Generic Modelling of Energy Management Methods in Hybrid Energy Systems Including Energy Storage

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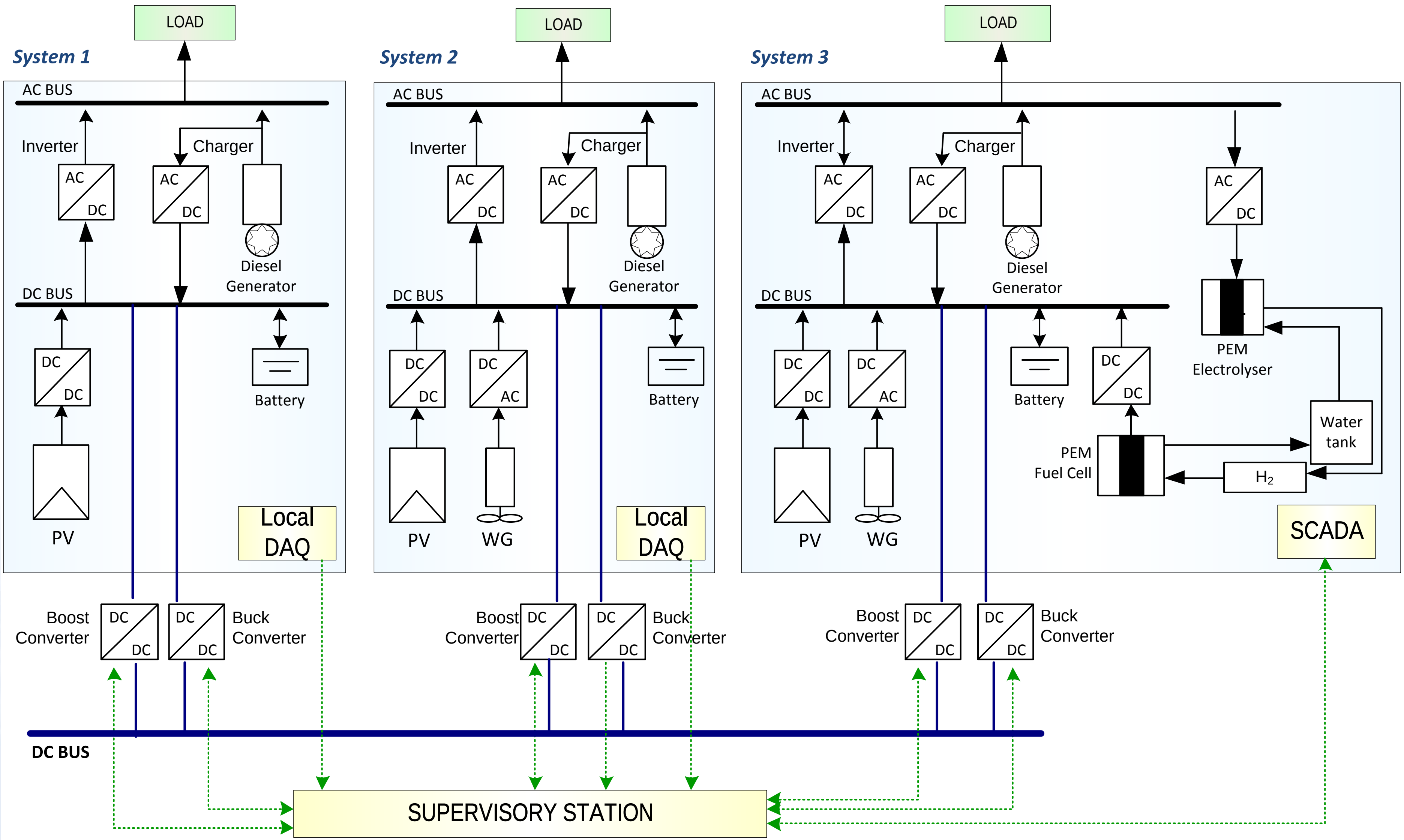
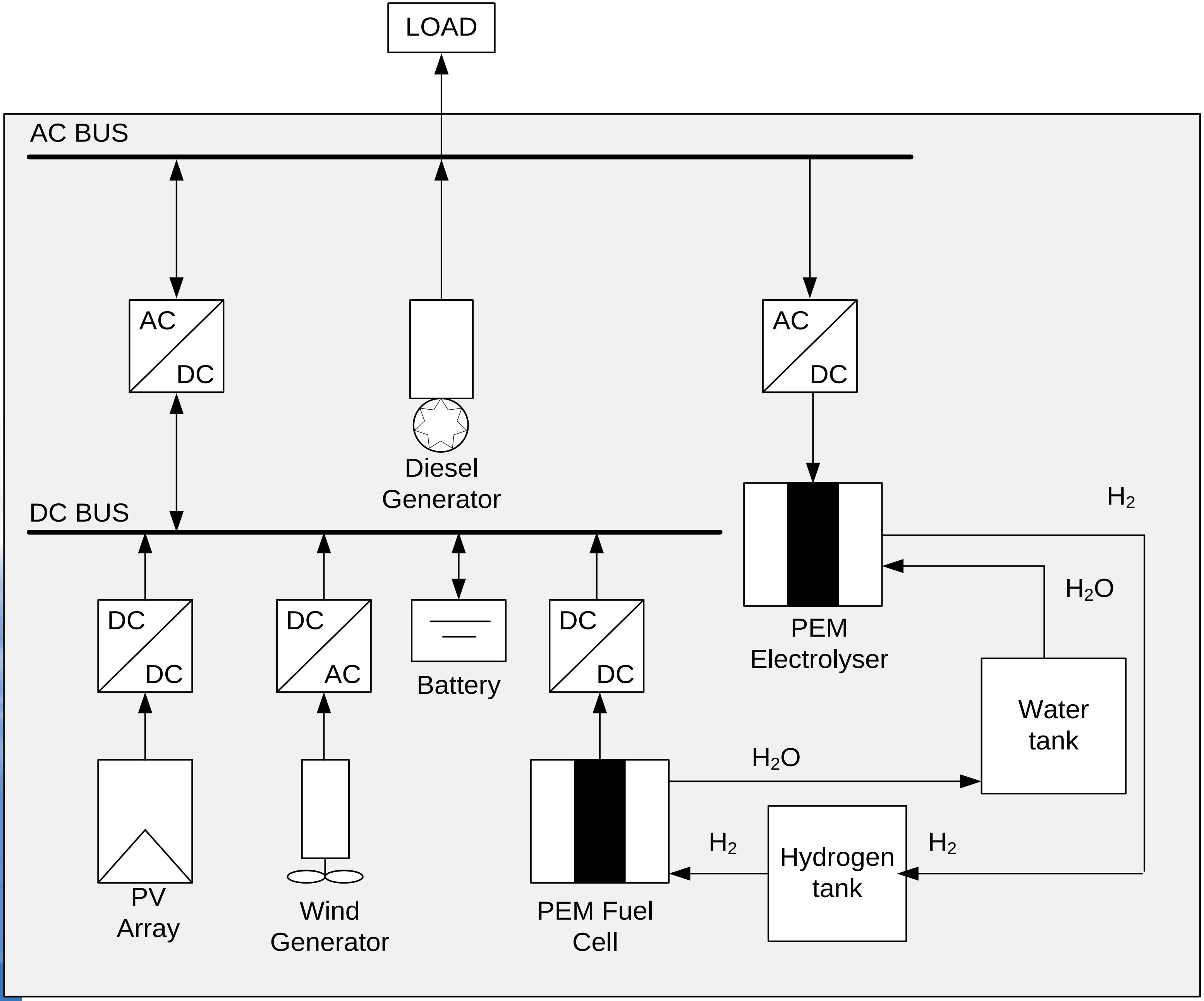
Outline

