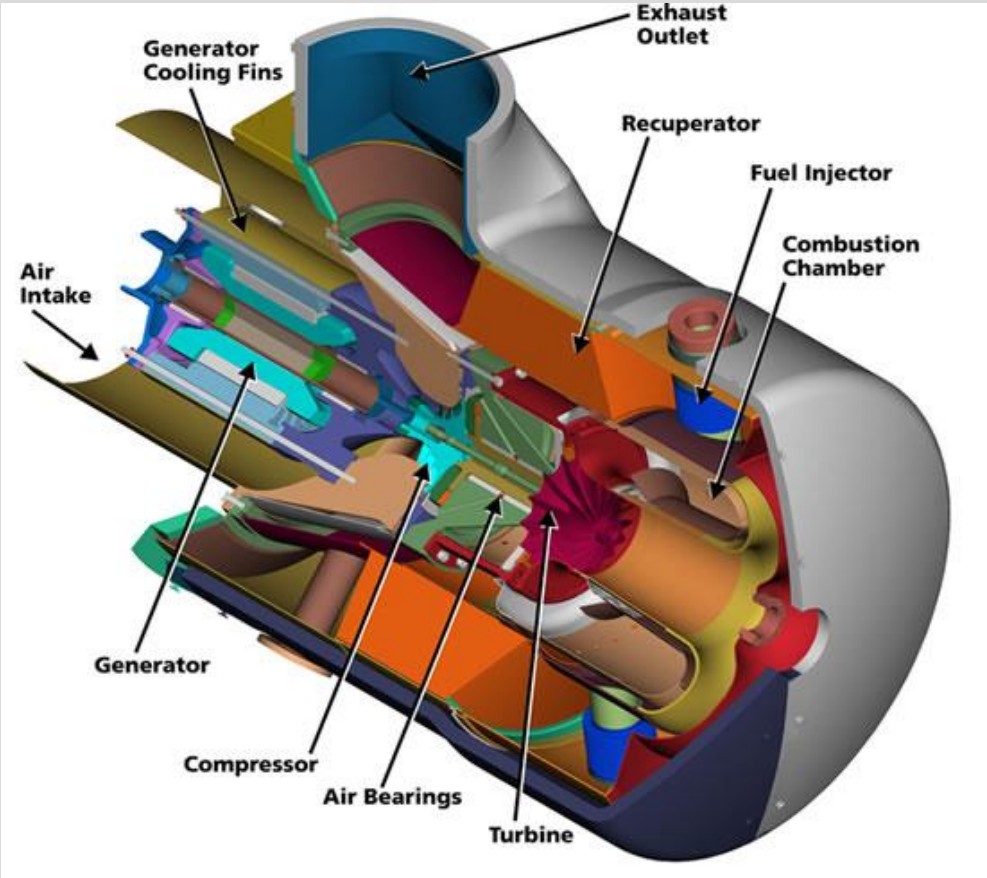
- » Low costs.
- » Good efficiency.
- » As polluting as gas engines.
- » Portable units.
- » Reserve support.
- » CHP capability.
- » Good start-up time.



DG TECHNOLOGIES: NONRENEWABLE

Microturbine (MT):

- » Low noise.
- » Small size.
- » Long maintenance intervals.
- » Fuel flexibility.
- » Good efficiency in CHP.
- » Peak shaving.
- » Stand-by power.
- » Fast start-up time.



DG TECHNOLOGIES: RENEWABLE/NONRENEWABLE

Fuel cell (FC):

- » Popular Technologies: Polymer Electrolyte Membrane (PEM) FC, and Solid Oxid (SO) FC.
- » High costs.
- » Low NOx emissions.
- » Still high CO2 emissions.
- » Very low noise.
- » Base load applications.
- » CHP capability.
- » Long start-up time.

		PEMFC	SOFC	MCFC	DMFC
Operating Temp. (°C)		80-150	800-1,000	>650	80 100
Fuel		H_2	H_2, hc	ng, hc	methanol
Electrical Effic. (%)		35-40	<45	44-50	15-30
Applications		FCV Power	Station. Power	Station. Power	Portable Power
Lifetime (h)	FCV	2,000	6,000	8,000	na
	Power	30,000	20,000	20,000	
Target lifetime (h)	FCV	4,000	40,000	40,000	
	Power	20,000	60,000	60,000	na

DG TECHNOLOGIES

Technology	Capital costs US$/kW	O&M costs US$/kWh	NO_x kg/MWh	CO_2 kg/MWh	Efficiency	Available size	Start up time	Main features	Applications
ICE Diesel ICE Gas-fired	350-500 600-1000	0.5-1 0.7-1.5	10 0.2-1	650 500-620	36-43% 28-42 %	A few kW to 30 MW	10 s to 15 min	*Mature industry *Fast start and stop *Low costs *High efficiency *CHP capability *High emissions	*Emergency power *Peak shaving *Load following *Reserve support *Grid On & Off
Combustion Turbine	650-900 (Size dependent)	0.4-0.5	0.3-0.5	580-680	20-45% (up to 55% in combined cycle)	500 kW to 265 MW	2-10 min	*Well established market and service *Readily available *Low costs *Good efficiency	*CHP *Base load *Portable units *Reserve support *Grid On & Off
Microurbine	700-1100	0.05-0.016	0.1	720	20-30% Up to 85% In CHP	25-500 kW	Up to 120 s	*Low Noise *Small Size *Long Maintenance Intervals *Flexibility in Fuel	*CHP *Peak Shaving *Stand-by power *Grid On & Off
Fuel Cell (PAFC)	4000 - 5500	0.05-0.01	0.005 to 0.01	430-490	36-42%	5-250 kW	1-4 h	*Very Low Noise *Good efficiency *Compact size *Negligible NO_x emissions *Reliable operation	*CHP *DC applications *Base load *Grid On & Off *Back up systems
Photovoltaics	6000 - 10000	1% of first investment annually	0	0	NA[a]	A few kW to more than 100 kW	Quick[b]	*Clean energy *Negligible noise *High costs *Environmental Dependant *No emissions	*Communication systems *Remote buildings *Household powering *Grid On & Off

[a] Not Applicable. [b] As fast as the system's DC/AC converter stabilizes.

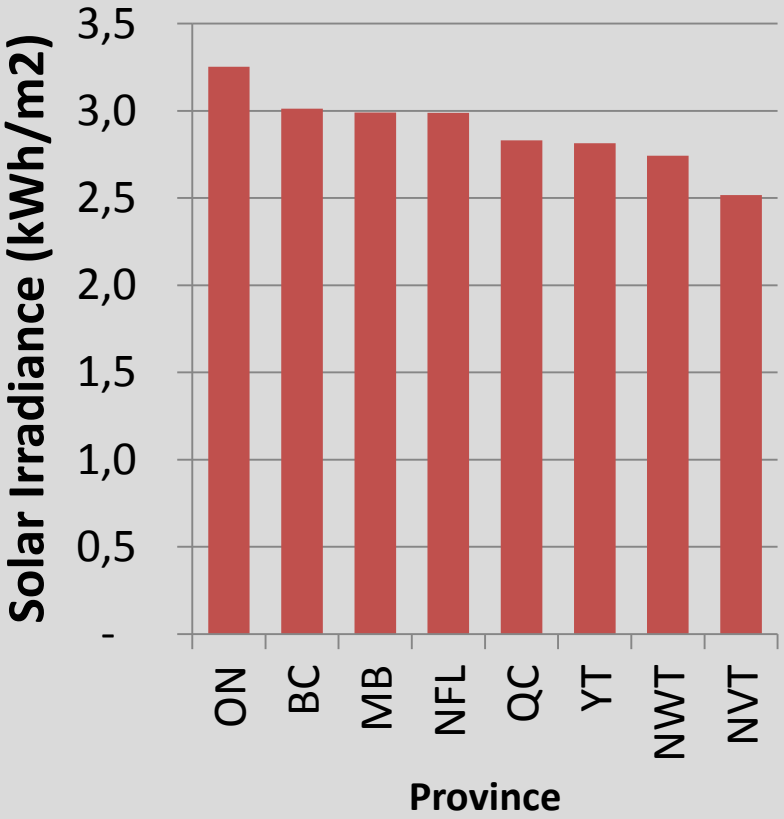
OPTIMAL PLANNING

- 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

Solar Resources:

- » Potential sites can achieve a capacity factor of 8-10%.
- » Even distribution of solar resource across the country.
- » Comparison with wind resource:
  - Simpler installation & maintenance in remote communities.
  - Higher prediction accuracy of expected energy.

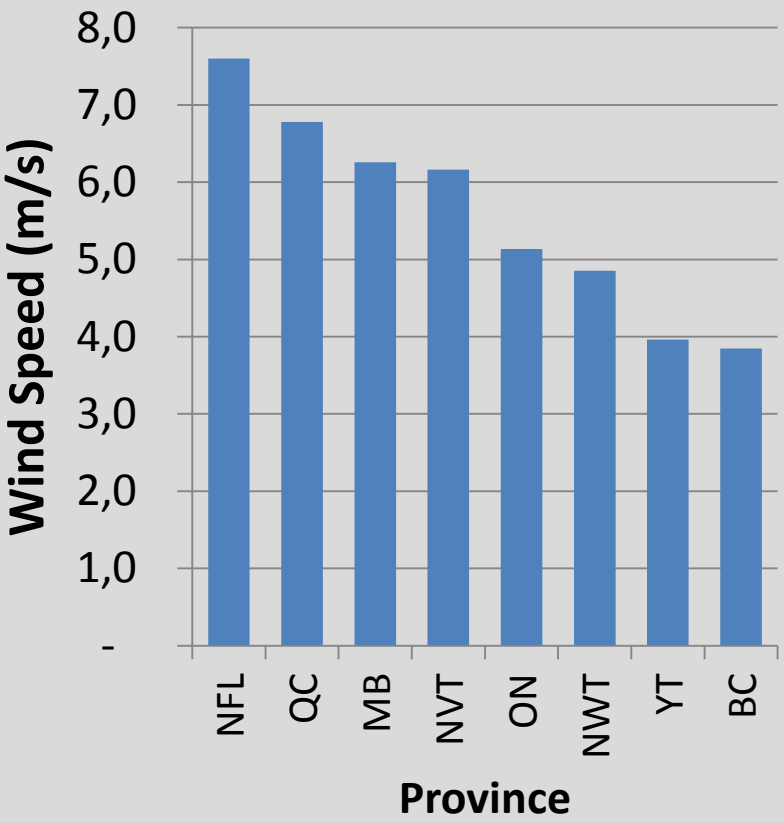


Source: NASA

OPTIMAL PLANNING

Wind resources:

- » Communities' annual average wind speed (WS):
  - 8 sites: WS > 8m/s
  - 25 sites: 7m/s ≤ WS < 8m/s
  - 28 sites: 6m/s ≤ WS < 7m/s
  - 29 sites: 5m/s ≤ WS < 6m/s
  - 48 sites: WS < 5m/s
- » Potential sites can achieve 20%-35% capacity factor.
- » Difficult to set a fixed federal incentive; a provincial approach is required.
- » Small wind relies on local wind currents difficult to be reflected in mesoscale models.



Source: Wind Atlas Canada

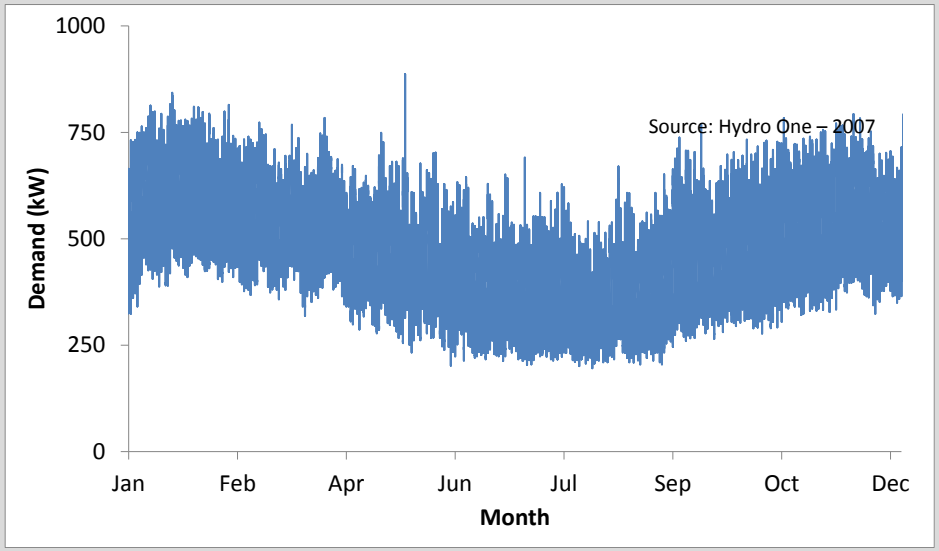
KASABONIKA EXAMPLE

Kasabonika Lake

KASABONIKA EXAMPLE

» Electricity Demand 2007:
- 12MWh/day
- 850kW peak

» Fuel:
- 1.0M-1.2M litre/year
- 3,600 ton/year CO2 eq.
- $ 1.8/litre



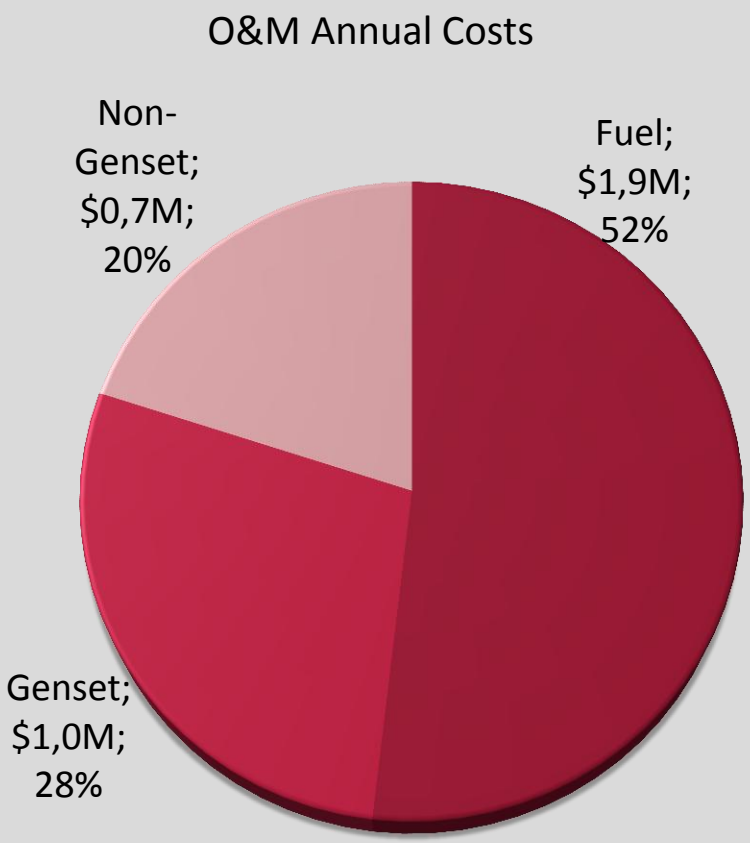
KASABONIKA EXAMPLE

Three O&M cost categories:

- » Fuel cost.
- » Genset related cost.
- » Non-Genset related cost.