- Energy Management Methods & Flow Charts
- State of (Directed) Graph
- Evolution Operator
- Complete Modelling
- Case Studies

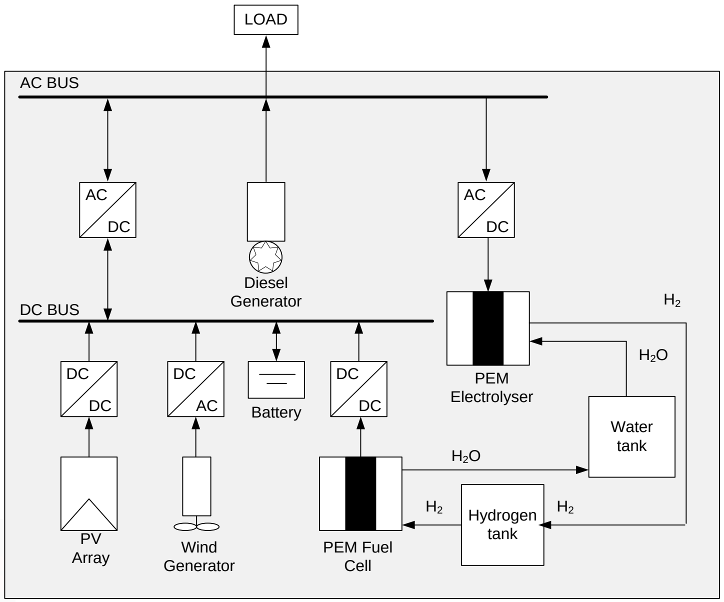
Motivating example…

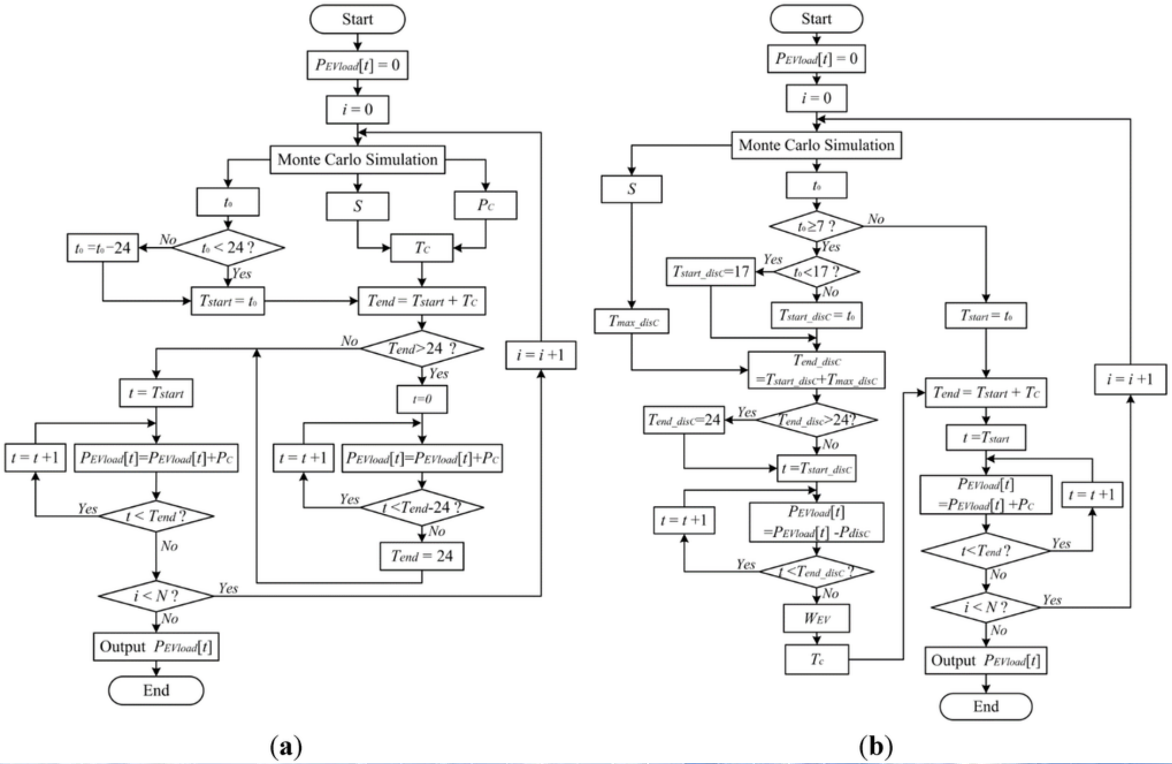


Hybrid Energy System

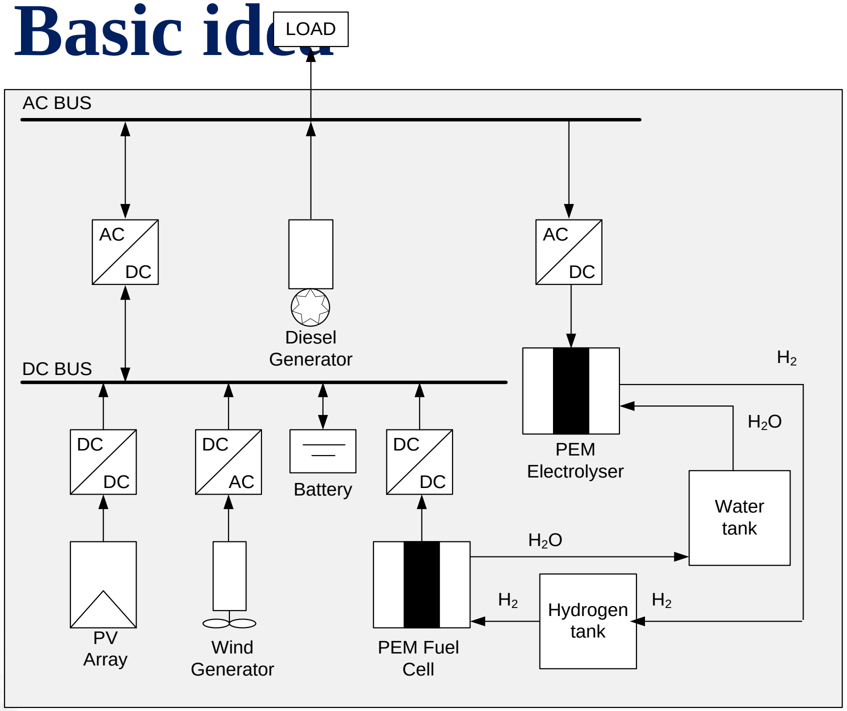


Energy Management Methods (EMM)