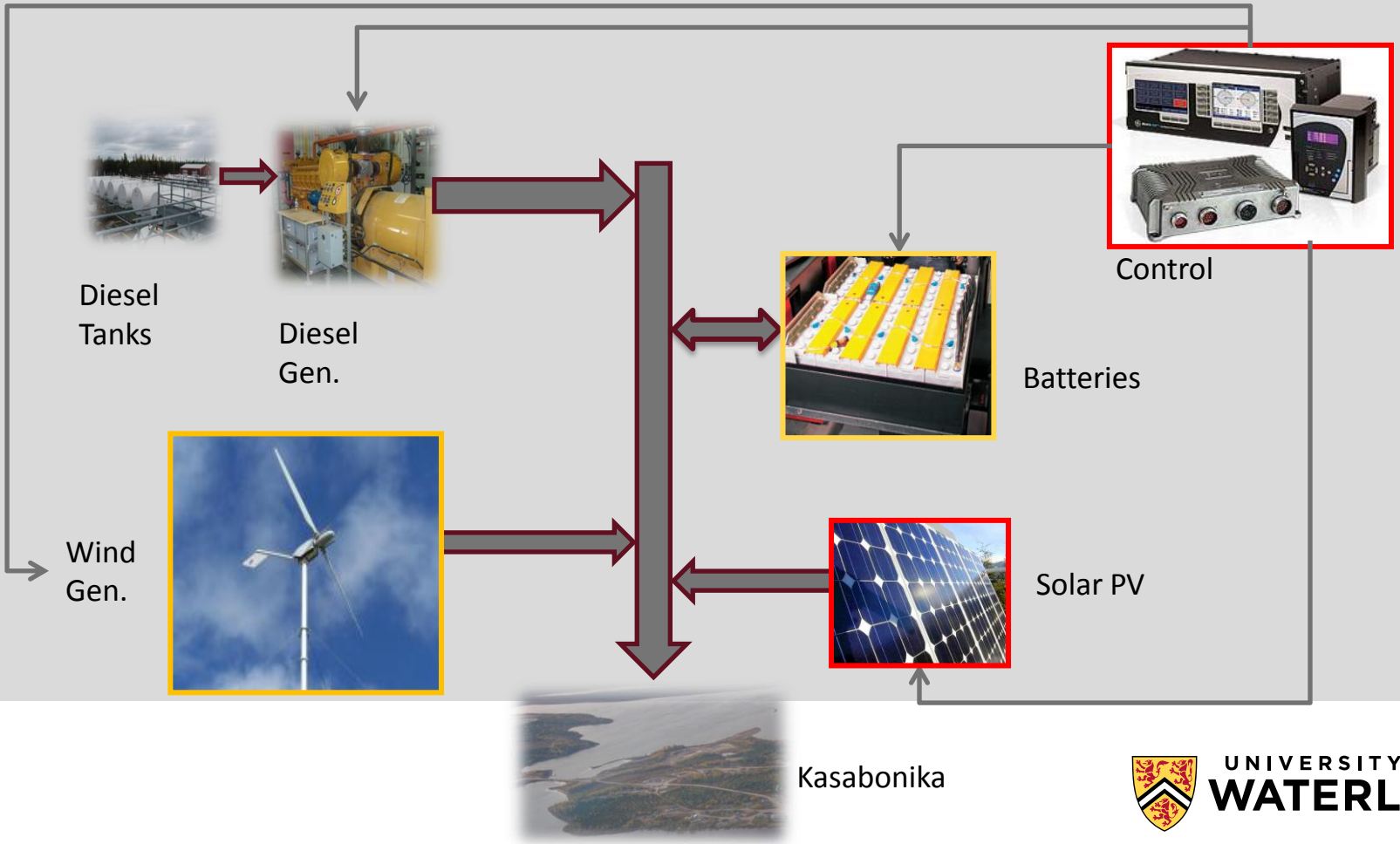
Total O&M cost:

- » $3.7M/year
- » Levelized energy cost: $0.84/kWh



KASABONIKA EXAMPLE

- Desired microgrid:



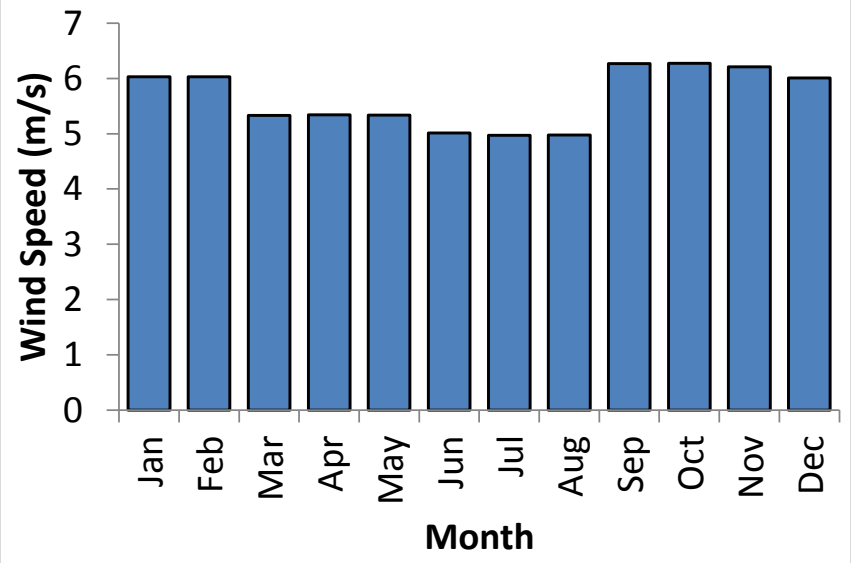
KASABONIKA EXAMPLE

Wind speed estimate (Canada Wind Atlas):

- » Annual average: 5.68 m/s @ 30m

Energy output estimate for 6x50kW WTs:

- » 436MWh/year
- » 10% of annual demand
- » 16.5% capacity factor



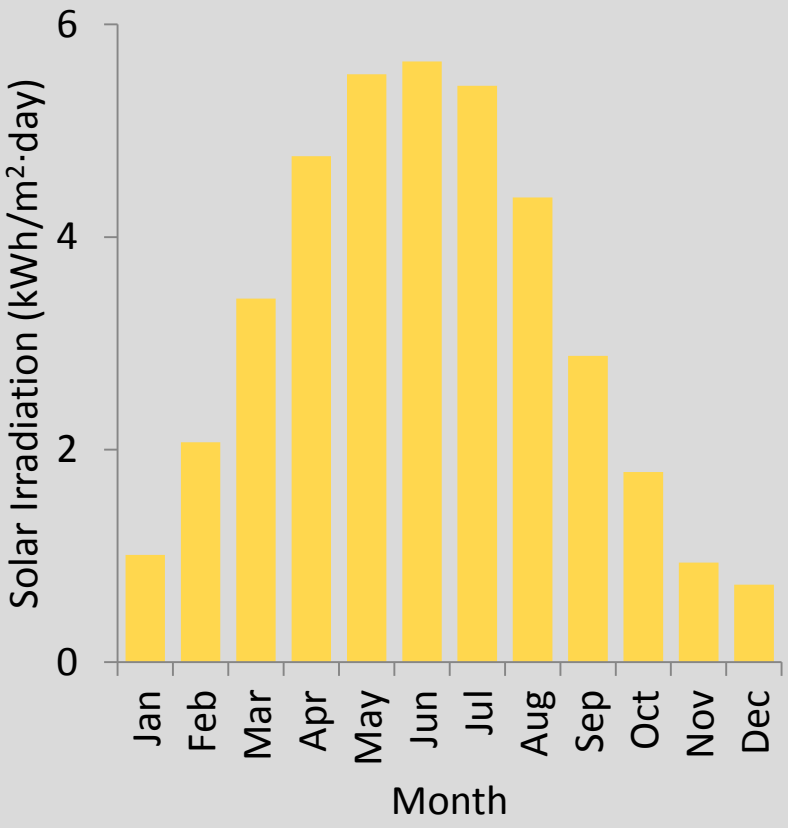
KASABONIKA EXAMPLE

Solar radiation estimate (NASA):

- » Annual: 3.22 kWh/m2·day

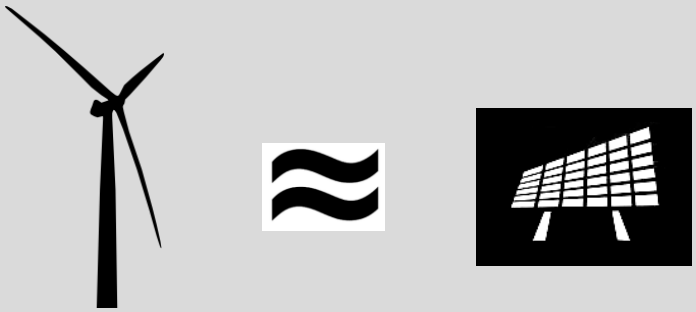
Energy output estimate for 300kW PV panels:

- » 395MWh/year
- » 9% of annual demand
- » 15% capacity factor



KASABONIKA EXAMPLE

- Similarity in the estimated wind and solar annual energy output at Kasabonika.
- Main differences:
  - » Cost:
    - Capital cost.
    - O&M costs.
  - » Maintenance:
    - Resources.
    - Expertise.
    - Spare parts.
  - » Installation process.



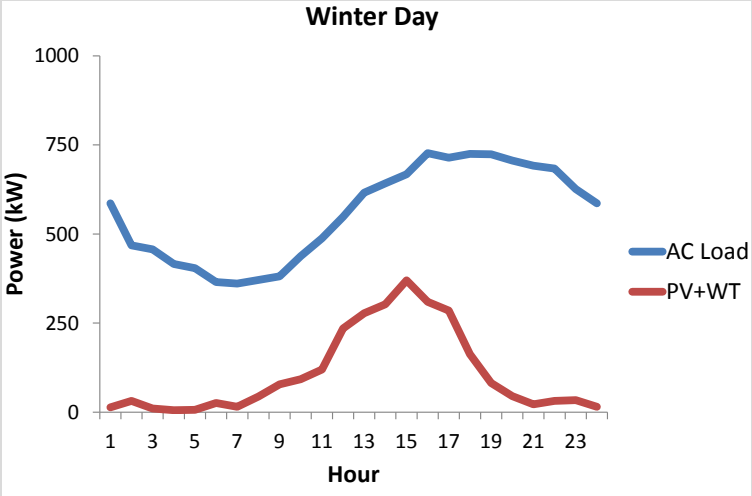
KASABONIKA EXAMPLE

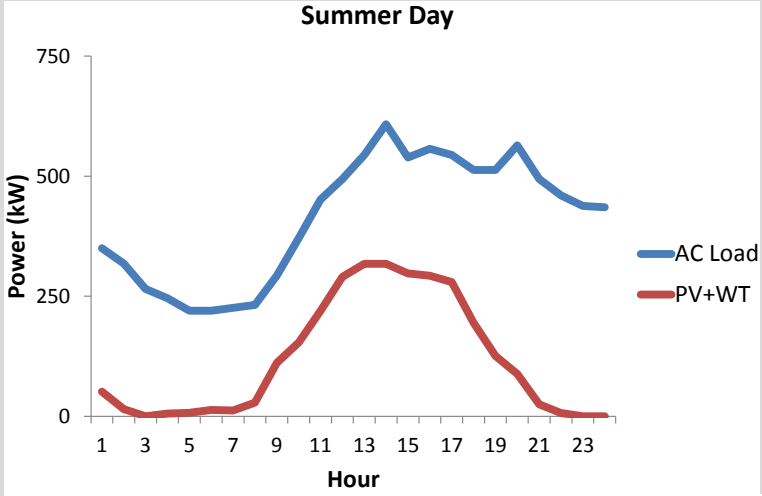
- Ranked sizing criteria for Wind/PV/DGS option:
  1. Wind/PV generation mix.
  2. High RE penetration without excess energy.
  3. Lower O&M costs within RE penetration range.
  4. Lower capital cost than DGS upgrade.

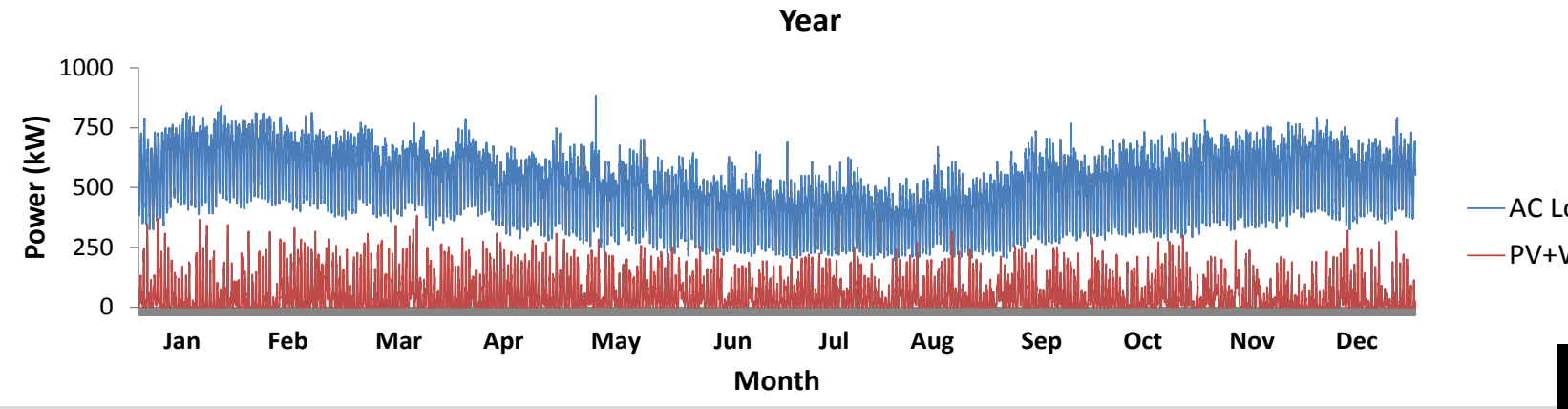
KASABONIKA EXAMPLE

- Hybrid system:
  - » PV: 250kWp
  - » WT: 2x50kW Turbines
  - » DGS: Current Diesel Generators
- Energy output (10% RE, 90%DGS):
  - » PV: 329MWh/year
  - » WT: 145MWh/year
  - » DGS: 4,420MWh/year

KASABONIKA EXAMPLE

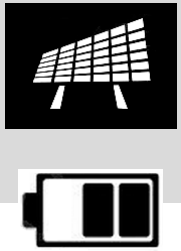






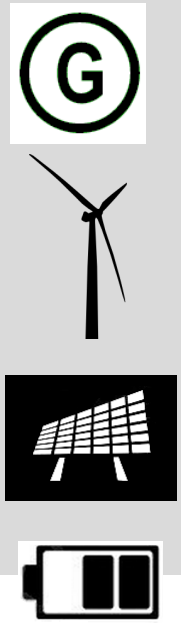
KASABONIKA EXAMPLE

- Ranked sizing criteria for Wind/PV/Storage/DGS option:
  1. Lower/equal capital cost than DGS upgrade.
  2. Wind/PV generation mix.
  3. Storage for excess energy in the system.
  4. Lower O&M costs within RE penetration range.

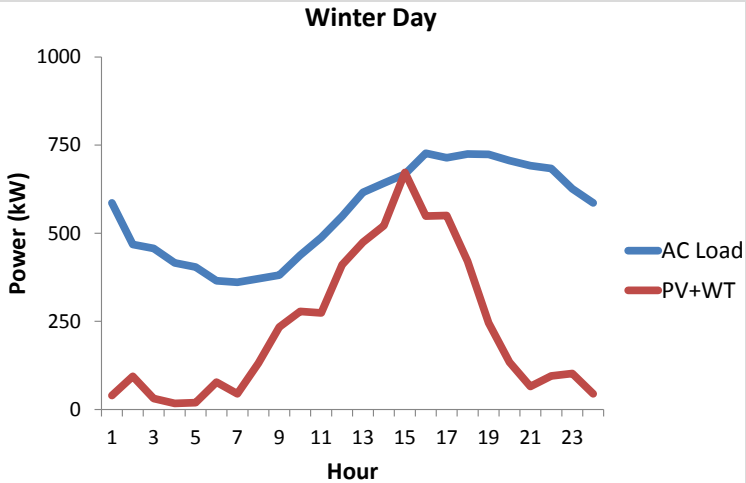


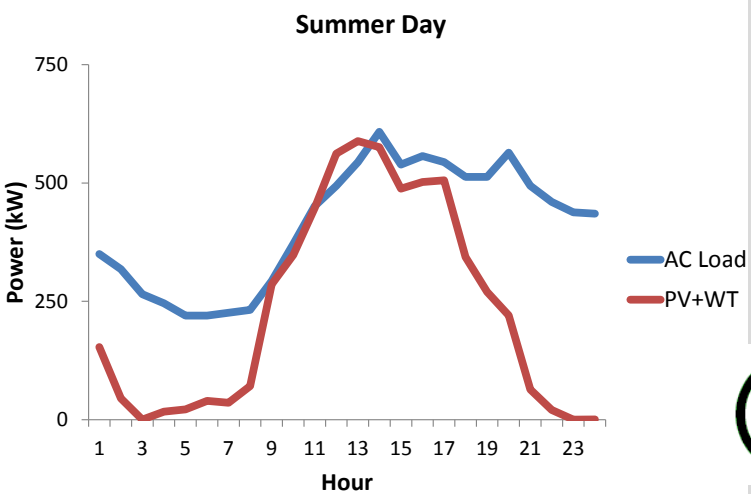
KASABONIKA EXAMPLE

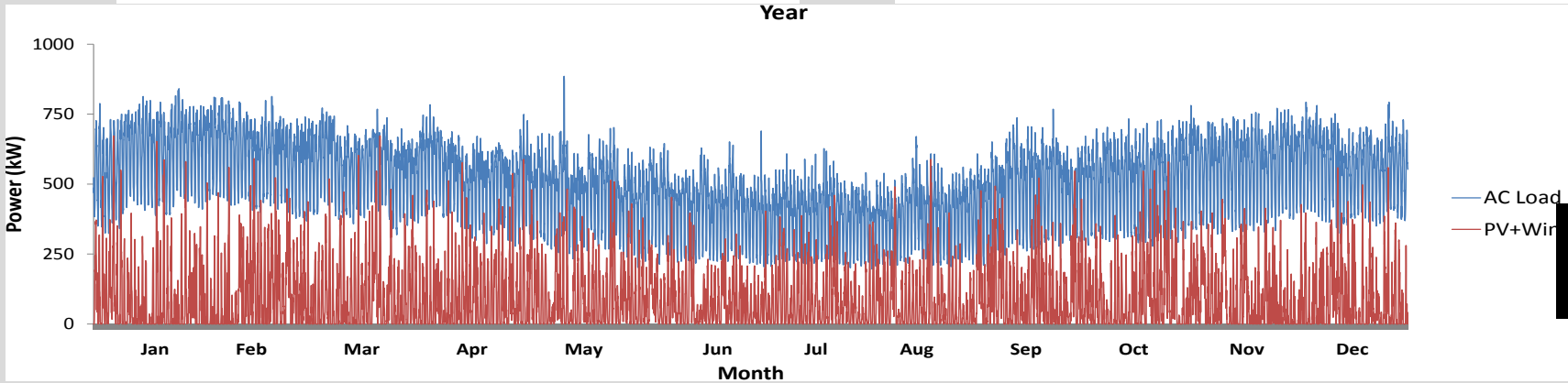
- Hybrid system:
  - » PV: 375kWp
  - » WT: 4x50kW Turbines
  - » DGS: Current diesel generators
  - » BT: 53kWh
- Energy output (18% RE, 82%DGS):
  - » PV: 493MWh/year
  - » WT: 290MWh/year
  - » DGS: 4,460MWh/year



KASABONIKA EXAMPLE



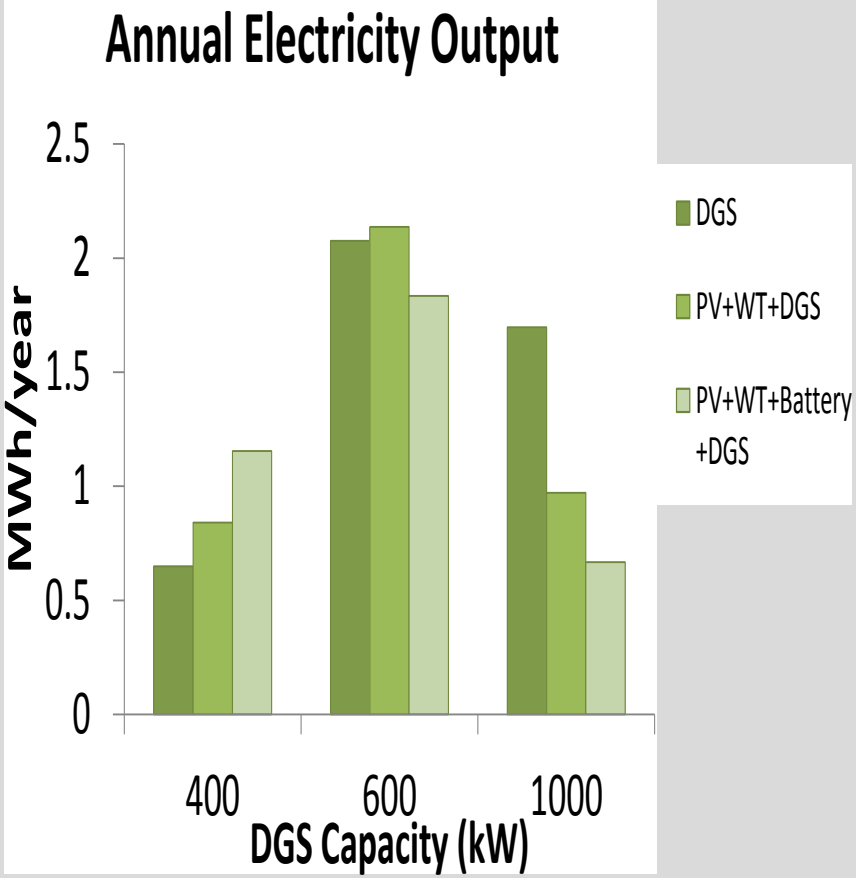




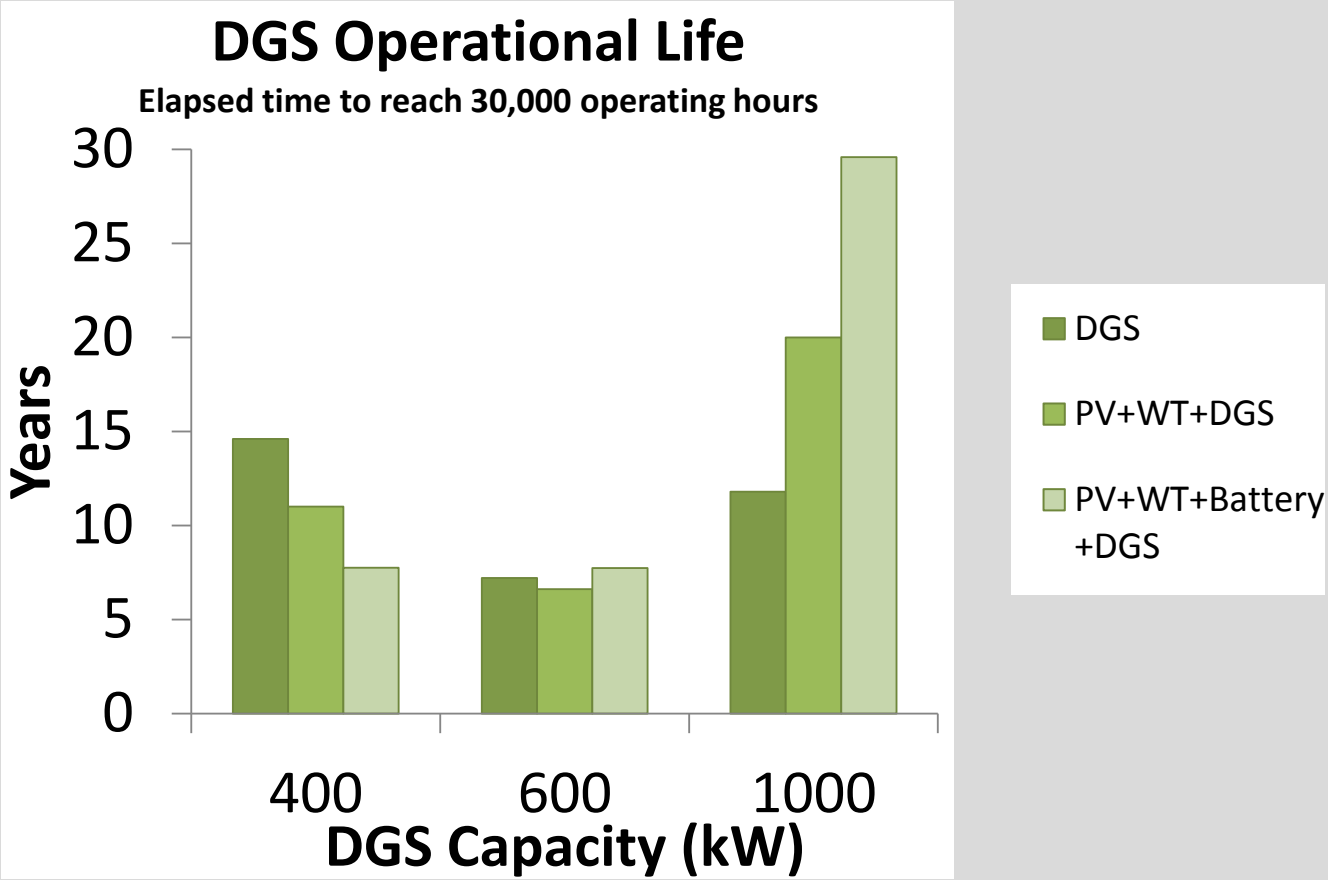
KASABONIKA EXAMPLE

RE effect on DGS:

- » Change in DGS capacity allocation.
- » 400kW DGS ↑
- » 600kW DGS =
- » 1000MW DGS ↓



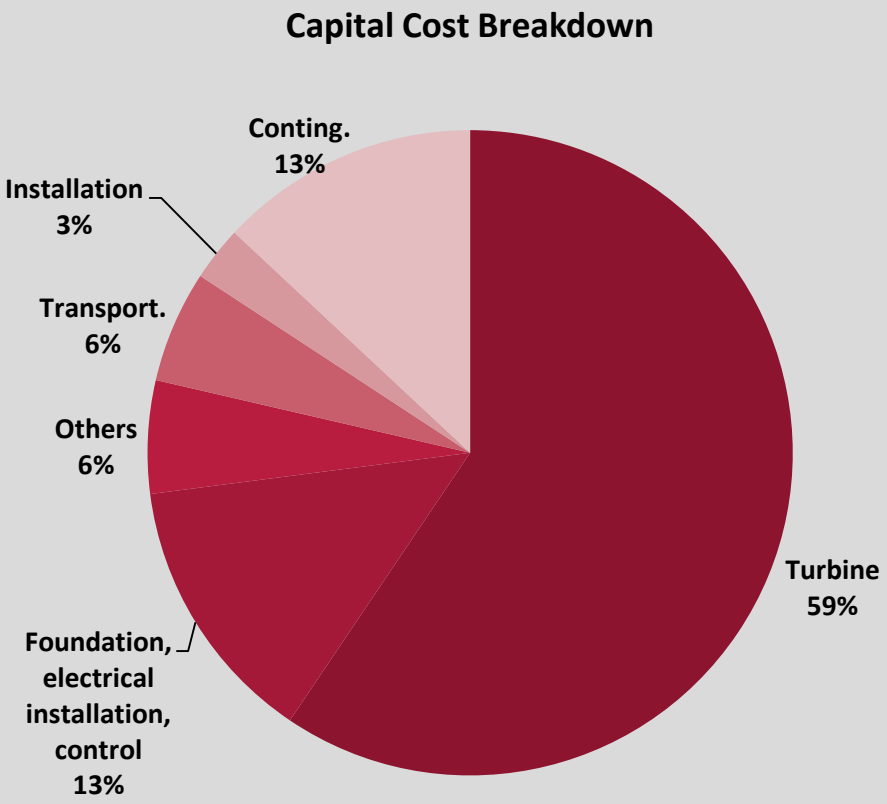
KASABONIKA EXAMPLE



KASABONIKA EXAMPLE

WT cost estimate:

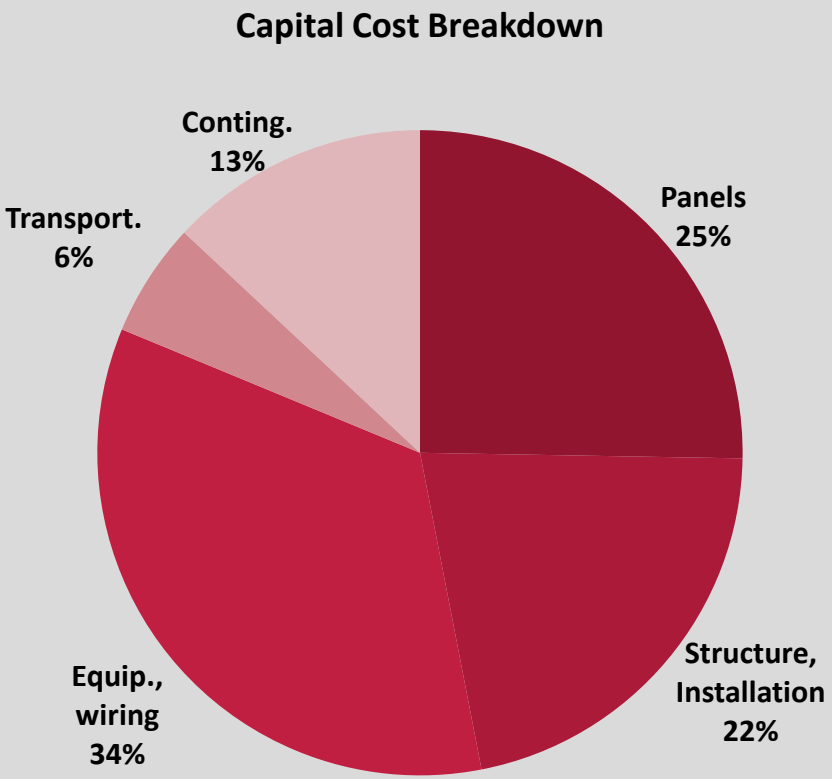
- » Capital cost: $9,250/kW
- » O&M cost: $250/kW·year
  3.5% of capital cost



KASABONIKA EXAMPLE

PV cost estimate:

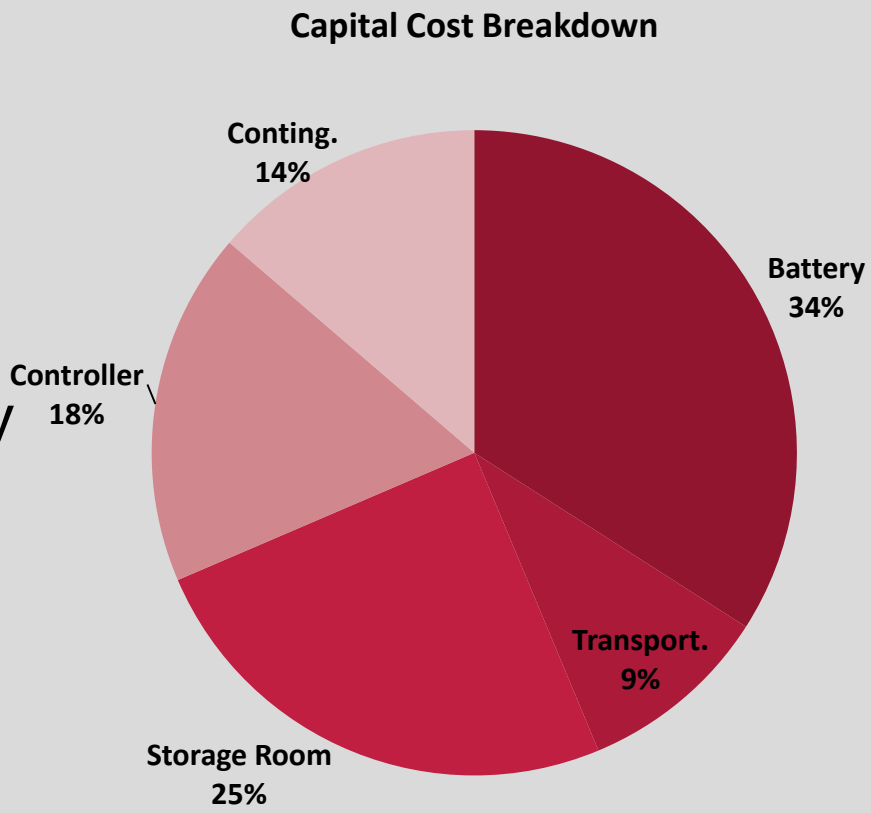
- » Capital cost: $11,00/kWp
- » O&M cost: 130/kWp·year 1.5% of capital cost