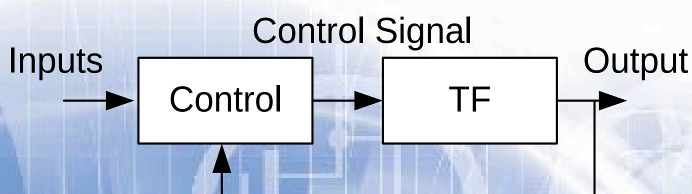


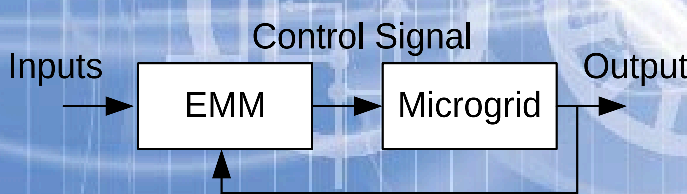


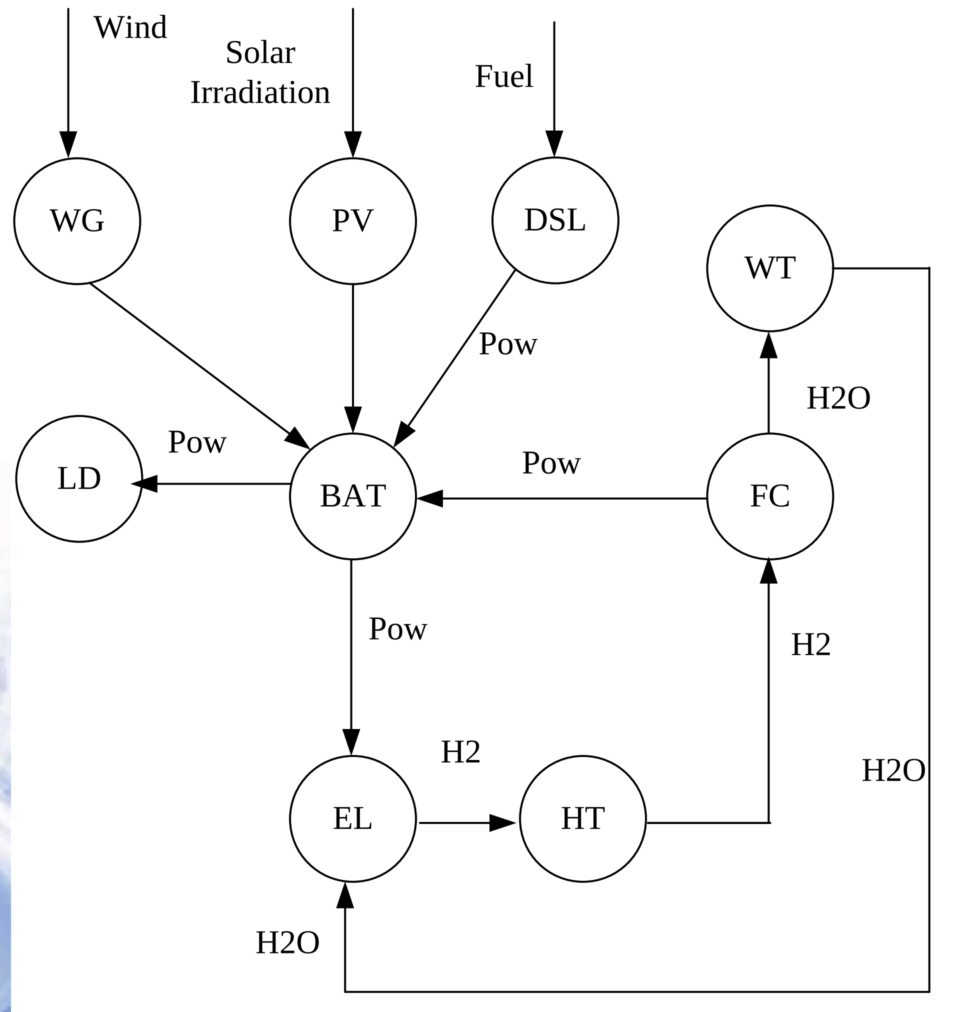
Basic idea



- Try to define/describe an EMM/microgrid by stating their main properties
- Control theory: mathematical models (ODEs, TFs, state space models…)



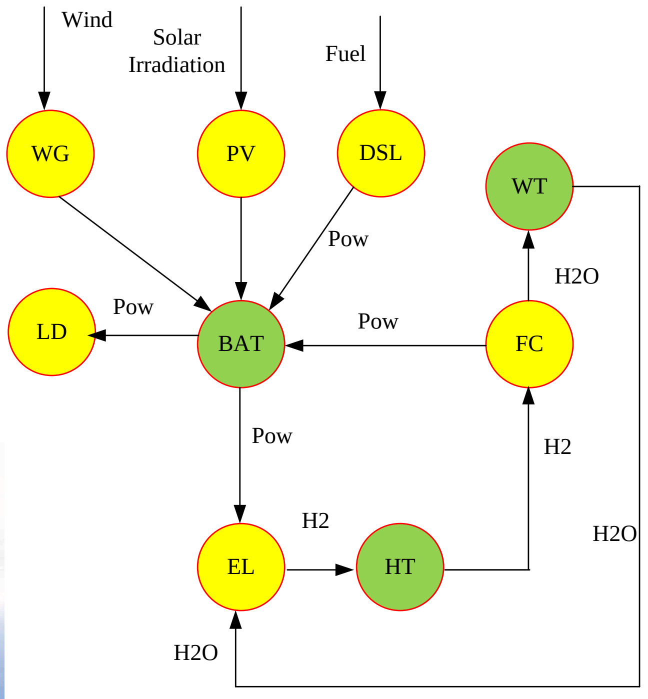




Dynamical System[1]:
{time, state of system, evolution operator}

[1] Elements of Applied Bifurcation Theory, Yuri Kuznetsov, Springer-Verlag New York, Chapter 1.

State of Graph



- Edges $F^{j}_{m\to n}(t)$ $F^{POW}_{FC\to BAT}(t)$ $F^{H_2}_{EL\to HT}(t)$
- Nodes
  - Accumulators $SOAcc^{l}(t)\in[0,1], l\in\{BAT, HT, WT\}$
  - Converters $\varepsilon_i(t)\in\{0,1\}, i\in\{FC, EL, PV\ldots\}$

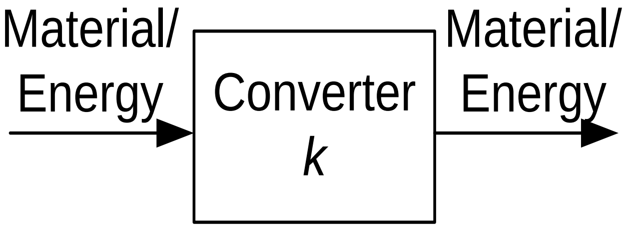
State of graph = $\left\{F^{j}_{m\to n}(t), SOAcc^{l}(t), \varepsilon_i(t)\right\}$

Evolution Operator

EMM = How to operate these converters

EMM = Evolution operator $=\varepsilon_i(t)$

Converter Operation



$$\varepsilon_k(t) = f\left(x(t), u(t), \mathrm{P}(t)\right)$$

$$x(t) = \left\{F^{j}_{m\to n}(t), SOAcc^{l}(t), \varepsilon_i(t)\right\}$$

$$u(t) = \left[Solar\ Irradiation, load\ \ profile...\right]$$

$$\mathrm{P}(t) = \left[\text{constraints, demanded values...}\right]$$

Required	$\varepsilon_k^{\mathrm{Req}}(t)$
Availability	$\varepsilon_k^{Avl}(t)$
General Condition	$\varepsilon_k^{Gen}(t)$

$$\varepsilon_k(t) = L\left\{\varepsilon_k^{Avl}(t), \varepsilon_k^{\mathrm{Req}}(t), \varepsilon_k^{Gen}(t)\right\}^{2}$$

[2] Giaouris et al, Performance investigation of a hybrid renewable power generation and storage system using systemic power management models, Energy, Vol. 61, pp. 621-635, Nov. 2013.