KASABONIKA EXAMPLE

Battery cost estimate:

- » Capital cost: $664/kWh
- » O&M cost: $17/kWh capacity installed·year



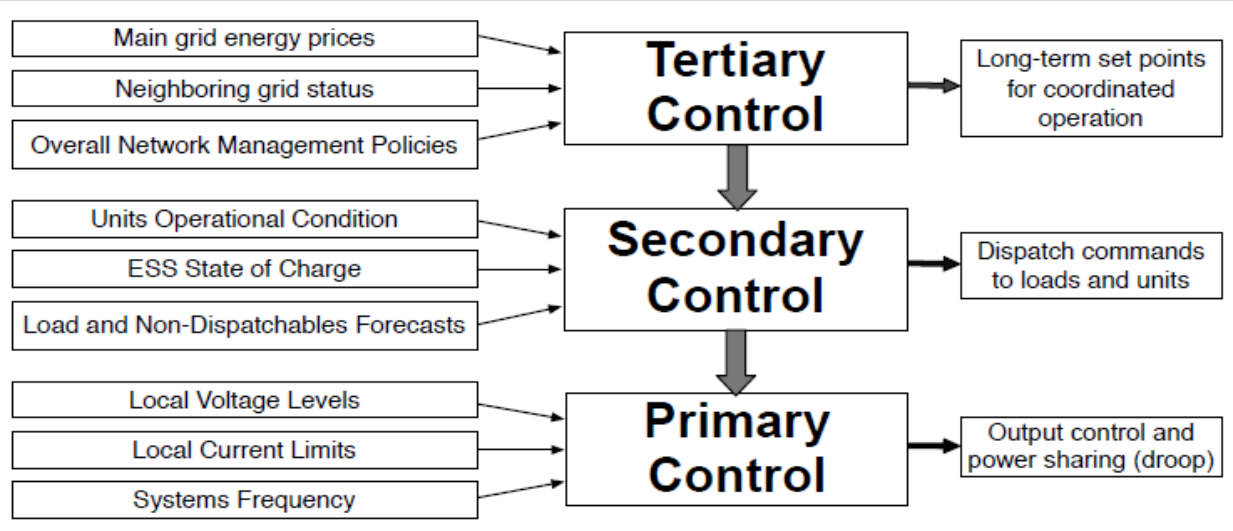
KASABONIKA EXAMPLE

Description	Unit	Baseline (DGS)	PV+WT+DGS	PV+WT+Battery+DGS
System Characteristics				
RE fraction	%	-	9%	18%
DGS	#	3	3	3
PV Capacity	kW	-	250	375
WT Capacity	kW	-	100	200
Battery Capacity	kWh	-	-	53
Fuel/Emissions				
Fuel Consumption	litre x 10^6	1.07	0.96	0.89
Fuel Reduction*	litre x 10^6	-	0.10	0.17
	%	-	10%	16%
Emissions	ton	3,325	2,999	2,784
Emission Reduction*	ton	-	326	541
	%	-	10%	16%
Capital Cost				
Solar Energy	M$	-	$ 2.89	$ 4.33
Wind Energy	M$	-	$ 0.97	$ 1.93
Storage	M$	-	$ -	$ 0.28
Tech/Proj.Mgmt Resources	M$	-	$ 0.96	$ 1.64
Total	**M$**	**-**	**$ 4.82**	**$ 8.18**
O&M Cost				
O&M Cost	M$	$ 3.73	$ 3.46	$ 3.30
O&M Cost Reduction+	**M$**	**-**	**$ 0.27**	**$ 0.43**

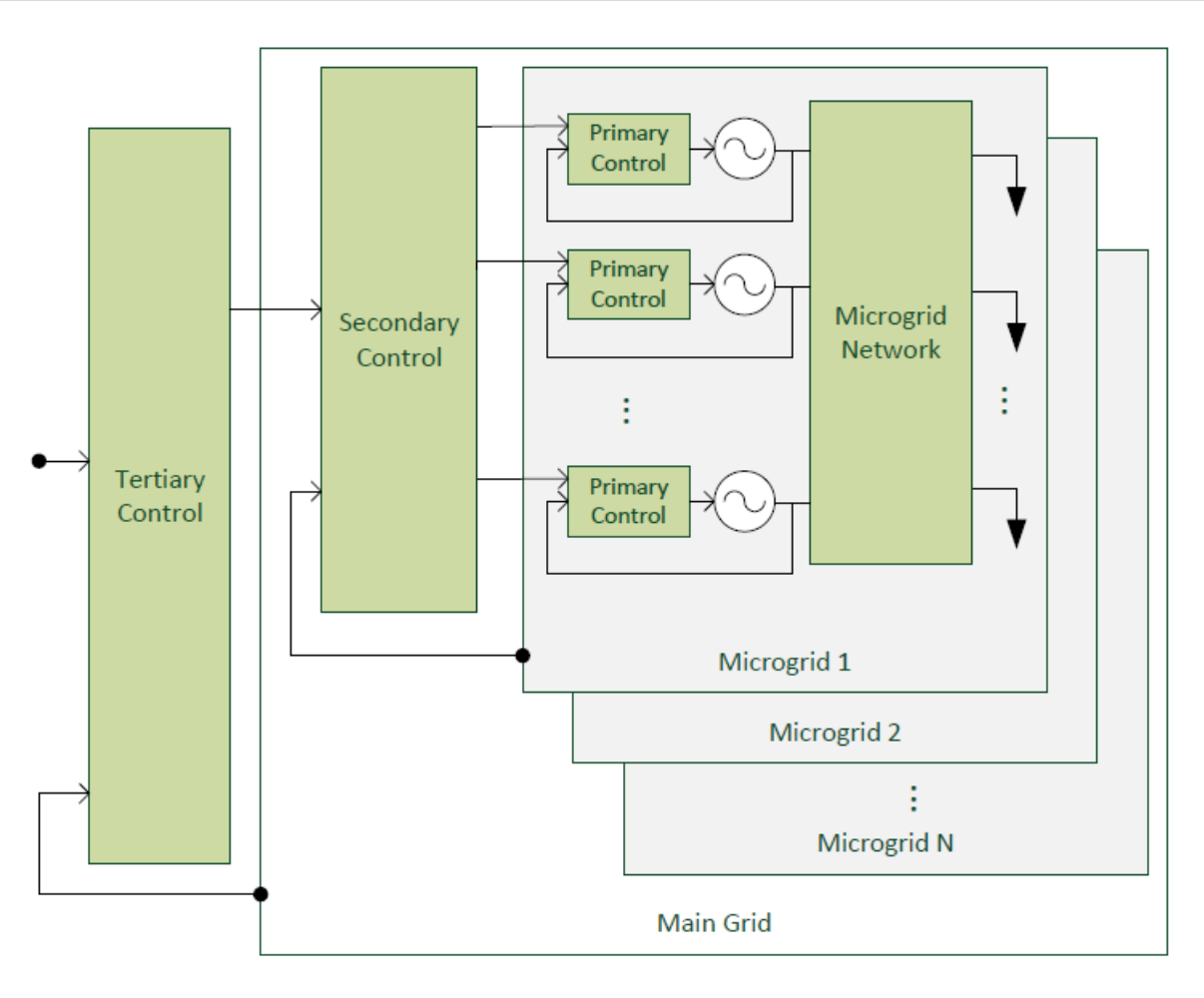
* Reduction compared to DGS Baseline

MICROGRID CONTROL

- Hierarchical centralized control:

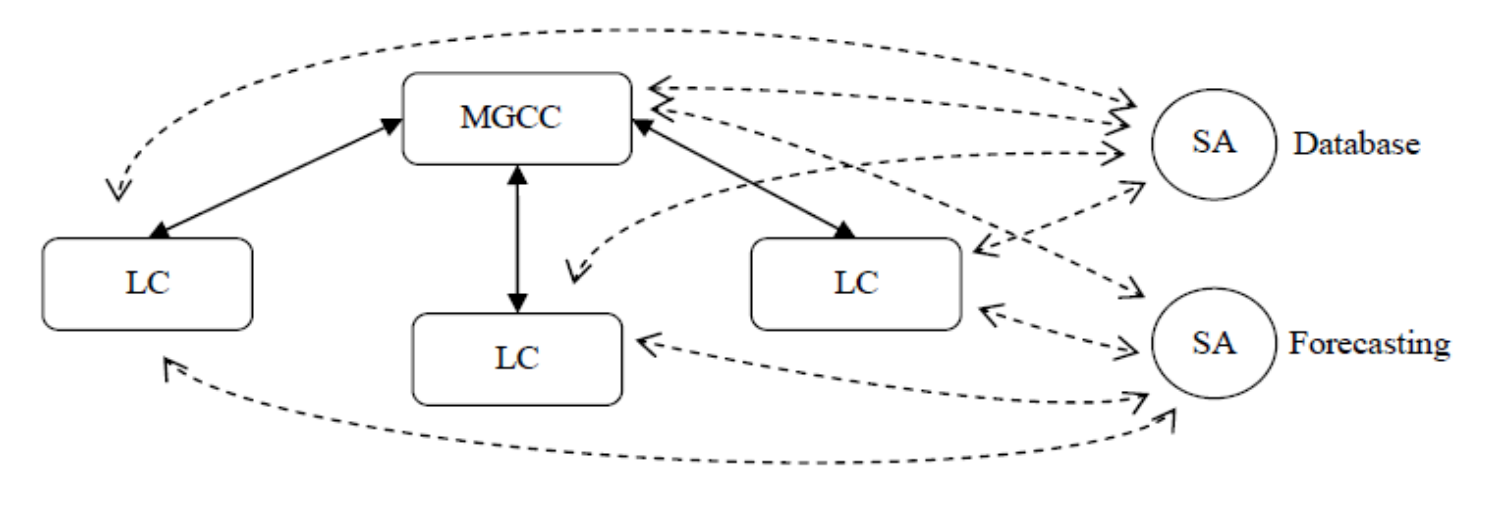


MICROGRID CONTROL



MICROGRID CONTROL

- Decentralized control:



MICROGRID CONTROL

- Grid-connected microgrids:
  - » V and particularly f control is not a major issue, as the grid provides these “services”.
  - » DGs on PQ control mode is the current “standard” in this case, including non-dispatchable DGs (solar PV and some wind generators).
  - » V control is being considered/implemented by LDCs when DGs allow (e.g. solar PV).

MICROGRID CONTROL

- Isolated (e.g. remote) microgrids:
  - » V and f control are a major issue and must be implemented.
  - » V control is prevalent in most DG technologies.
  - » F control is available and “dependable” only in diesel generators, microturbines/CHP turbines and energy (battery) storage systems.

MICROGRID CONTROL

- As more DGs of various technologies are added to microgrids (on- or off-grid), the need to coordinate controls is important:
  - » Primary controls are based on droops to “allocate” control, as in large grids.
  - » Secondary controls:
    - Hierarchical, centralized controls similar to those found in large grids (e.g. SVR, AGC).
    - Distributed controls:
      - Agent based controls.
      - Distributed OPF approaches.

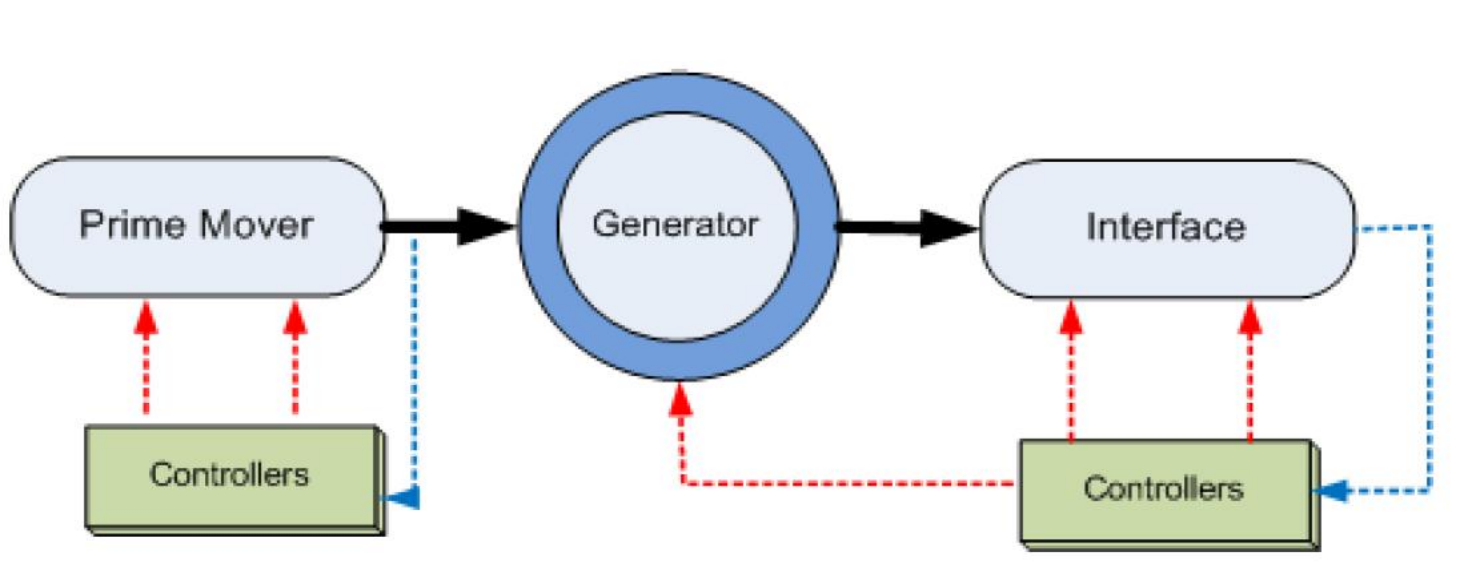
MICROGRID CONTROL

» Tertiary controls:

- The main objective is to optimize the control with an "overall" (central or distributed) optimization of the grid.
- Not widely implemented in large grids in practice, where is only applied to V control.
- It can be viewed as optimal control coordination of multiple microgrids and their common grid.

MICROGRID CONTROL

- V and f controls depend on the DG technology:



MICROGRID CONTROL

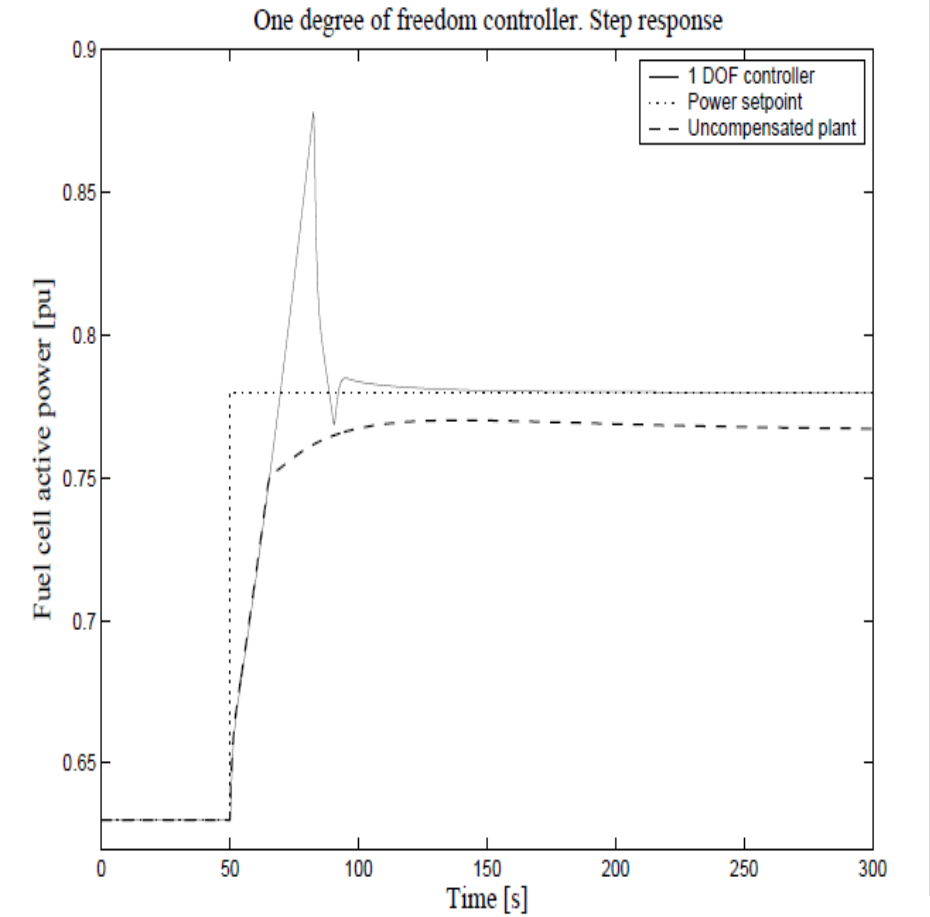
- V controls:
  - » Available in diesel gen. sets, microturbines, CHP turbines, VSC-based DGs (solar PV, some wind generators, fuel cells), DFIG-based wind generators (usually found in farms and not “individually” as part of microgrids), battery storage systems.
  - » Not available in IM-based wind turbines (old, but somewhat prevalent technology in remote, small microgrids).

V AND F CONTROL

- F controls:
  - » Available and dependable in diesel gen. sets, microturbines/CHP turbines and battery storage systems, given their dispatchability and relatively fast response.
  - » Not available in non-dispatchable sources, i.e. solar PV, wind, small hydro.

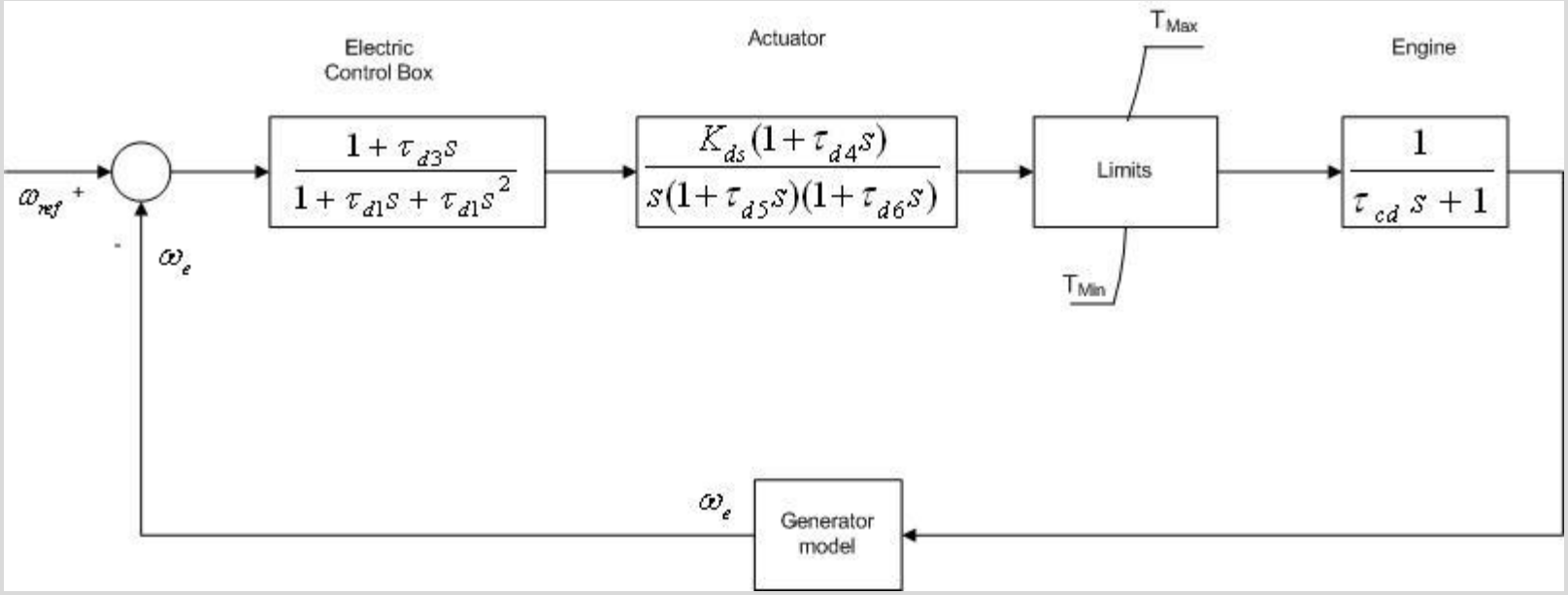
V AND F CONTROL

- Fuel cells are slow to respond to power order changes, unless combined with storage systems on the dc side of the VSC (“large” capacitors, super capacitors, batteries).
- Demand-responsive (elastic) loads can provide f control.



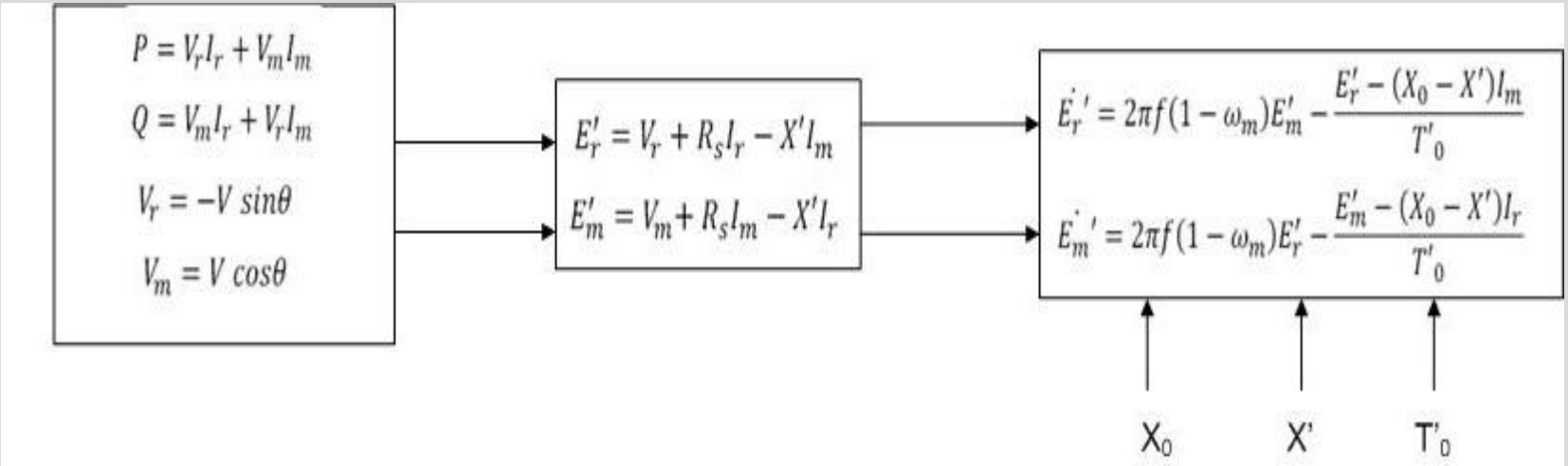
V AND F CONTROL

- Diesel generator: It's basically a "standard" SM-based generator with the same primary V and f regulators.



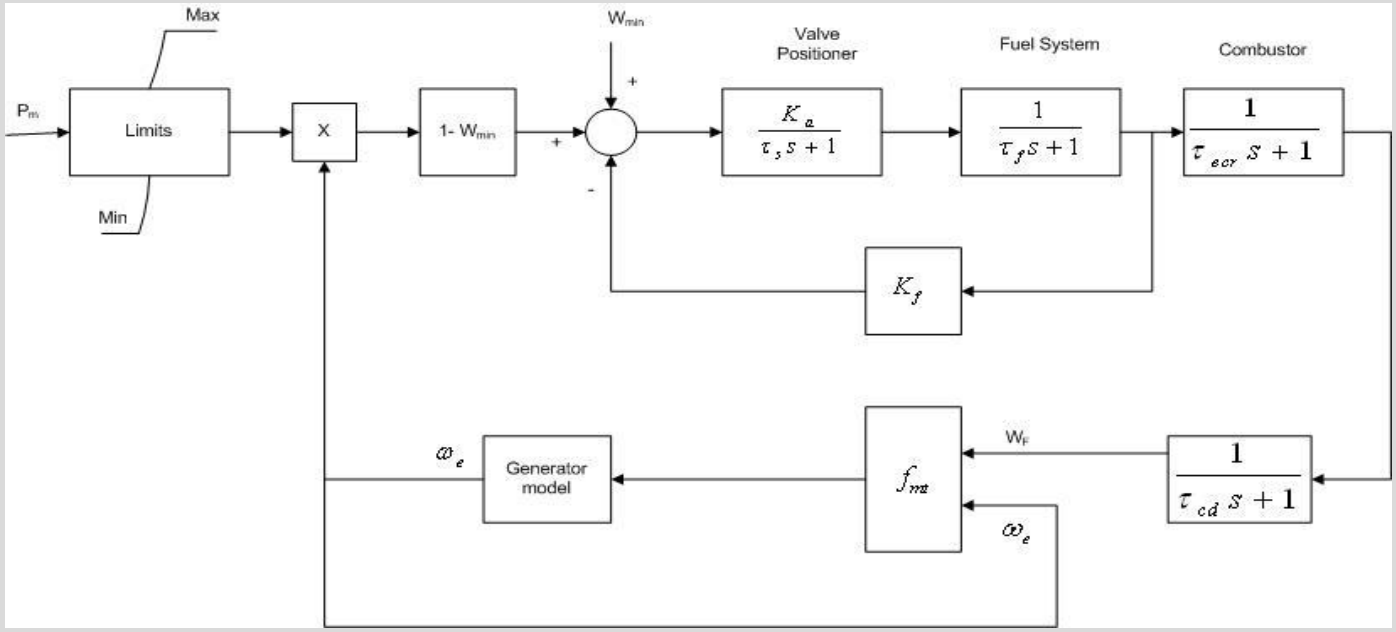
V AND F CONTROL

- Wind turbine generator: In remote, small microgrids, it's likely to be a fixed speed wind turbine with a direct-grid-connected induction generator, and thus neither V nor f control is possible.



V AND F CONTROL

- Micro turbine generator:
  - » It's dispatchable and has a fast response, and thus can be used for f control:

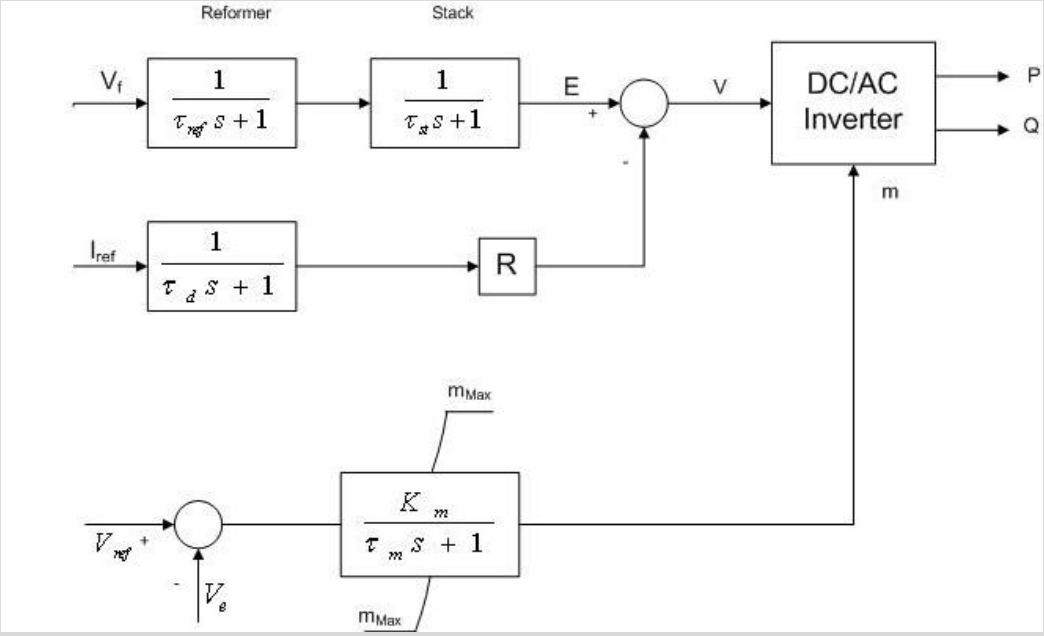


V AND F CONTROL

- If the generator is a synchronous machine, which is common, V control is not an issue.
- If the generator is an induction machine, a VSC interface is used, which allows V control.

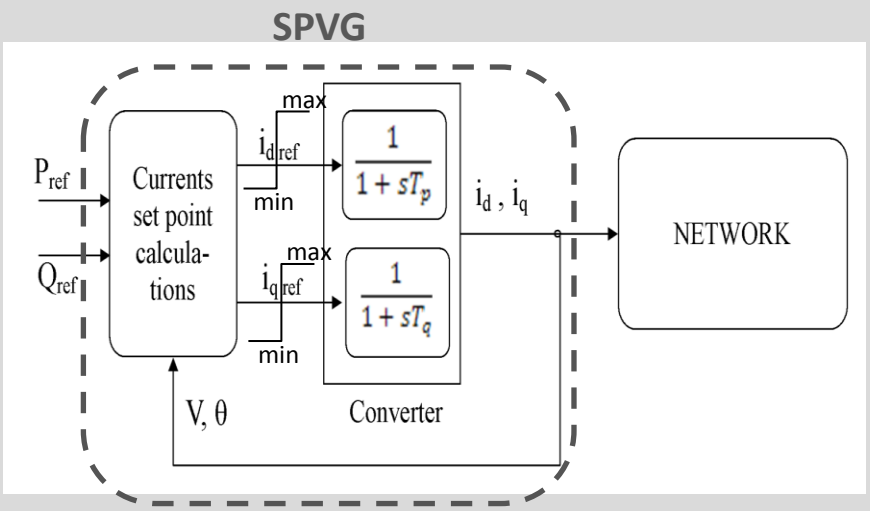
V AND F CONTROL

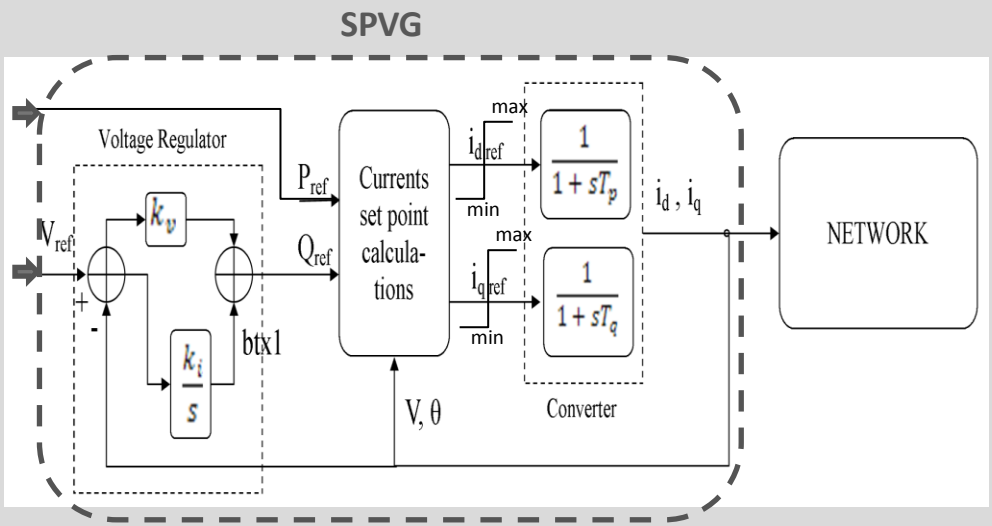
- Fuel cell: V control is not an issue through the VSC interface, but frequency control capability is limited due to its slow response to power set point changes.



V AND F CONTROL

- Solar PV generator: Since power cannot be controlled, it's not adequate for f control, but the VSC interface allows V control.