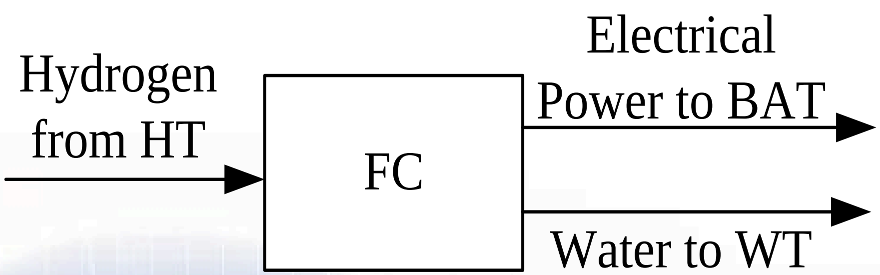
Example

"The state of charge of the battery is low"
"There is available H_2 in the Hydrogen Tank"
"The Water Tank is not completely full"

$$\rho_{FC}^{SOAcc^{BAT}}(t) = SOAcc^{BAT}(t) < Lo_{FC}^{SOAcc^{BAT}}(t)$$

$$\rho_{FC}^{SOAcc^{HT}}(t) = SOAcc^{HT}(t) > Lo_{FC}^{SOAcc^{HT}}(t)$$

$$\rho_{FC}^{SOAcc^{WT}}(t) = SOAcc^{WT}(t) < Up_{FC}^{SOAcc^{WT}}(t)$$

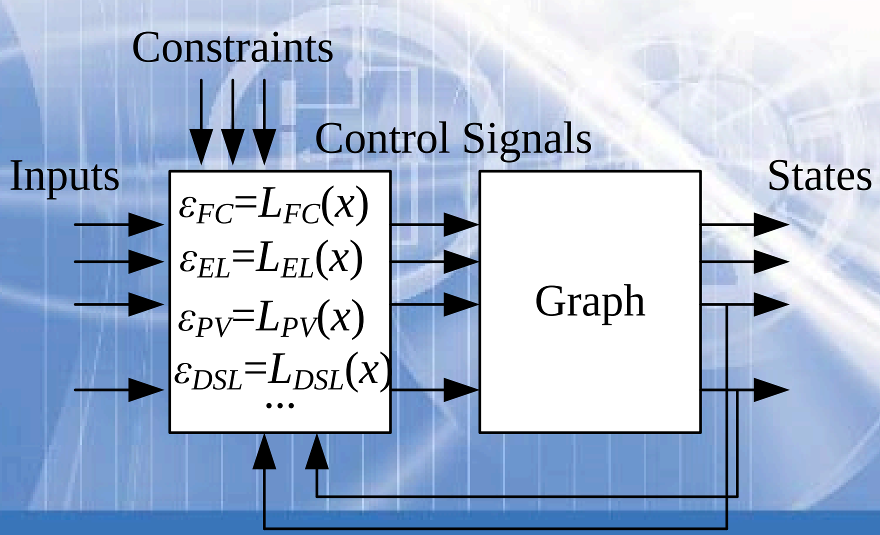


$$\varepsilon_{FC}^{Avl}(t) = \rho_{FC}^{SOAcc^{HT}}(t) \wedge \rho_{FC}^{SOAcc^{WT}}(t)$$

$$\varepsilon_{FC}^{\mathrm{Req}}(t) = \rho_{FC}^{SOAcc^{BAT}}(t)$$

$$\varepsilon_{FC}^{Gen}(t) = \left[\varepsilon_{DSL}(t^{-}) = 0\right]$$

$$\varepsilon_{FC}(t) = \varepsilon_{FC}^{Avl}(t) \wedge \varepsilon_{FC}^{\mathrm{Req}}(t) \wedge \varepsilon_{FC}^{Gen}(t)$$



Complete system

Connection	Symbol	Equation
$c_{1,\,PV\to BAT}$	$\varepsilon_{PV\to BAT}(t)$	$\bigcap_c \left[\varepsilon^{c}_{PV\to BAT}(t)\right],\ c\in\{Avl,Req,Gen\}$
	$\varepsilon^{Avl}_{PV\to BAT}(t)$	1
	$\varepsilon^{Req}_{PV\to BAT}(t)$	$\rho^{SOAcc^{BAT}}_{PV\to BAT}(t)\vee r^{SOAcc^{BAT}}_{PV\to BAT}(t)$
	$\varepsilon^{Gen}_{PV\to BAT}(t)$	1
	$\rho^{SOAcc^{BAT}}_{PV\to BAT}(t)$	$SOAcc^{BAT}(t)<str^{SOAcc^{BAT}}_{PV\to BAT}(t)$
$c_{1,\,WG\to BAT}$	$\varepsilon_{WG\to BAT}(t)$	$\bigcap_c \left[\varepsilon^{c}_{WG\to BAT}(t)\right],\ c\in\{Avl,Req,Gen\}$
	$\varepsilon^{Avl}_{WG\to BAT}(t)$	1
	$\varepsilon^{Req}_{WG\to BAT}(t)$	$\rho^{SOAcc^{BAT}}_{WG\to BAT}(t)\vee r^{SOAcc^{BAT}}_{WG\to BAT}(t)$
	$\varepsilon^{Gen}_{WG\to BAT}(t)$	1
	$\rho^{SOAcc^{BAT}}_{WG\to BAT}(t)$	$SOAcc^{BAT}(t)<str^{SOAcc^{BAT}}_{WG\to BAT}(t)$
$c_{1,DSL\to BAT}$	$\varepsilon_{DSL\to BAT}(t)$	$\bigcap_c \left[\varepsilon^{c}_{DSL\to BAT}(t)\right],\ c\in\{Avl,Req,Gen\}$
	$\varepsilon^{Avl}_{DSL\to BAT}(t)$	1
	$\varepsilon^{Req}_{DSL\to BAT}(t)$	$\rho^{SOAcc^{BAT}}_{DSL\to BAT}(t)\vee r^{SOAcc^{BAT}}_{DSL\to BAT}(t)$
	$\varepsilon^{Gen}_{DSL\to BAT}(t)$	1
	$\rho^{SOAcc^{BAT}}_{DSL\to BAT}(t)$	$\left[SOAcc^{BAT}(t)<str^{SOAcc^{BAT}}_{DSL\to BAT}(t)\right]\vee \left[\left[str^{SOAcc^{BAT}}_{DSL\to BAT}(t)<SOAcc^{BAT}(t)<stp^{SOAcc^{BAT}}_{DSL\to BAT}(t)\right]\wedge\left[\varepsilon_{DSL\to BAT}(t^{-})\right]\right]$
$c_{1,\,CP\to FT}$ $c_{2,\,CP\to FT}$	$\varepsilon_{CP\to FT}(t)$	$\bigcap_c \left[\varepsilon^{c}_{CP\to FT}(t)\right],\ c\in\{Avl,Req,Gen\}$
	$\varepsilon^{Avl}_{CP\to FT}(t)$	$r^{SOAcc^{BF}}_{CP\to FT}(t)\vee \rho^{SOAcc^{BF}}_{CP\to FT}(t)$
	$\varepsilon^{Req}_{CP\to FT}(t)$	$r^{SOAcc^{FT}}_{CP\to FT}(t)\vee \rho^{SOAcc^{FT}}_{CP\to FT}(t)$
	$\varepsilon^{Gen}_{CP\to FT}(t)$	1
	$\rho^{SOAcc^{BF}}_{CP\to FT}(t)$	$\left[SOAcc^{BF}(t)>str^{SOAcc^{BF}}_{CP\to FT}(t)\right]\vee \left[\left[stp^{SOAcc^{BF}}_{CP\to FT}(t)<SOAcc^{BF}(t)<str^{SOAcc^{BF}}_{CP\to FT}(t)\right]\wedge\left[\varepsilon_{CP\to FT}(t^{-})\right]\right]$
	$\rho^{SOAcc^{FT}}_{CP\to FT}(t)$	$SOAcc^{FT}(t)<str^{SOAcc^{FT}}_{CP\to FT}(t)$

$c_{1,FC\to BAT}$ $c_{2,FC\to BAT}$ $c_{3,\,FC\to BAT}$	$\varepsilon_{FC\to BAT}(t)$	$\bigcap_c \left[\varepsilon^{c}_{FC\to BAT}(t)\right],\ c\in\{Avl,Req,Gen\}$
	$\varepsilon^{Avl}_{FC\to BAT}(t)$	$\bigcap_l \left[r^{SOAcc^{l}}_{FC\to BAT}(t)\vee \rho^{SOAcc^{l}}_{FC\to BAT}(t)\right],\ l\in\{FT,WT\}$
	$\varepsilon^{Gen}_{FC\to BAT}(t)$	1
	$\varepsilon^{Req}_{FC\to BAT}(t)$	$\rho^{SOAcc^{BAT}}_{FC\to BAT}(t)\vee r^{SOAcc^{BAT}}_{FC\to BAT}(t)$
	$\rho^{SOAcc^{FT}}_{FC\to BAT}(t)$	$SOAcc^{FT}(t)>str^{SOAcc^{FT}}_{FC\to BAT}$
	$\rho^{SOAcc^{WT}}_{FC\to BAT}(t)$	$SOAcc^{WT}(t)<str^{SOAcc^{WT}}_{FC\to BAT}(t)$
	$\rho^{SOAcc^{BAT}}_{FC\to BAT}(t)$	$\left[SOAcc^{BAT}(t)<str^{SOAcc^{BAT}}_{FC\to BAT}(t)\right]\vee \left[\left[str^{SOAcc^{BAT}}_{FC\to BAT}(t)<SOAcc^{BAT}(t)<stp^{SOAcc^{BAT}}_{FC\to BAT}(t)\right]\wedge\left[\varepsilon_{FC\to BAT}(t^{-})\right]\right]$
$c_{1,EL\to BF}$ $c_{2,EL\to BF}$ $c_{3,EL\to BF}$	$\varepsilon_{EL\to BF}(t)$	$\bigcap_c \left[\varepsilon^{c}_{EL\to BF}(t)\right],\ c\in\{Avl,Req,Gen\}$
	$\varepsilon^{Req}_{EL\to BF}(t)$	$r^{SOAcc^{BF}}_{EL\to BF}(t)\vee \rho^{SOAcc^{BF}}_{EL\to BF}(t)$
	$\varepsilon^{Avl}_{EL\to BF}(t)$	$\bigcap_l \left[r^{SOAcc^{l}}_{EL\to BF}(t)\vee \rho^{SOAcc^{l}}_{EL\to BF}(t)\right],\ l\in\{BAT,WT\}$
	$\varepsilon^{Gen}_{EL\to BF}(t)$	1
	$\rho^{SOAcc^{BF}}_{EL\to BF}(t)$	$SOAcc^{BF}(t)<str^{SOAcc^{BF}}_{EL\to BF}(t)$
	$\rho^{SOAcc^{BAT}}_{EL\to BF}(t)$	$\left[SOAcc^{BAT}(t)>str^{SOAcc^{BAT}}_{EL\to BF}(t)\right]\vee \left[\left[stp^{SOAcc^{BAT}}_{EL\to BF}(t)<SOAcc^{BAT}(t)<str^{SOAcc^{BAT}}_{EL\to BF}(t)\right]\wedge\left[\varepsilon_{EL\to BF}(t^{-})\right]\right]$
	$\rho^{SOAcc^{WT}}_{EL\to BF}(t)$	$SOAcc^{WT}(t)>str^{SOAcc^{WT}}_{EL\to BF}(t)$

FC and EL

$$\rho_{EL \to HT}^{SOAcc^{BAT}}(t) = SOAcc^{BAT}(t) > str_{EL \to BF}^{SOAcc^{BAT}}(t)$$

$$\rho_{EL \to HT}^{SOAcc^{WT}}(t) = SOAcc^{WT}(t) > str_{EL \to HT}^{SOAcc^{WT}}(t)$$

$$\rho_{EL \to HT}^{SOAcc^{BF}}(t) = SOAcc^{BF}(t) < str_{EL \to HT}^{SOAcc^{BF}}(t)$$

$$\varepsilon_{EL}(t) = \rho_{EL \to HT}^{SOAcc^{BAT}}(t) \wedge \rho_{EL \to HT}^{SOAcc^{WT}}(t) \wedge \rho_{EL \to HT}^{SOAcc^{BF}}(t)$$

$$\rho_{FC \to BAT}^{SOAcc^{BAT}}(t) = SOAcc^{BAT}(t) < str_{FC \to BAT}^{SOAcc^{BAT}}(t)$$

$$\rho_{FC \to BAT}^{SOAcc^{FT}}(t) = SOAcc^{FT}(t) > str_{FC \to BAT}^{SOAcc^{FT}}(t)$$

$$\rho_{FC \to BAT}^{SOAcc^{WT}}(t) = SOAcc^{WT}(t) < str_{FC \to BAT}^{SOAcc^{WT}}(t)$$

$$\varepsilon_{FC}(t) = \rho_{FC \to BAT}^{SOAcc^{BAT}}(t) \wedge \rho_{FC \to BAT}^{SOAcc^{FT}}(t) \wedge \rho_{FC \to BAT}^{SOAcc^{WT}}(t)$$

Ignore specific conditions

$$\rho_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t) = SOAcc^{BAT}(t) < str_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t)$$

$$\rho_{FC\rightarrow BAT}^{SOAcc^{FT}}(t) = SOAcc^{FT}(t) > str_{FC\rightarrow BAT}^{SOAcc^{FT}}(t)$$

$$\rho_{FC\rightarrow BAT}^{SOAcc^{WT}}(t) = SOAcc^{WT}(t) < str_{FC\rightarrow BAT}^{SOAcc^{WT}}(t)$$

$$\varepsilon_{FC}(t) = \rho_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t) \wedge \rho_{FC\rightarrow BAT}^{SOAcc^{FT}}(t) \wedge \rho_{FC\rightarrow BAT}^{SOAcc^{WT}}(t)$$

$$\varepsilon_{FC}(t) = \left[\rho_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t) \wedge r_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t)\right] \vee \left[\left[r_{FC\rightarrow BAT}^{SOAcc^{FT}}(t) \vee \rho_{FC\rightarrow BAT}^{SOAcc^{FT}}(t)\right] \wedge \left[r_{FC\rightarrow BAT}^{SOAcc^{WT}}(t) \vee \rho_{FC\rightarrow BAT}^{SOAcc^{WT}}(t)\right]\right]$$

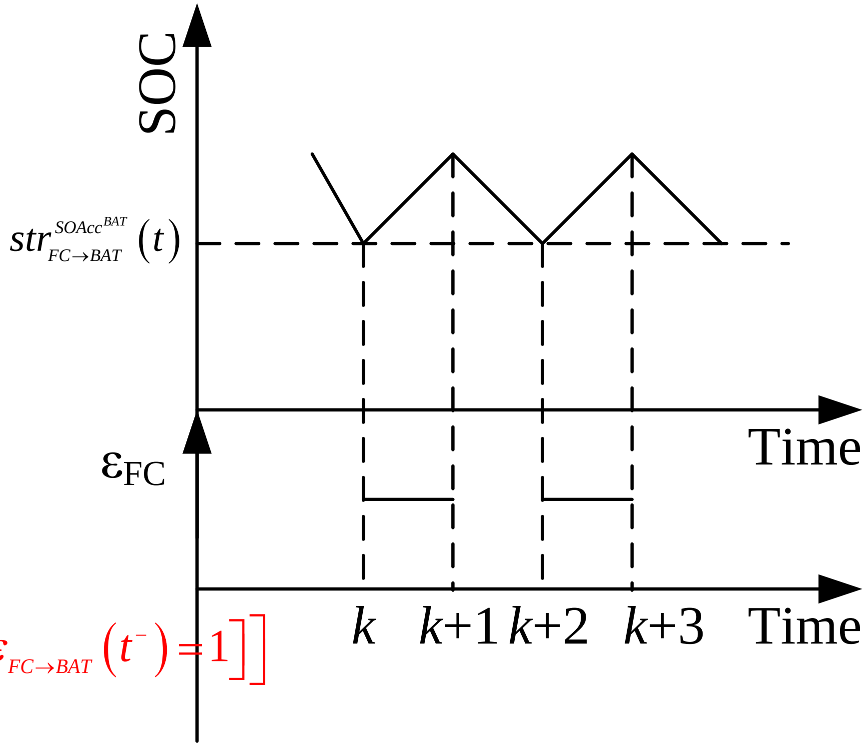
Hysteresis zones for chattering

$$\rho_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t) = SOAcc^{BAT}(t) < str_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t)$$

$$\rho_{FC\rightarrow BAT}^{SOAcc^{FT}}(t) = SOAcc^{FT}(t) > str_{FC\rightarrow BAT}^{SOAcc^{FT}}(t)$$

$$\rho_{FC\rightarrow BAT}^{SOAcc^{WT}}(t) = SOAcc^{WT}(t) < str_{FC\rightarrow BAT}^{SOAcc^{WT}}(t)$$

$$\varepsilon_{FC}(t) = \rho_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t) \wedge \rho_{FC\rightarrow BAT}^{SOAcc^{FT}}(t) \wedge \rho_{FC\rightarrow BAT}^{SOAcc^{WT}}(t)$$



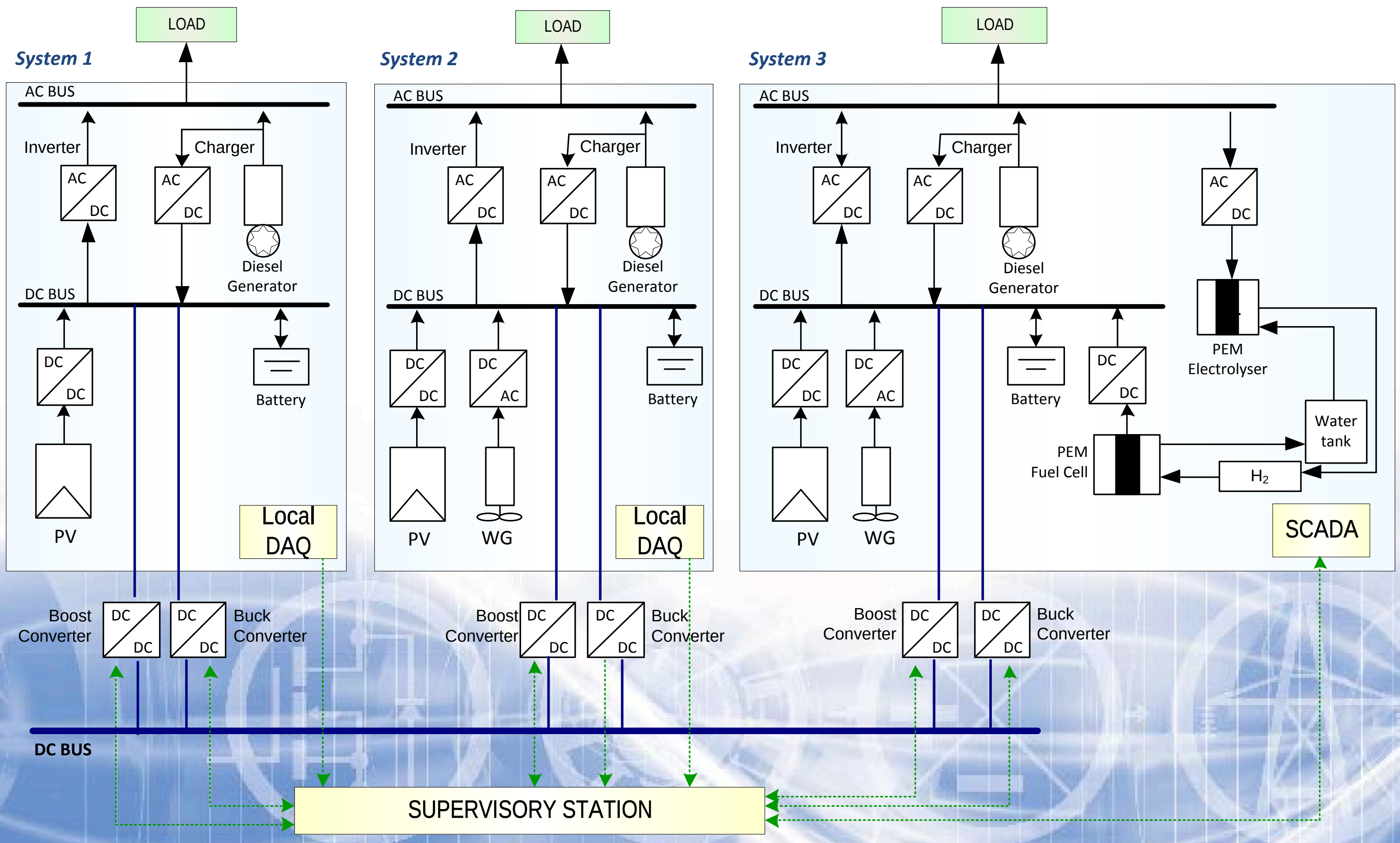
$$\rho_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t) = \left[SOAcc^{BAT}(t) < str_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t)\right]$$

$$\vee\left[\left[str_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t) < SOAcc^{BAT}(t) < stp_{FC\rightarrow BAT}^{SOAcc^{BAT}}(t)\right] \wedge \left[\varepsilon_{FC\rightarrow BAT}(t^{-}) = 1\right]\right]$$

Compact expression

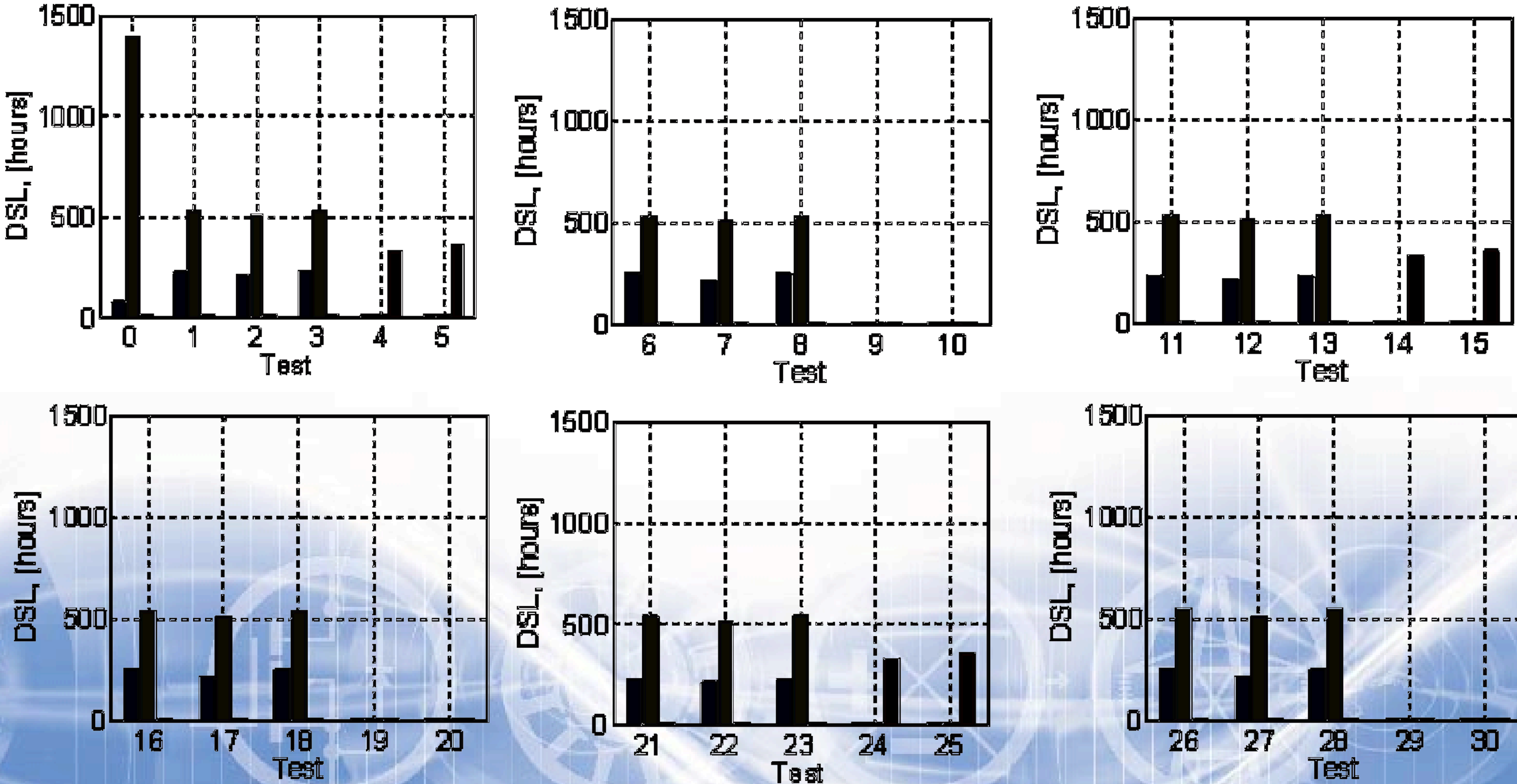
$\varepsilon_{FC\to BAT}(t)$	$\bigcap_{c}\left[\varepsilon_{FC\to BAT}^{c}(t)\right], c\in\{Avl,Req,Gen\}$
$\varepsilon_{FC\to BAT}^{Avl}(t)$	$\bigcap_{l}\left[r_{FC\to BAT}^{SOAcc^{l}}(t)\vee\rho_{FC\to BAT}^{SOAcc^{l}}(t)\right], l\in\{FT,WT\}$
$\varepsilon_{FC\to BAT}^{Gen}(t)$	1
$\varepsilon_{FC\to BAT}^{Req}(t)$	$\rho_{FC\to BAT}^{SOAcc^{BAT}}(t)\vee r_{FC\to BAT}^{SOAcc^{BAT}}(t)$
$\rho_{FC\to BAT}^{SOAcc^{FT}}(t)$	$SOAcc^{FT}(t)>str_{FC\to BAT}^{SOAcc^{FT}}$
$\rho_{FC\to BAT}^{SOAcc^{WT}}(t)$	$SOAcc^{WT}(t)<str_{FC\to BAT}^{SOAcc^{WT}}(t)$
$\rho_{FC\to BAT}^{SOAcc^{BAT}}(t)$	$\left[SOAcc^{BAT}(t)<str_{FC\to BAT}^{SOAcc^{BAT}}(t)\right]\vee\left[\left[str_{FC\to BAT}^{SOAcc^{BAT}}(t)<SOAcc^{BAT}(t)<stp_{FC\to BAT}^{SOAcc^{BAT}}(t)\right]\wedge\left[\varepsilon_{FC\to BAT}(t^{-})\right]\right]$

Results



System 1
LOAD
AC BUS
Inverter
Charger
AC
DC
Diesel
Generator
DC BUS
DC
DC
Battery
PV
Local
DAQ
System 2
LOAD
AC BUS
Inverter
Charger
Diesel
Generator
DC BUS
DC
AC
Battery
PV
WG
Local
DAQ
System 3
LOAD
AC BUS
Inverter
Charger
Diesel
Generator
DC BUS
Battery
PEM
Electrolyser
Water
tank
PEM
Fuel Cell
H2
PV
WG
SCADA
Boost
Converter
Buck
Converter
DC BUS
SUPERVISORY STATION

Results[2]



[2] Giaouris et al, Performance investigation of a hybrid renewable power generation and storage system using systemic power management models, Energy, Vol. 61, pp. 621-635, Nov. 2013.

Results…

$$\varepsilon_k(t) = f\left(x(t), u(t), \mathrm{P}(t)\right)$$

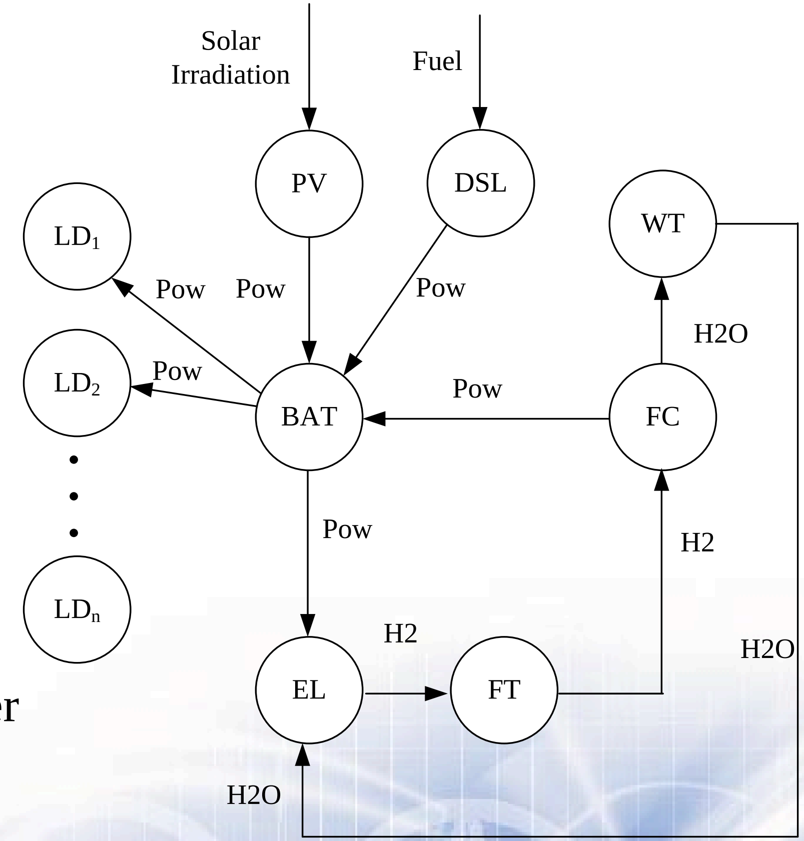
$$x(t) = \left\{F_{m\to n}^{j}(t), SOAcc^{l}(t), \varepsilon_i(t)\right\}$$

$$u(t) = \left[Solar\ Irradiation, load\ \ profile...\right]$$

$$\mathrm{P}(t) = \left[\text{constraints, demanded values...}\right]$$

$$\varepsilon_{FC}(t) = \left(\varepsilon_{FC}^{Avl}(t) \wedge \varepsilon_{FC}^{\mathrm{Re}q}(t) \wedge \varepsilon_{FC}^{Gen}(t)\right) \vee \varepsilon_{FC}^{LD}(t)$$

Based on load/weather forecasting



Results…

$$\varepsilon_k(t) = f\left(x(t), u(t), \mathrm{P}(t)\right)$$

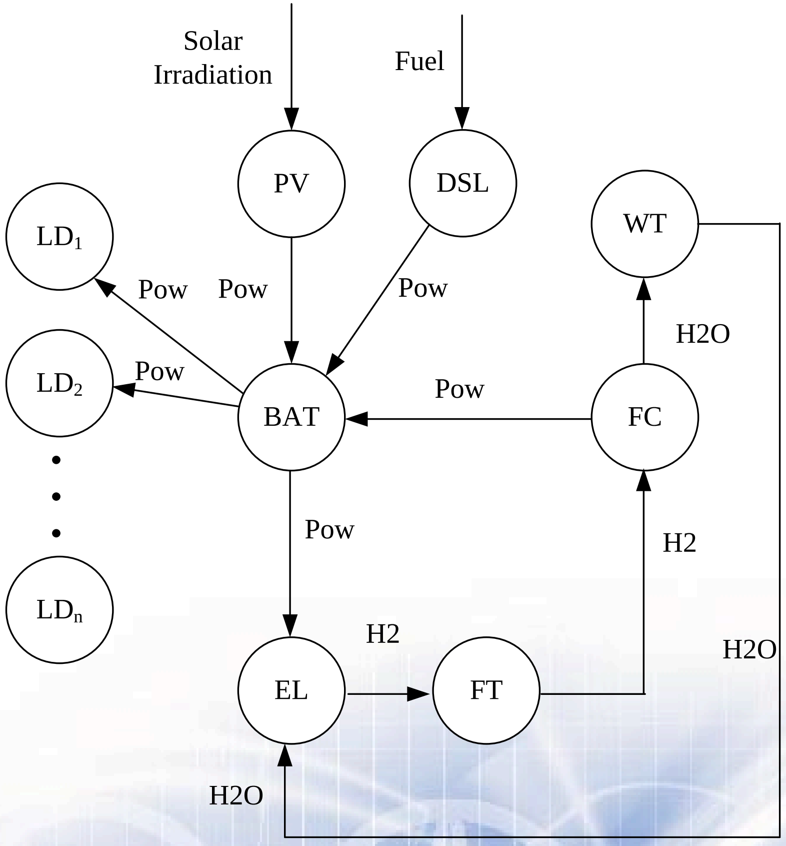
$$x(t) = \left\{F^{j}_{m\rightarrow n}(t), SOAcc^{l}(t), \varepsilon_i(t)\right\}$$

$$u(t) = \left[Solar\ Irradiation, load\ \ profile...\right]$$

$$\mathrm{P}(t) = \left[\text{constraints, demanded values...}\right]$$

$$\varepsilon_{LD_i}(t) = \varepsilon^{Avl}_{LD_i}(t) \wedge \varepsilon^{\mathrm{Req}}_{LD_i}(t) \wedge \varepsilon^{Gen}_{LD_i}(t) \wedge \varepsilon^{LD}_{LD_i}(t)$$

Load shifting



Results…

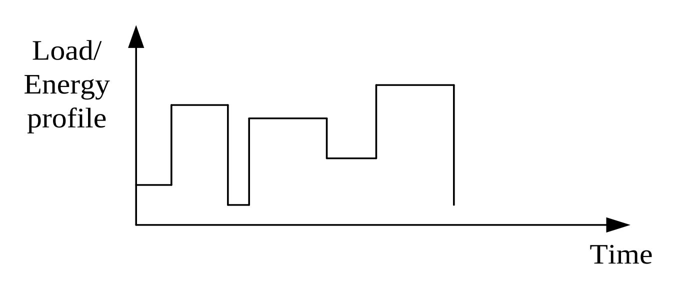
$$\varepsilon_k(t) = f\left(x(t), u(t), \mathrm{P}(t)\right)$$

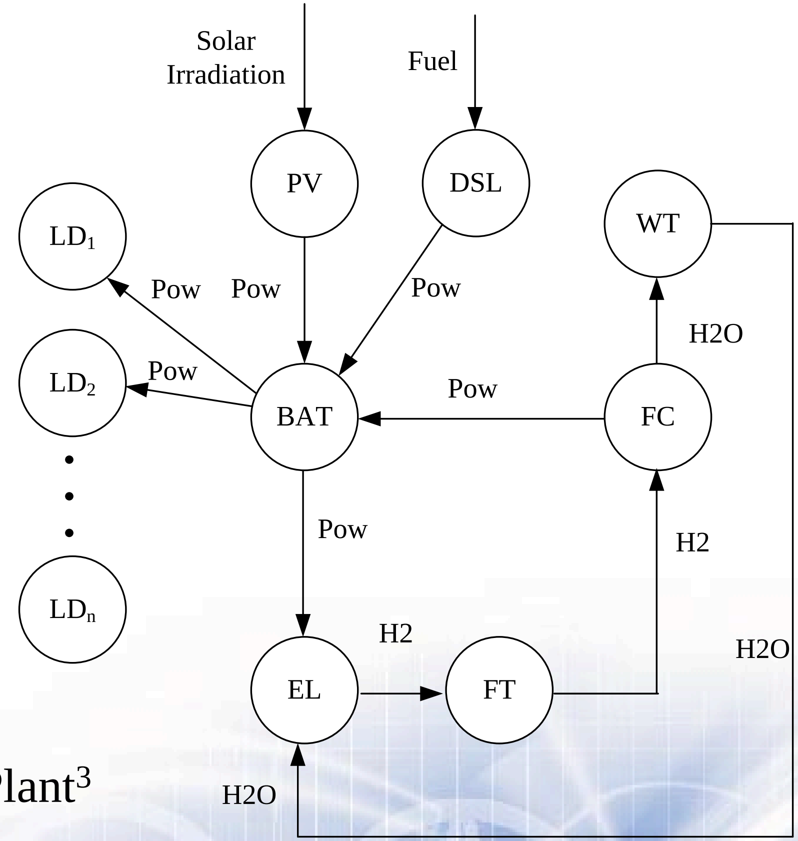
$$x(t) = \left\{F^{j}_{m\to n}(t), SOAcc^{l}(t), \varepsilon_i(t)\right\}$$

$$u(t) = \left[Solar\ Irradiation, load\ \ profile...\right]$$

$$\mathrm{P}(t) = \left[\text{constraints, demanded values...}\right]$$

$$\rho_{FC}^{SOAcc^{BAT}}(t) = SOAcc^{BAT}(t) < Lo_{FC}^{SOAcc^{BAT}}(t)$$





Virtual Power Plant[3]

[3] Giaouris et al, Power grand composite curves shaping for adaptive energy management of hybrid microgrids, Renewable Energy, vol. 95, pp. 433-448, 2016.

Summary

- A systematic approach to describe HES/EMM
  - Unified modelling approach
  - Study, Control, Optimise HES/EMM
- Several examples that include
  - Constant load
  - Multiple random loads
  - Load shifting
  - Generate specific load/energy profiles

Newcastle University

CESI National Centre for Energy Systems Integration

School of Electrical and Electronic Engineering

Any Questions?