ENERGY MANAGEMENT PROBLEM

- An Energy Management System (EMS) is a set of protocols and computer applications designed to assist power system operators in the operation of the grid.
- There computer applications incorporate online data analysis and include:
  - » State estimation.
  - » OPF.
  - » Voltage control/reactive power optimization.
  - » Security assessment.
  - » Load forecasting.

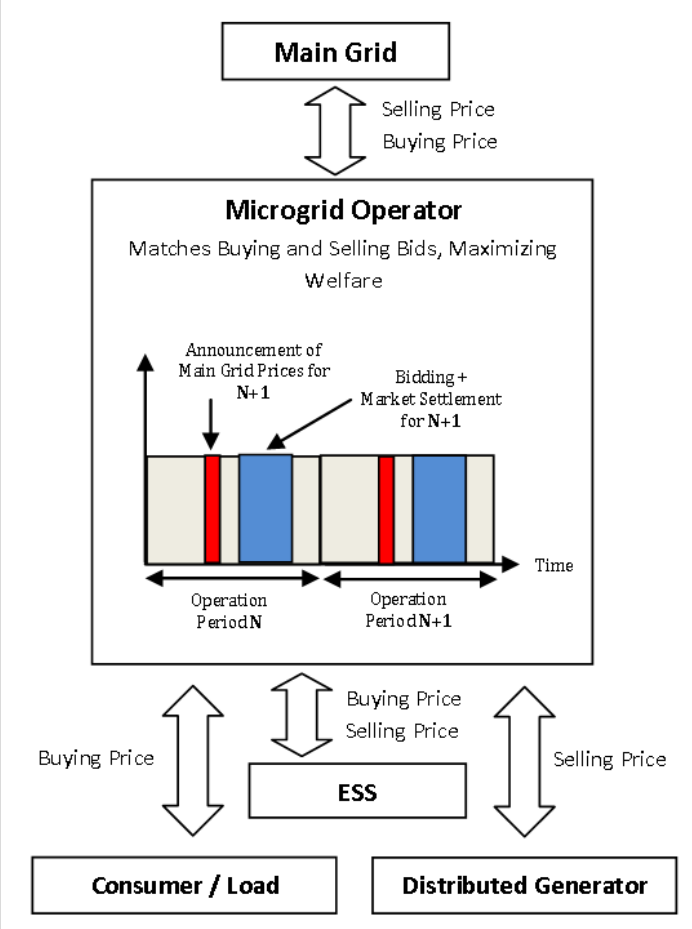
ENERGY MANAGEMENT PROBLEM

- In microgrids, all the EMS applications must be performed by an autonomous automated system as part of the secondary control level.
- The operation of an EMS in a microgrid becomes more challenging due to the critical demand-supply balance, low inertia of the system and the presence of energy storage systems.

ENERGY MANAGEMENT PROBLEM

- The general EMS case:
  - » Find the optimal or near optimal unit commitment of units.
  - » Find the optimal or near optimal dispatch of units.
  - » Find the optimal or near optimal voltage settings.
- Challenges for EMS in microgrids:
  - » Intermittent and hard to predict generation.
  - » System states are coupled in time due to Unit Commitment (UC) decisions and Energy Storage Systems (ESS).
  - » Multiple objectives (e.g. total cost, GHG emissions)
  - » Multiple owners and sometimes conflicting objectives.

DECENTRALIZED EMS

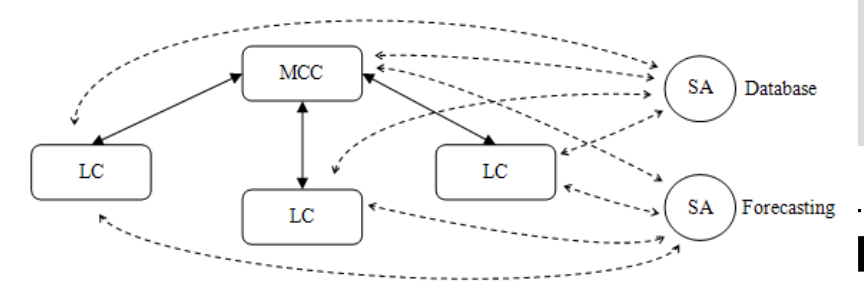


Advantages:

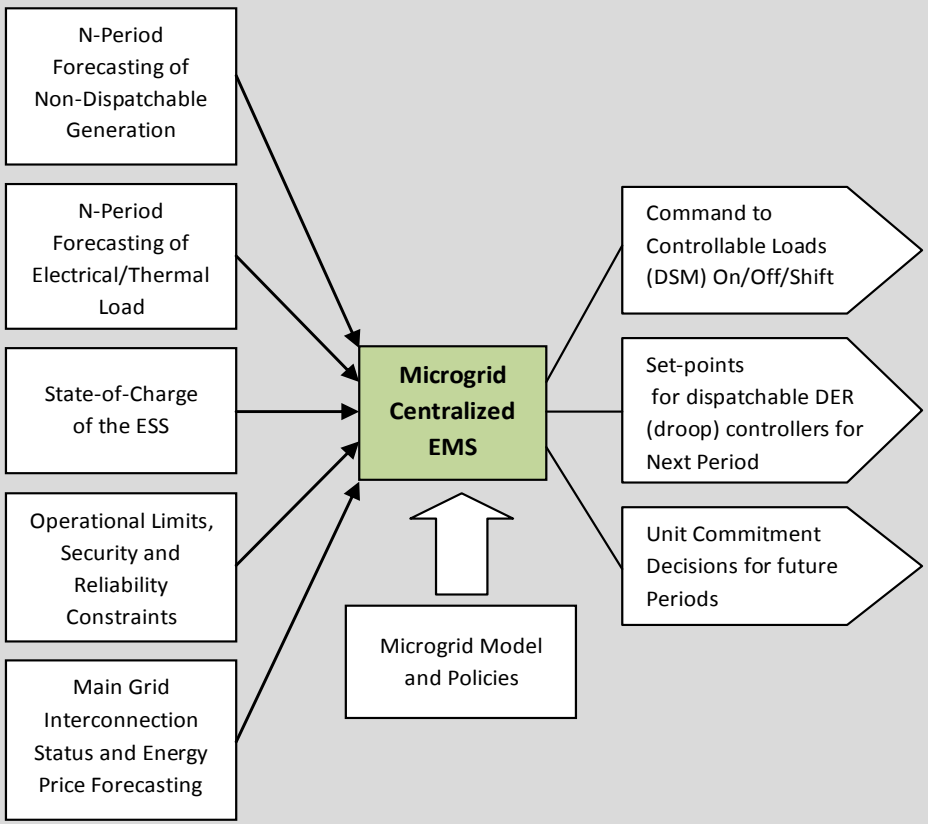
- » Market-like environment, with direct incentive for investments.
- » More suitable for grid-connected mode with multiple owners.
- » Distributed decision-making, capturing local updated information and objectives.
- » Allows for "plug-in" approach.

Disadvantages:

- » Not able to send appropriate signals for multi-stage operation planning with intermittent generation.
- » Has problems in oligopolic microgrids (stand-alone) and requires special rules to make intermittent sources competitive.



CENTRALIZED EMS



Advantages:

- » Allows the implementation of traditional optimization methods.
- » Able to handle multi-period optimization.
- » More suitable for stand-alone operation, when demand-supply balance within the microgrid is critical.

Disadvantages:

- » Obligates the different actors to share information about operation costs and constraints.
- » Difficult to implement in a multiple-owner microgrid with different and conflicting objectives.
- » The EMS needs to be re-adjusted when more units are added.

EMS MODEL

- The EMS defines the optimal steady-state conditions of a microgrid while considering its security and reliability, and can be formulated as a multi-step optimization problem as follows:

$$
\begin{aligned}
min \quad & \sum_{k_t=t}^{t+K} F\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) \\
s.t. \quad & z_{k_t+1} = w\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) && \forall k_t = t, \dots, t+K \\
& g_{k_t}\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) = 0 && \forall k_t = t, \dots, t+K \\
& h_{k_t}\left(x_{k_t}, z_{k_t}, u_{k_t}, p_{k_t}\right) \leq 0 && \forall k_t = t, \dots, t+K \\
& \left\| u_{k_t+1} - u_{k_t} \right\| \leq \Delta u_{k_t}^{max} && \forall k_t = t, \dots, t+K
\end{aligned}
$$

Outputs:

- Unit commitment
- Dispatch of units
- Voltage settings

z_{kt} Vector of discrete time-dependent variables, typically state of charge of storage systems.

p_{kt} Vector of parameters representing the best available estimation at step $k = t$ of system demand, intermittent generation, fuel prices, etc., for all the time-steps in the multi-stage horizon.

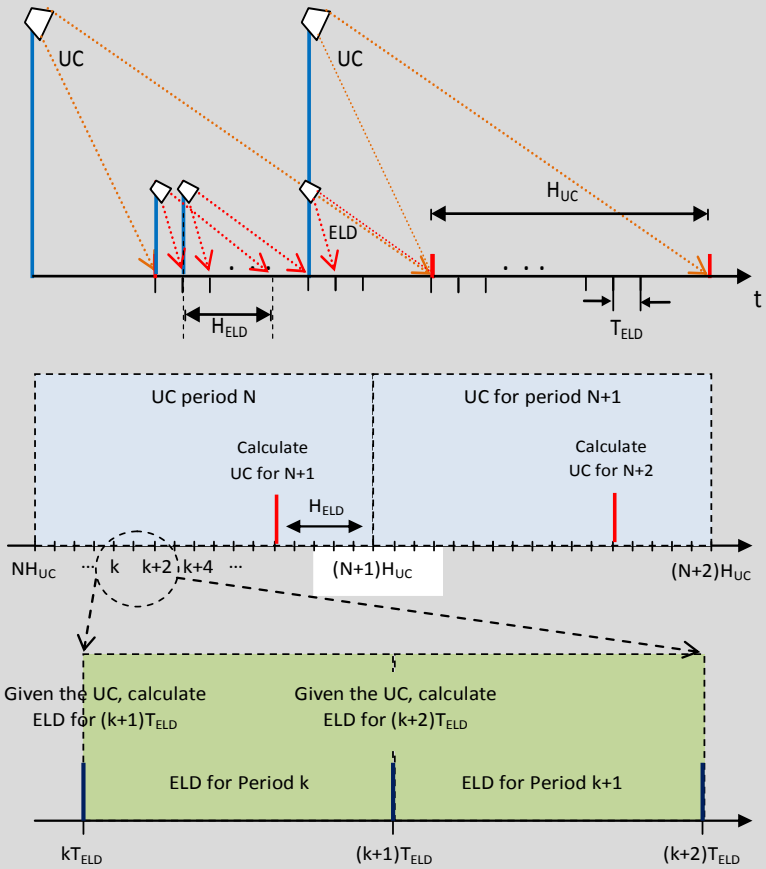
u_{kt} Vector representing the control variables.

x_{kt} Represents the time-independent variables, such as voltages and phase angles.

EMS MODEL

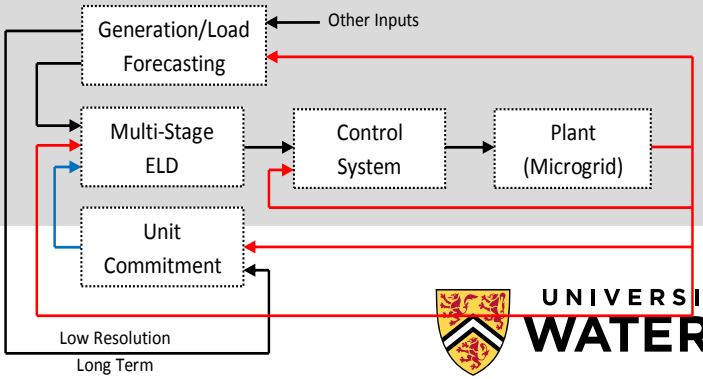
- Based on a Model Predictive Control (MPC) approach:
  - » An optimization problem is formulated and solved at each discrete time-step.
  - » At each time-step, the solution to the optimal control problem is solved over a certain pre-defined horizon using the current state of the system as the initial state.
  - » The optimization calculates a control sequence for the whole horizon, but only the control action for the next time step is implemented.
  - » The process is repeated at the next time-step.

EMS MODEL

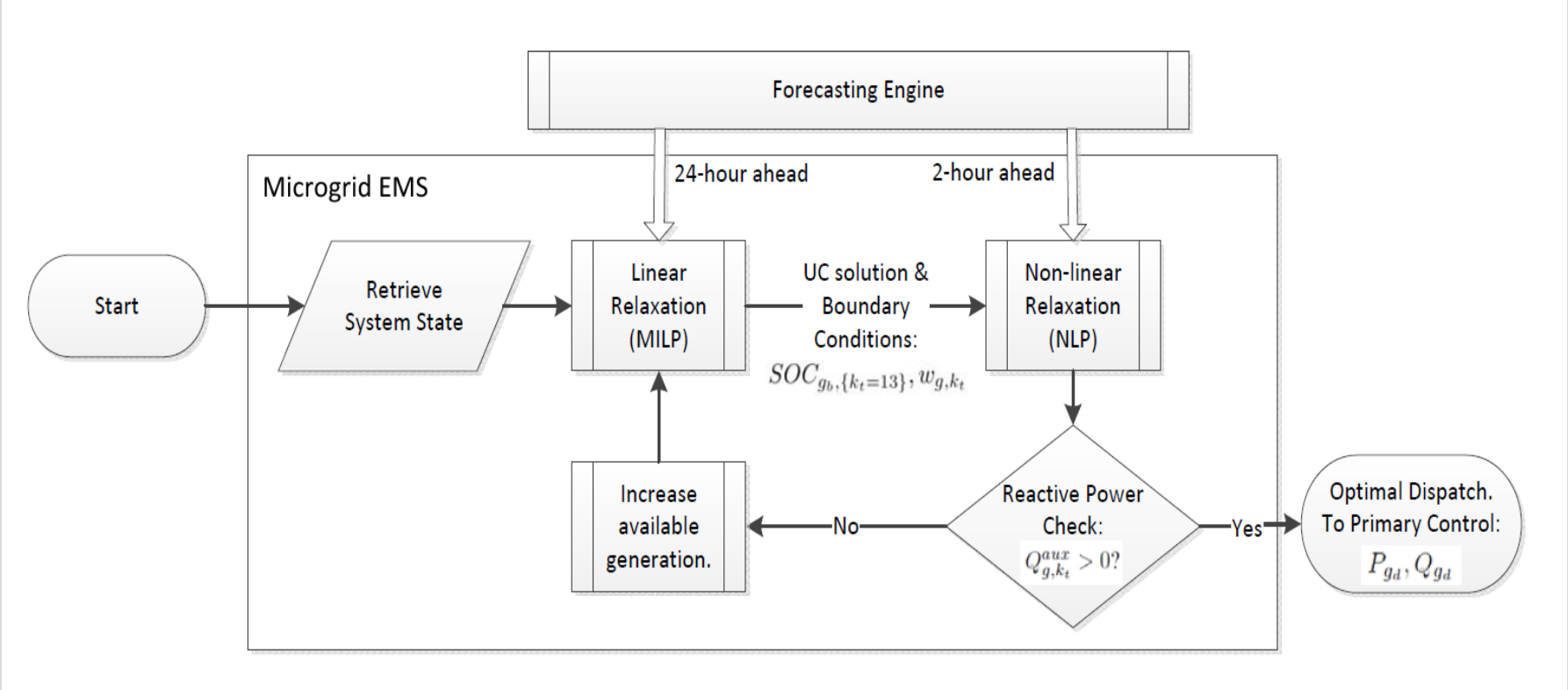


Decoupled approach:

- » 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.).



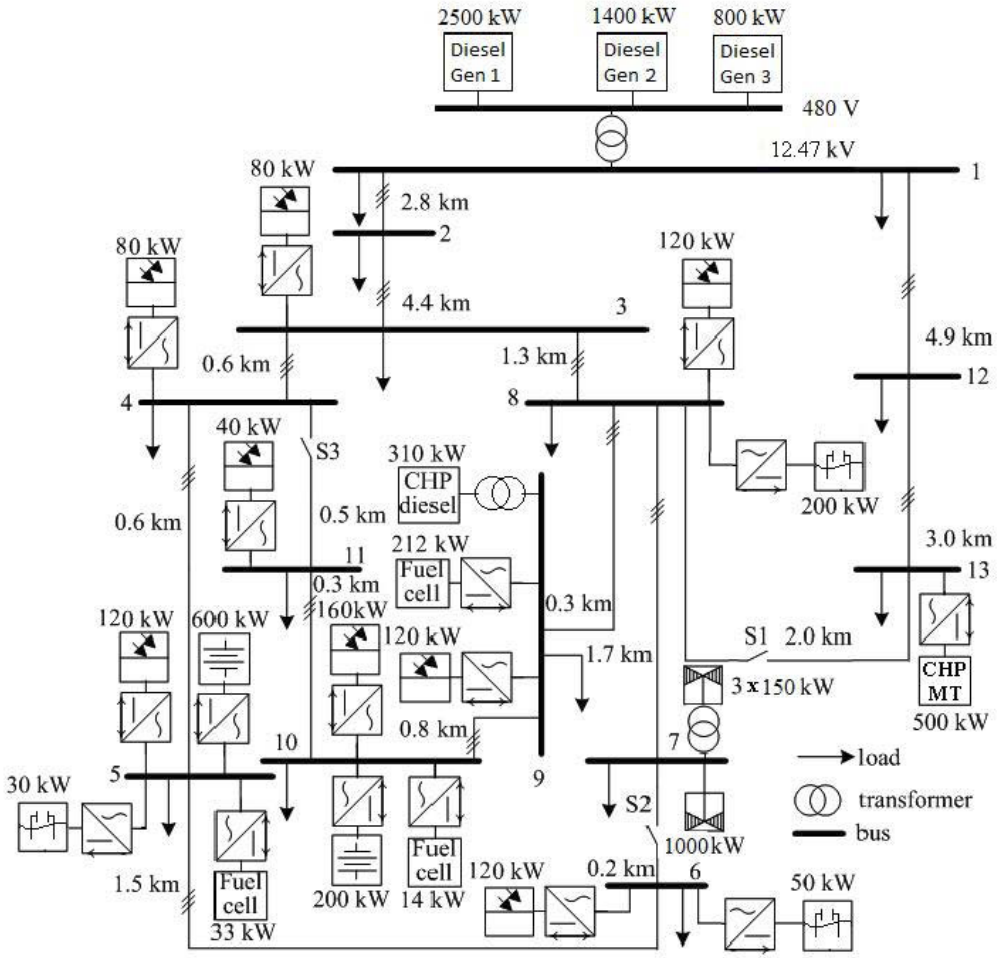
EMS MODEL


Forecasting Engine
Microgrid EMS
24-hour ahead
2-hour ahead
Start
Retrieve System State
Linear Relaxation (MILP)
UC solution & Boundary Conditions:
$SOC_{g_b,\{k_t=13\}}, w_{g,k_t}$
Non-linear Relaxation (NLP)
Increase available generation.
No
Reactive Power Check:
$Q^{aux}_{g,k_t} > 0?$
Yes
Optimal Dispatch. To Primary Control:
P_{g_d}, Q_{g_d}

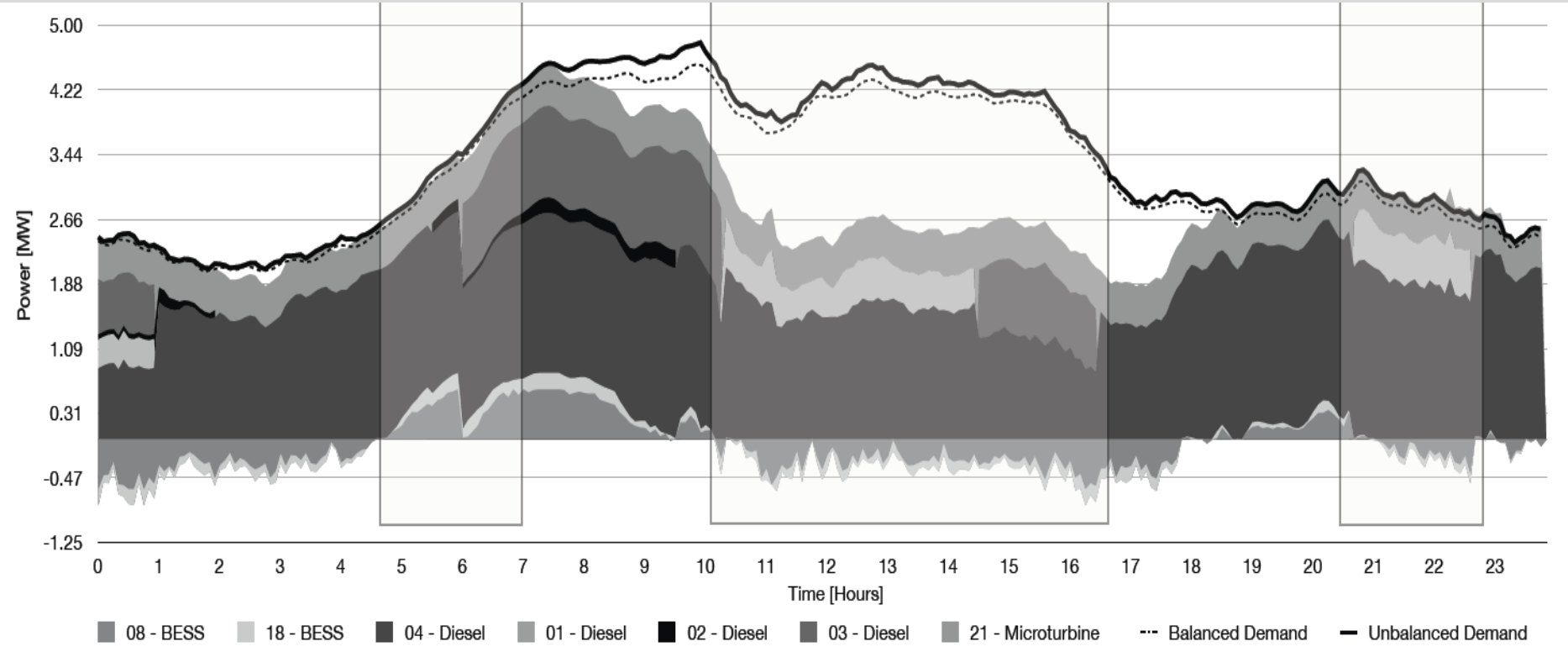
EMS MODEL

- Detailed 3-phase model to represent unbalanced conditions typical of microgrids (distribution networks).
- Consider forecast uncertainties (e.g. wind and solar generation, load), which can have a significant effect on load balance in isolated microgrids:
  - » Robust optimization approach: considers budget of uncertainty.
  - » Stochastic optimization approach: considers the probability of the forecasts.
  - » Interval (affine) arithmetic: represents uncertainties in terms of intervals.

EMS EXAMPLE


2500 kW
Diesel Gen 1
1400 kW
Diesel Gen 2
800 kW
Diesel Gen 3
480 V
12.47 kV
1
80 kW
2.8 km
2
80 kW
120 kW
4.4 km
3
4.9 km
0.6 km
1.3 km
12
4
8
40 kW
S3
310 kW
CHP diesel
200 kW
0.6 km
0.5 km
212 kW
Fuel cell
3.0 km
11
13
0.3 km
0.3 km
120 kW
600 kW
160kW
120 kW
1.7 km
S1
2.0 km
3 x 150 kW
CHP MT
500 kW
0.8 km
10
7
load
30 kW
5
9
transformer
S2
bus
1000kW
Fuel cell
120 kW
0.2 km
6
1.5 km
Fuel cell
200 kW
14 kW
50 kW
33 kW

EMS EXAMPLE

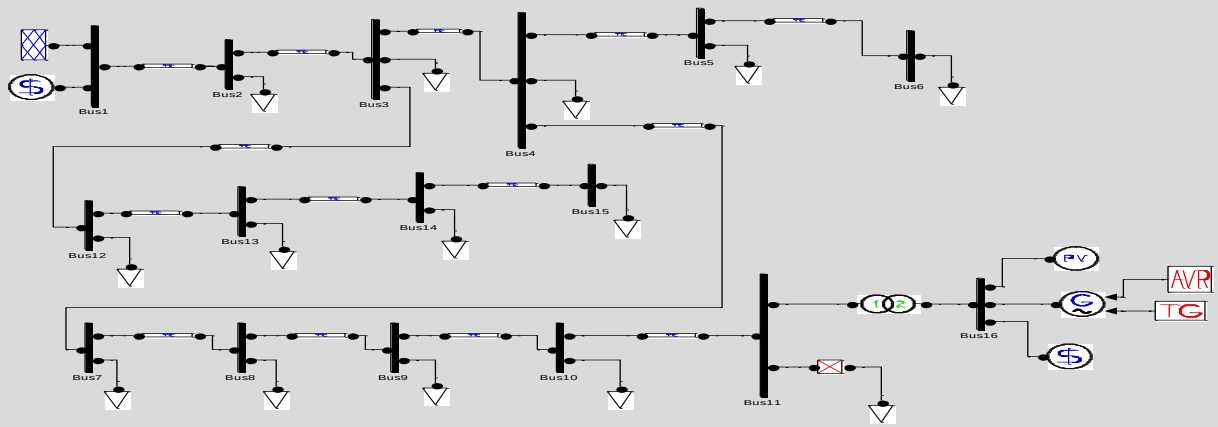

5.00
4.22
3.44
2.66
1.88
1.09
0.31
-0.47
-1.25
Power [MW]
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time [Hours]
08 - BESS
18 - BESS
04 - Diesel
01 - Diesel
02 - Diesel
03 - Diesel
21 - Microturbine
Balanced Demand
Unbalanced Demand

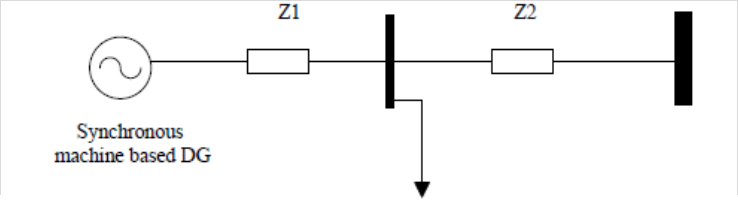
STABILITY

- There is a lack of understanding of the dynamics of DGs under unbalanced conditions.
- A full characterization of the unbalanced system in stability analyses allows a better understanding of dynamic behaviour of DGs.
- Most DGs nowadays are equipped with small synchronous generators (e.g., diesel generators, microturbines)

STABILITY

- Test microgrid based on Kumamoto distribution test system:





STABILITY

- Stability studies:
  - » Voltage stability studies based on P-V and P-L curves.
  - » Transient stability studies based on time domain simulations to study contingencies.
  - » Small perturbation stability studies using a model identification approach to compute the eigenvalues.

VOLTAGE STABILITY

- Static model:
  - » Three-phase power flow.
  - » Load:

$$Z_{al} = (1+k)Z_l$$

$$Z_{bl} = Z_l$$

$$Z_{cl} = (1-k)Z_l$$

- Dynamic model:
  - » Time domain simulations using PSCAD/EMTDC.
  - » Detailed generator and AVR model.

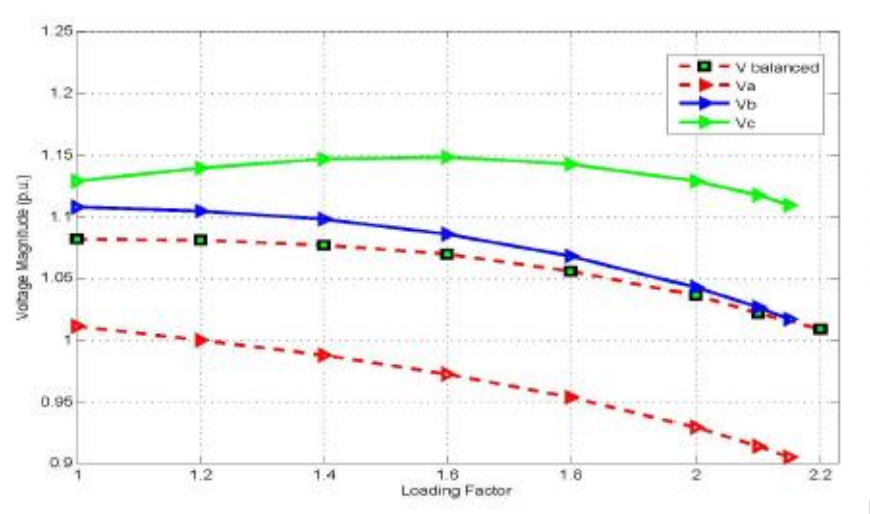
VOLTAGE STABILITY

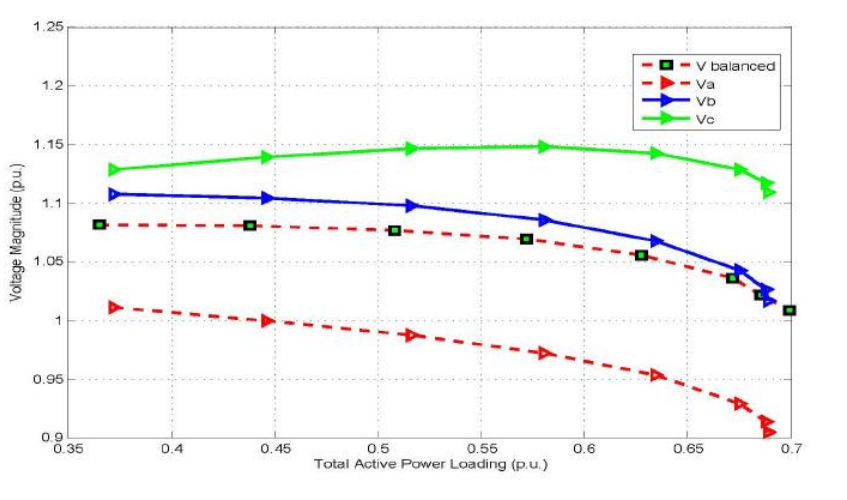
- When the system unbalancing increases, the maximum loadability of the system decreases:

$k(\%)$	Maximum loading factor (p.u.)		Maximum active power loadability (p.u.)	
	TDS	Three-phase PF	TDS	Three-phase PF
0	2.2	2.24	0.692	0.6925
5	2.2	2.24	0.692	0.6925
10	2.2	2.22	0.691	0.6923
15	2.2	2.22	0.691	0.6917
20	2.15	2.20	0.689	0.6912
25	2.1	2.18	0.687	0.6903

VOLTAGE STABILITY

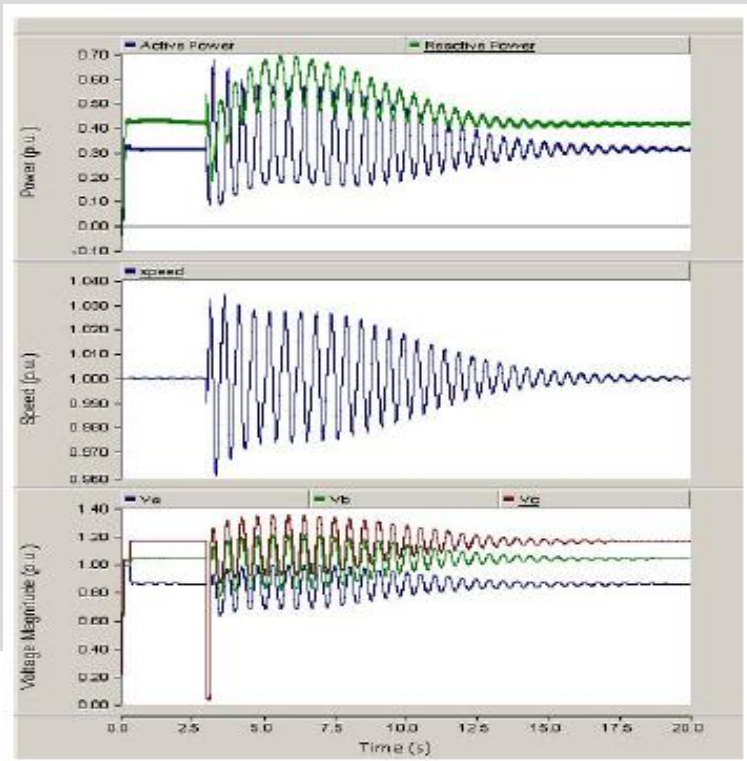
- Load voltage versus loading factor and PV curves for *k* = 20%:

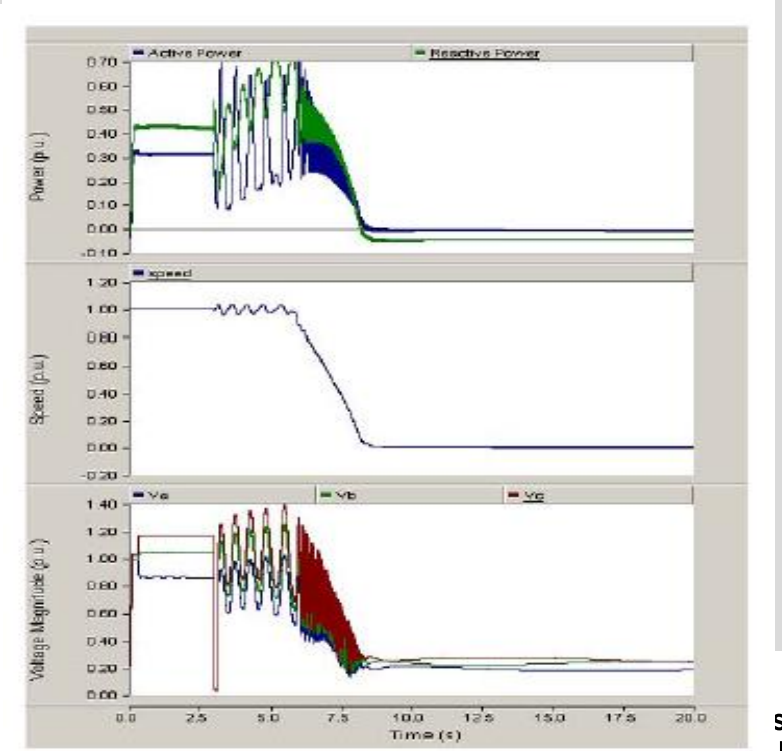




TRANSIENT STABILITY

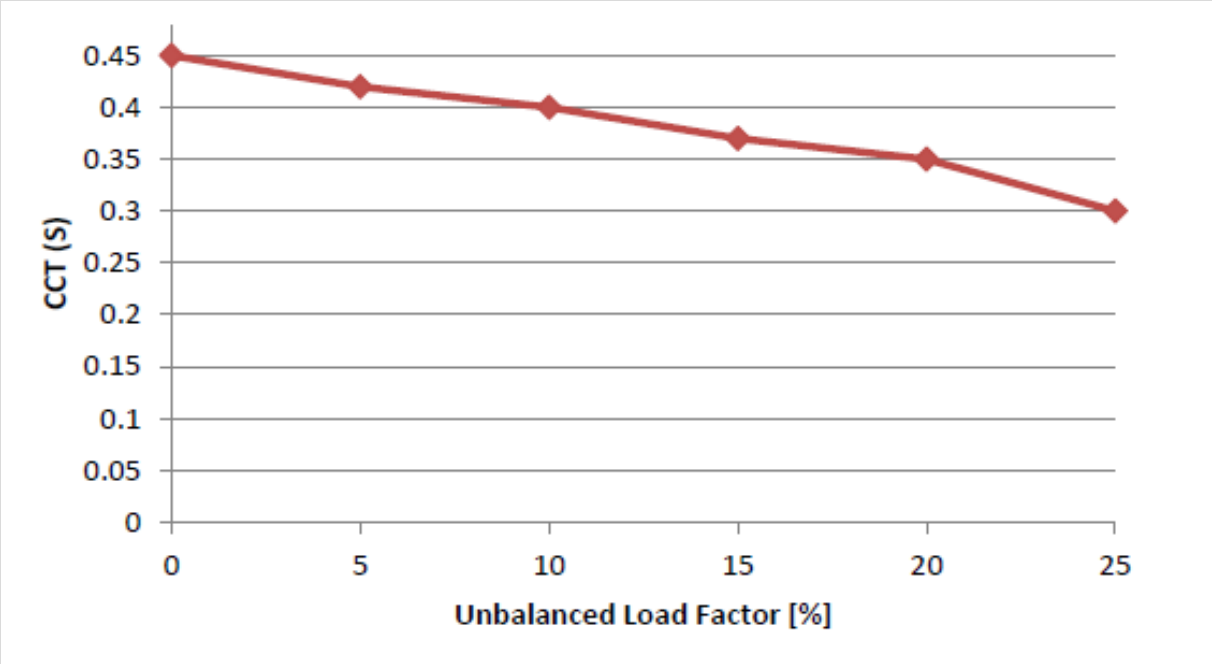
- Transient behavior of the synchronous machine at *l* = 1.5 p.u. and *k* = 25% for the studied fault before and after the CCT:





TRANSIENT STABILITY

- CCT at base load (*l* = 1 p.u.) for a three-phase-to-ground fault:

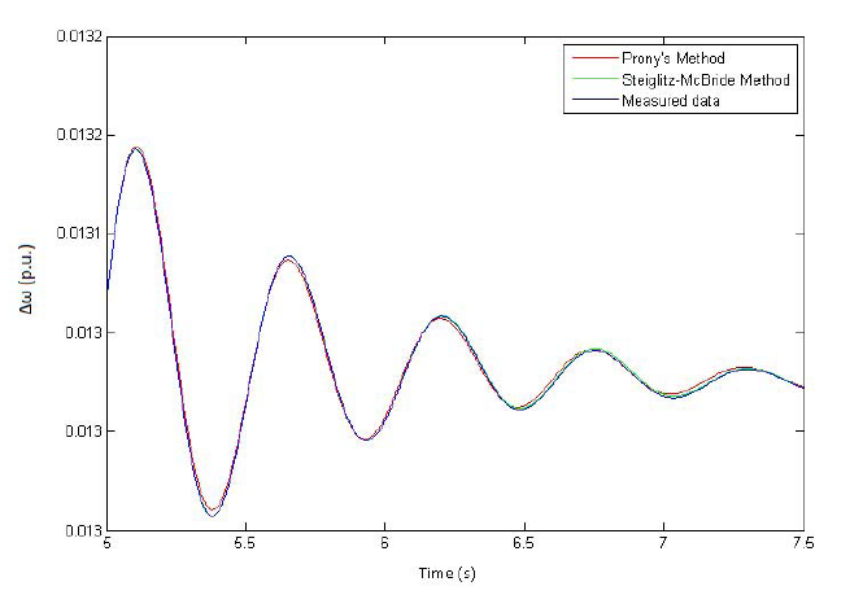


SMALL-PERTURBATION STABILITY

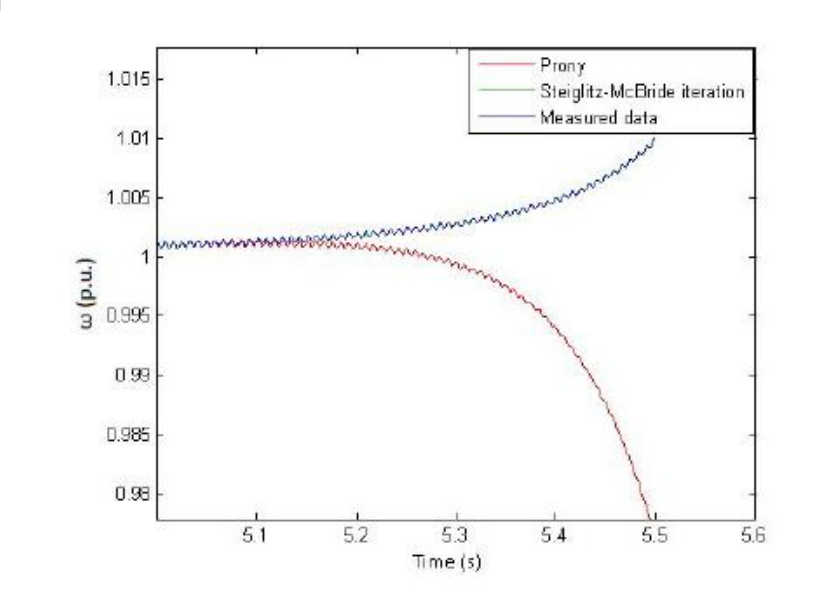
- Many commercial programs use phasor models for small-perturbation stability studies.
- Unbalanced generators show sustained small oscillations in steady state conditions; hence, standard phasor-based linearization techniques are not applicable in this case.
- A simulation based approach is hence necessary to study the problem using modal estimation:
  - » Prony method.
  - » Steiglitz-McBride iteration method.

SMALL-PERTURBATION STABILITY

Measured data and estimated signal with a large disturbance:

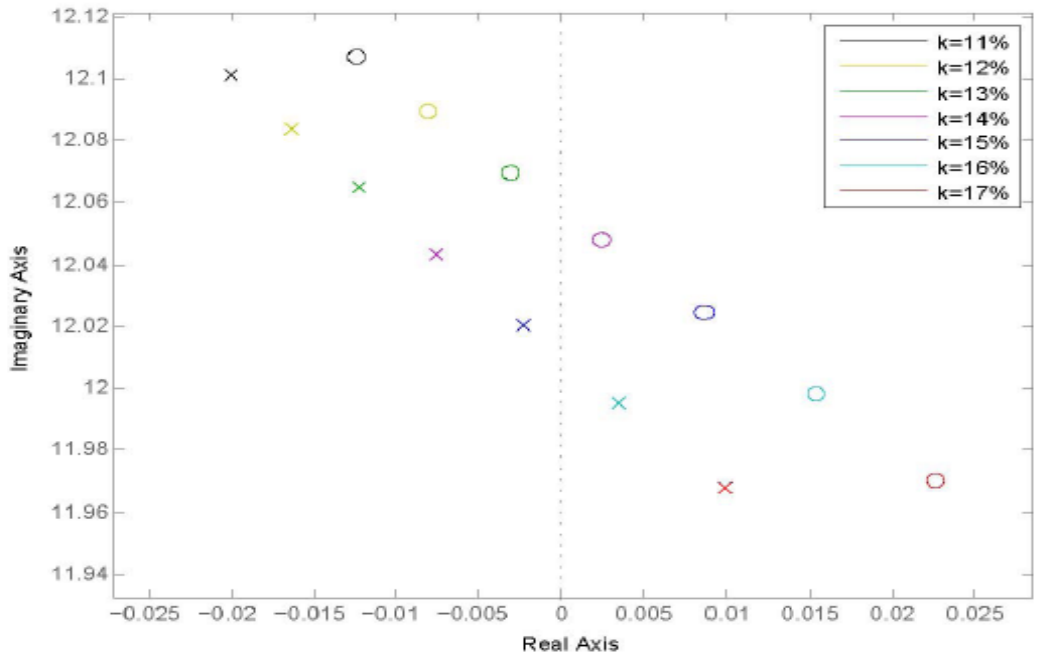


Measured data and estimated signal when the system is unstable:



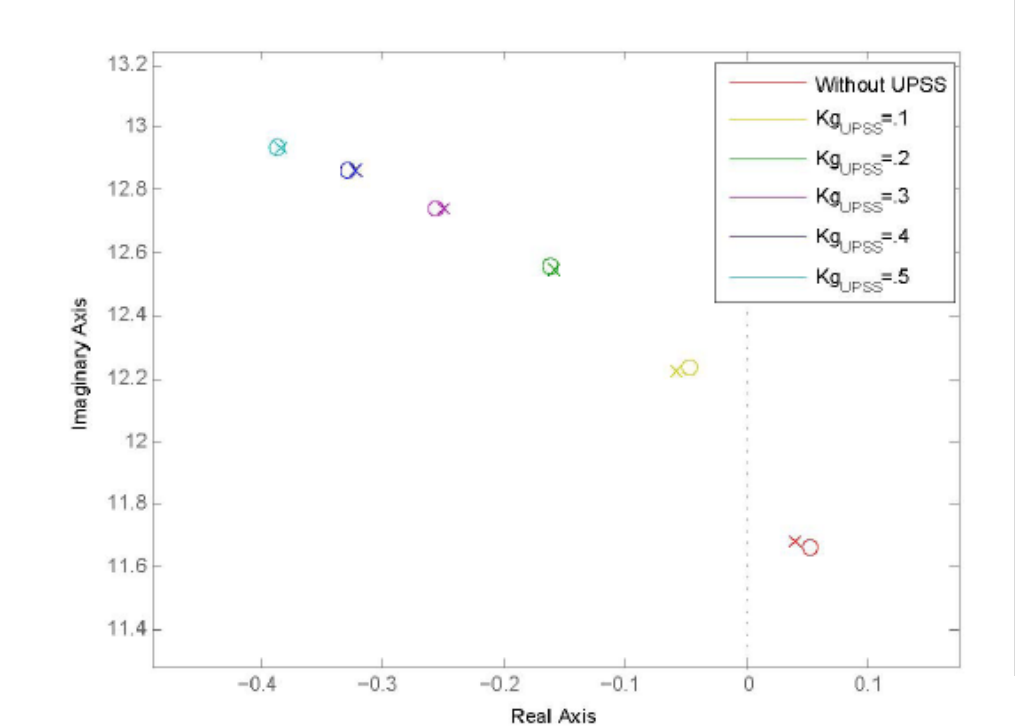
SMALL-PERTURBATION STABILITY

- At high loading conditions and *k* = 15%, the critical poles cross the imaginary axis and thus the system experiences a Hopf Bifurcation with 1.91 Hz frequency:

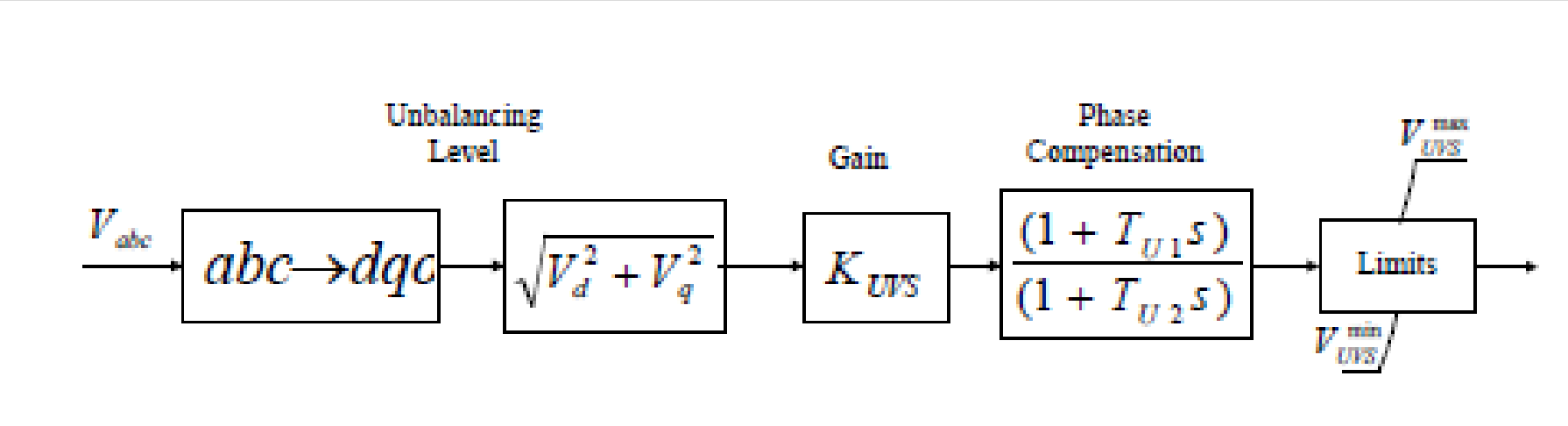


SMALL-PERTURBATION STABILITY

- Loading level *l* = 2.2 p.u. and unbalancing of *k* =25%:



UNBALANCED VOLTAGE STABILIZER (UVS)



UVS

- Transient behavior of generator speed with and without UVS at high loading conditions: