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Predictive management of batteries in microgrids equipped with electric vehicles

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Summary

Introduction

1) Context

2) Strategies and case study

Observations

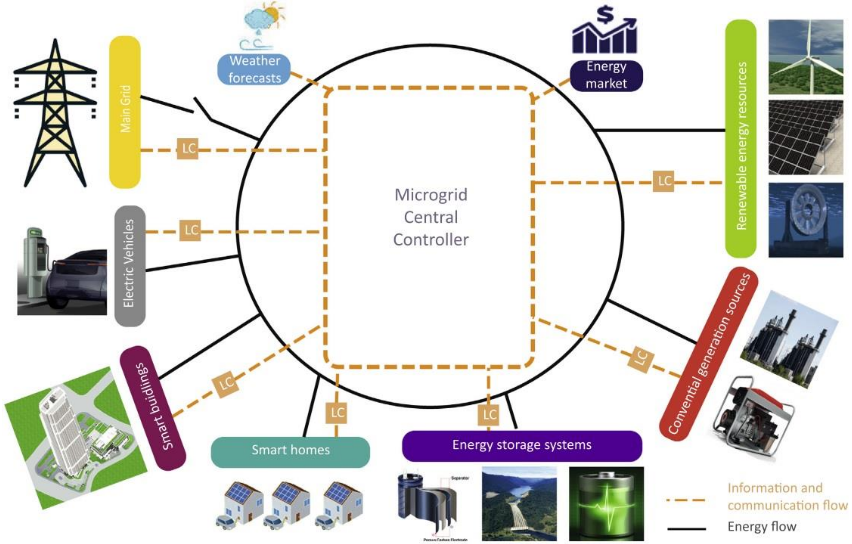
- increase of the penetration of renewable energy sources into the main grid: centralized generation ⟶ distributed generation
- deployment of microgrids
- deployment of electric vehicles

Microgrid challenges

- manage storage efficiently, minimize the impact of intermittent resources, improve microgrid resiliency, reliability, power quality, and robustness, handle new energy usages…

⟶ need for efficient management strategies for microgrids equipped with electric vehicles

⟶ **what is the best strategy to be implemented to handle storage system regarding computation time, economical cost and carbon footprint?**



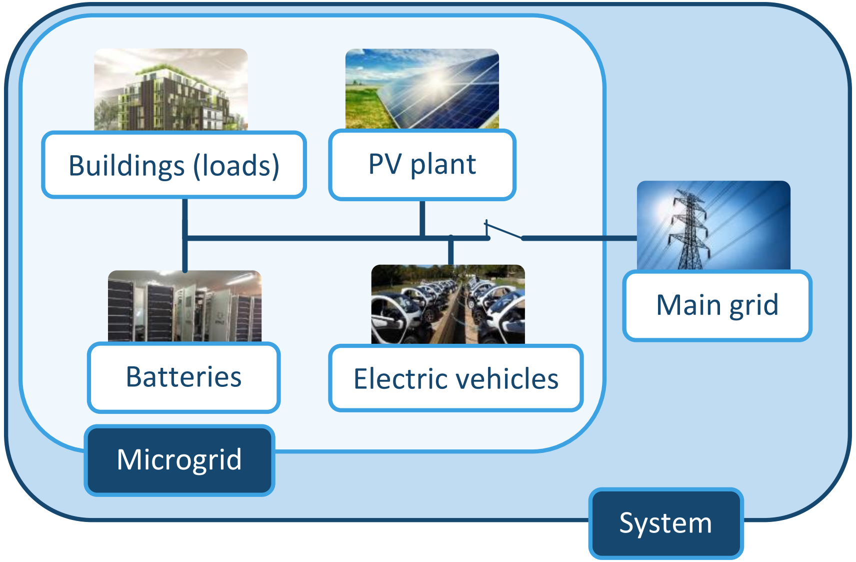
Microgrid components

Zia, Muhammad Fahad, Elhoussin Elbouchikhi, and Mohamed Benbouzid. 2018. 'Microgrids Energy Management Systems: A Critical Review on Methods, Solutions, and Prospects'. *Applied Energy* 222 (July): 1033–1055.

Strategies
- $\mathrm{MPC_{ib}}$: management of independent batteries
- **$\mathbf{MPC_{fb}}$: management of a fictitious battery**

Components of the on-grid microgrid
- buildings: loads (MG 1, MG 2 and MG 3)
- PV plant (MG 1, MG 2 and MG 3)
- bank of batteries
- electric vehicles (from 2 to 16)

Power purchase agreement and carbon dioxide emissions
- electricity prices data
- **carbon dioxide emissions** data (RTE for MG 1, electricitymap for MG 2 and MG 3)



Microgrid components

I/Management approaches for batteries

1) Reference strategy: rule-based algorithm
2) MPC for storage management in microgrids
3) Storage management strategies: $\mathrm{MPC_{ib}}$ and $\mathrm{MPC_{fb}}$
4) Optimization problem
5) Optimization soft constraints
6) Optimization hard constraints

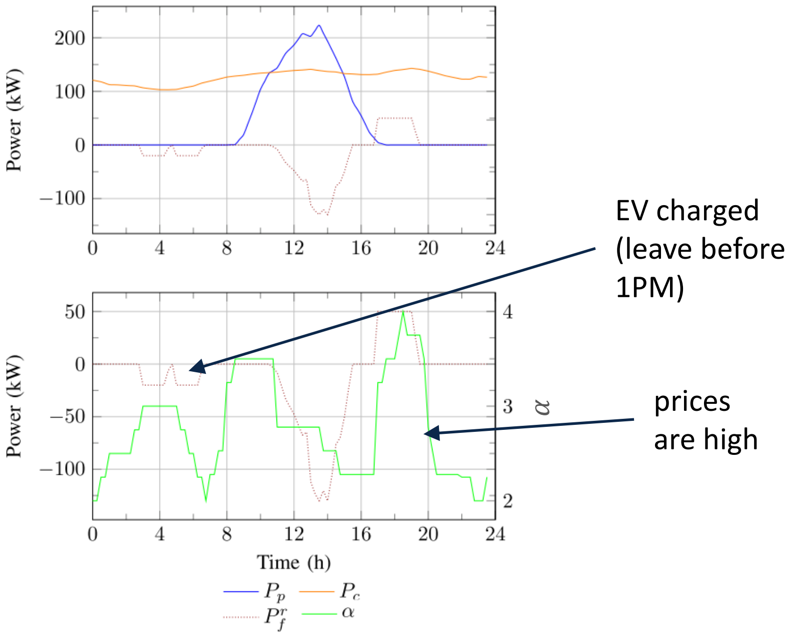
Five different rules

1. charge the batteries with PV power generation surplus
2. charge the batteries after 1PM if they aren't fulfilled
3. charge the EV batteries when the EV arrive in the parking lot, if they leave before 1PM
4. discharge the batteries when electricity prices are high
5. discharge the batteries when the period of high electricity prices is over

Sum of normalized electricity prices and carbon dioxide emissions in real time: $\alpha = C_r + G_r$

Sum of all batteries power:

$$P_f^r(k+i) = P_b(k+i) + \sum_{j=1}^{n} \left(P_v(k+i,j)\right)$$



MG 1: power and α

P_c: power consumed by the microgrid (kW)

P_p: power produced by the microgrid (kW)

P_f: sum of charge/discharge power for all batteries (kW)

k: actual step

i: prediction step

P_b: power of charge/discharge of the bank of batteries (kW)

P_v: power of charge/discharge of mobile batteries (kW)

j: electric vehicle indices

α: sum of normalized electricity prices and carbon dioxide emissions

C_r: electricity purchase tariff (€/kWh)

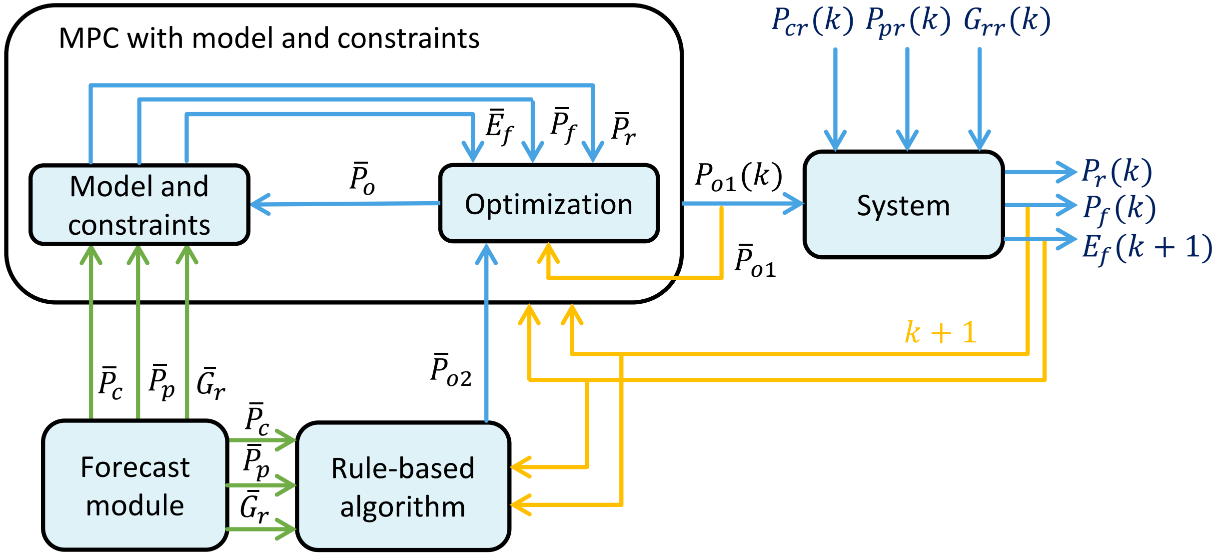
G_r: carbon dioxide emission from the main grid production (gCO_2/kWh_{eq})

Forecast module

- forecasted power generation, power consumption and CO_2 emissions

Model-predictive control

- **initial conditions for batteries usage given by the rule-based algorithm**
- batteries usage optimized along the prediction horizon
- optimization problem solved at each time step
- solution only applied in real time for the next time step



Model-predictive control scheme

E_f: sum of state of charge of all batteries (kWh)

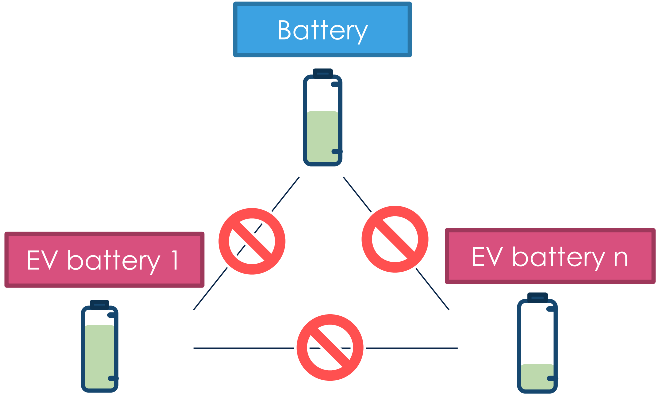
P_o: optimized vector: $\bar{P}_r$ or $\bar{P}_b$ and $\bar{P}_v$

P_{o1}: solution from MPC of the optimized vector

P_{o2}: solution from the Rule-based algorithm for the optimized vector (kW)

P_r: power furnished by the main grid (kW)

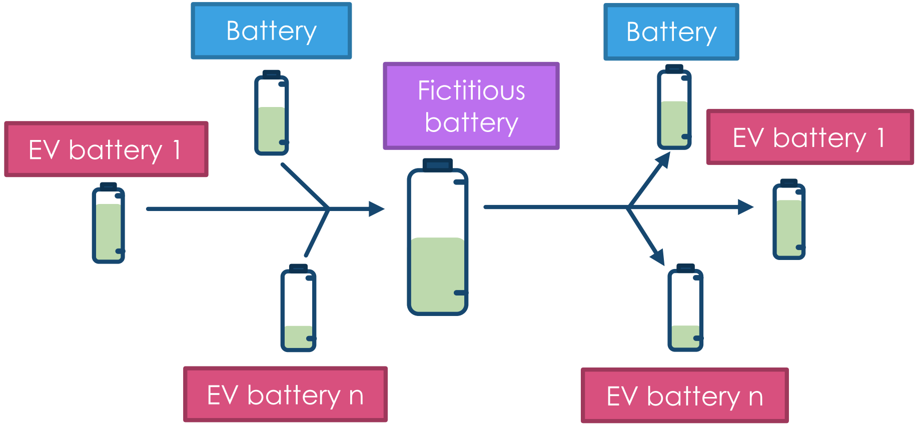
Independent batteries strategy (MPC_{ib})



Independent batteries

- standard strategy for energy storage management
- each battery has its own charge profile
- **one optimization vector for each battery is needed**

Fictitious battery strategy (MPC_{fb})



Fictitious battery

- all batteries are grouped as **one fictitious battery**
- all batteries share the same charge profile
- **only one optimization vector is needed with the aim of reducing computation time**

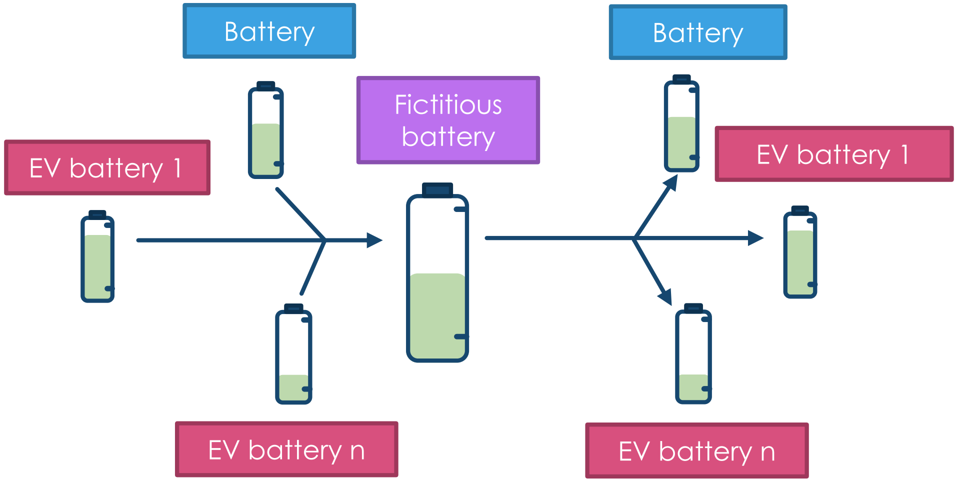
Fictitious battery strategy $(\mathrm{MPC_{fb}})$

Algorithm split into 4 steps:

1. sum of all the battery constraints to create the fictitious battery
2. calculation of the fictitious charge/discharge power and energy stored
3. identification of groups of batteries depending on EV departure time (EV leaving first are in group 1)
4. charging/discharging of the batteries depending on the group they belong

→ EV leaving first are charged first (charging phases)
→ the bank of batteries is discharged first (discharging phases)

→ **ensure EV leaving first are charged before they leave the parking lot**



Fictitious battery

I/ Management approaches for batteries

4) Optimization problem

Objectives

- reduce economical cost
- **reduce carbon footprint**
- ensure full charge of the electric vehicles available
- satisfy the system constraints

Objective function

$$J = \frac{1}{N_p}\sum_{i=1}^{H_p}(\varphi_a P_r(k+i) \times C_r(k+i) + \varphi_b P_r(k+i) \times G_r(k+i))$$
$$+ \varphi_c \Delta\varepsilon + \varphi_d\, \gamma_a + \varphi_e\, \gamma_b + \varphi_f\, \gamma_c$$

with $P_r(k+i) = P_c(k+i) - P_p(k+i) - P_f(k+i)$

Minimization of the objective function

MPC$_{\mathrm{ib}}$ strategy: $\boldsymbol{P_v^*}, \boldsymbol{P_b^*} = \arg\min_{P_v, P_b}(J)$

MPC$_{\mathrm{fb}}$ strategy: $\boldsymbol{P_r^*} = \arg\min_{P_r}(J)$

For electric vehicles (EV)

Minimize the gap between the desired state of charge $E_{vs}(i_f, j)$ and the real state of charge $E_{vr}(i_f, j)$ of the EV batteries before the EV leave the parking lot:

$$\Delta\varepsilon = \sum_{j=1}^{n} \frac{E_{vs}(i_f, j) - E_{vr}(i_f, j)}{E_{vs}(i_f, j)}$$

J: objective function

H_p: forecast horizon (h)

φ: weights

γ_a: soft constraint on the number of cycle per day for the battery

γ_b: soft constraint for in-rush current for the battery

γ_c: soft constraint on maximum power bought from the main grid

N_p: number of time step per hour

i_f: departure time of the electric vehicle indices

$\Delta\varepsilon$: State of charge difference between expected and real value (kWh)

Life cycle objective (bank of batteries)

Minimize the gap between the desired number of cycles per day and the number of real cycles:

$$\gamma_a = |N_c - 1|$$

$$N_c = \frac{\beta \sum_{i=1}^{Hp} |P_b(k+1)|}{2 \times N_p \times DOD}$$

To respect smooth charging/discharging phases

→ penalization of the objective function if the charging (resp. discharging) process is interrupted to discharge (resp. charge) the batteries:

$$\gamma_a := \gamma_a + \varphi_g \frac{|E_b(k+i+1) - E_b(k+i)|}{2 \times DOD}$$

Inrush current constraint (bank of batteries)

Limit the daily variations (v) of the state of charge:

$$\gamma_b = (N_v^{min} - v)$$
$$\gamma_b = (v - N_v^{max})$$
$$N_v^{min} \leq v \leq N_v^{max}$$

Purchased power penalties

If the power extracted from the main grid exceeds the defined threshold:

$$P_l(k+i) = P_r(k+i) - P_r^{max} \text{ if } P_r(k+i) \leq P_r^{max}$$

$$\gamma_c = \sum_{i=1}^{Hp} |P_l(k+i)|$$

N_c: number of charge cycle for the bank of batteries

E_b: battery state of charge (kWh)

DOD: Depth of discharge (kWh)

N_v^{min}: minimum number of state variation of the bank of batteries

N_v^{max}: maximum number of state variation of the bank of batteries

v: number of state variation of the bank of batteries

β: round-trip efficiency

P_l: power extracted above agreement limit (kW)

P_r^{max}: maximum power extracted from the main grid (kW)

Both strategies ($\mathrm{MPC_{ib}}$ and $\mathrm{MPC_{fb}}$)

Bank of batteries power bounded by P_b^{min} and P_b^{max} and EV power bounded by P_v^{min} and P_v^{max}:

$$P_b^{min} \leq P_b \leq P_b^{max}$$
$$P_v^{min} \leq P_v \leq P_v^{max}$$

Bank of batteries energy bounded by E_b^{min} and E_b^{max} and EV energy bounded by E_v^{min} and E_v^{max}:

$$E_b^{min} \leq E_b \leq E_b^{max}$$
$$E_v^{min} \leq E_v \leq E_v^{max}$$

Fictitious battery strategy ($\mathrm{MPC_{fb}}$)

Fictitious battery power bounded by P_f^{min}/P_f^{max} with the available charge/discharge power (c/d):

$$c(k+i) = -\frac{N_p}{\beta}\left(E_v^{max}(k+i,l) - E_v(k+i,l)\right)$$
$$d(k+i) = \frac{N_p}{\beta}\left(E_v^{min}(k+i,l) - E_v(k+i,l)\right)$$
$$P_f^{min} = \sum_{l=1}^{n+1} c(k+i,l)\,,\ P_f^{max} = \sum_{l=1}^{n+1} d(k+i,l)$$
$$P_f^{min} \leq P_f \leq P_f^{max}$$

Fictitious battery energy bounded by E_f^{min} and E_f^{max}:

$$E_f^{min} = E_b^{min} + \sum_{l=1}^{n} E_v^{min}(k+i,l)$$
$$E_f^{max} = E_b^{max} + \sum_{l=1}^{n} E_v^{max}(k+i,l)$$
$$E_f^{min} \leq E_f \leq E_f^{max}$$

c/d: available charge/discharge power for a battery (kW)

l: battery indices

$n+1$: bank of batteries index

E_b^{min}, E_b^{max}: minimum and maximum state of charge of the bank of batteries (kWh)

P_b^{min}, P_b^{max}: minimum and maximum power of the bank of batteries (kW)

E_v^{min}, E_v^{max}: minimum and maximum state of charge of the EV batteries (kWh)

P_v^{min}, P_v^{max}: minimum and maximum power of the EV batteries (kW)

E_f^{min}, E_f^{max}: minimum and maximum state of charge of the fictitious battery (kWh)

P_f^{min}, P_f^{max}: minimum and maximum power of the fictitious battery (kW)

II/ Results analysis

1) Batteries behaviour

2) Economical and ecological results

3) Performance and computation time results

Batteries' charge profile for all strategies

- preferentially **charged** in case of PV power generation surplus or when α is low
- preferentially **discharged** when α is high

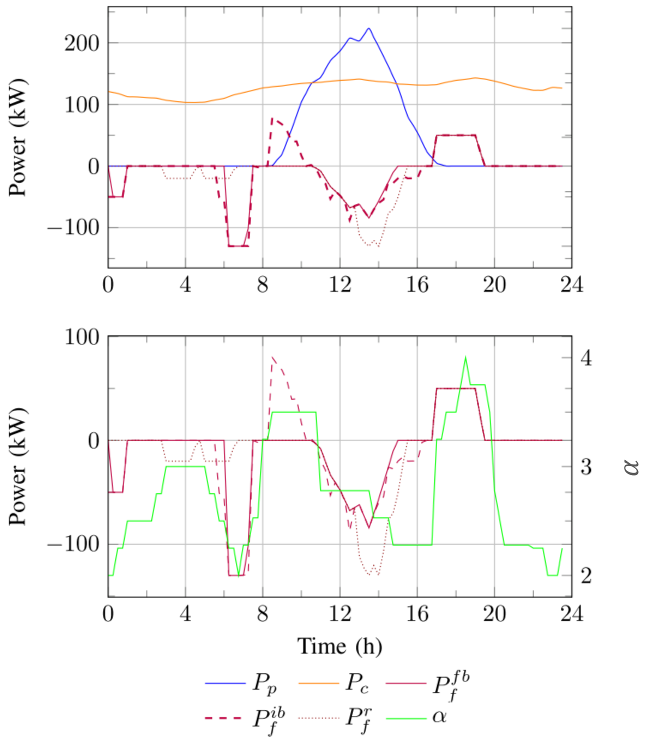
Both MPC strategies

- batteries charged at better times (α is low) than with the rule-based algorithm

Strategy $\mathbf{MPC_{ib}}$

- number of daily charge cycles for EV batteries is higher than with the other strategies

$\longrightarrow$ **degrades EV batteries' lifetime**



MG 1: power and α

P_f^{ib}: sum of all batteries power for the independent battery strategy (kW)

P_f^{fb}: fictitious battery power (kW)

Economic cost reduction for 1-day simulations (the rule-based strategy is the reference strategy)

Economic cost reduction (€)		Number of electric vehicles			
Microgrid	Strategy	2	4	8	16
MG 1	MPC_{ib}	0.9	6.2	15.9	27.8
	MPC_{fb}	0.9	2.5	3.2	21.4
MG 2	MPC_{ib}	4.4	8.7	20.6	40.3
	MPC_{fb}	2.3	5.1	11.0	29.7
MG 3	MPC_{ib}	4.3	5.3	15.5	49.9
	MPC_{fb}	5.3	5.2	8.1	35.3

CO_2 emissions reduction for 1-day simulations (the rule-based strategy is the reference strategy)

CO_2 emissions reduction ($kgCO_2$)		Number of electric vehicles			
Microgrid	Strategy	2	4	8	16
MG 1	MPC_{ib}	0	0.3	0.5	0.3
	MPC_{fb}	0	0.6	0.4	0.3
MG 2	MPC_{ib}	8.0	14.4	25.6	41.1
	MPC_{fb}	5.7	14.3	25.4	41.1
MG 3	MPC_{ib}	16.0	17.2	24.2	35.4
	MPC_{fb}	16.0	16.8	24.5	36.2

- both MPC strategies: **reduction of CO_2 emissions** and economic cost compared to the rule-based strategy
- MPC_{ib}: better results than with MPC_{fb} (more flexibility in terms of management)
- rule-based strategy with 16 EV penalized by power limitations for MG 2 and MG 3
- low reduction of CO_2 emissions achieved for MG 1 (FR)

Performance assessment for 1-day simulations (the rule-based strategy is the reference strategy)

Performance enhancement [J]		**Number of electric vehicles**			
Microgrid	**Strategy**	**2**	**4**	**8**	**16**
MG 1	MPC_{ib}	0.6	5.8	14.9	17.9
	MPC_{fb}	0.6	3.7	7.7	14.2
MG 2	MPC_{ib}	4.1	7.7	14.0	59.0
	MPC_{fb}	2.6	6.3	10.3	55.0
MG 3	MPC_{ib}	12.0	12.7	22.7	83.9
	MPC_{fb}	12.0	12.4	18.9	76.3

- MPC_{fb}: less effective than MPC_{ib}
- **MPC_{fb}: computation time is much lower than MPC_{ib}**
- **MPC_{ib}: too slow when there is too much EV (16) in the fleet**

→ **MPC_{fb}: good option for real-time implementation**

Computation time for 1-day simulations*

Computation time (sec)		**Number of electric vehicles**			
Microgrid	**Strategy**	**2**	**4**	**8**	**16**
MG 1	MPC_{ib}	526	4902	5104	12777
	MPC_{fb}	473	698	879	681
MG 2	MPC_{ib}	1730	2821	1860	29318
	MPC_{fb}	427	1395	1397	2065
MG 3	MPC_{ib}	459	620	1527	4668
	MPC_{fb}	506	536	591	3024

*Calculation server composed of two Intel Xeon Gold 6230 2.10 GHz processors, with 20 cores and 40 threads, 512 Go of RAM and an average CPU mark of 26657

Conclusion and perspectives

Conclusion and perspectives

Conclusion

- two MPC strategies are proposed:
  - $\mathrm{MPC_{ib}}$ for management of independent batteries
  - **$\mathbf{MPC_{fb}}$ for management of a fictitious battery**
- MPC strategies are more efficient than the rule-based strategy:
  - economical cost is reduced
  - **carbon dioxide emissions are reduced**
- $\mathrm{MPC_{fb}}$: less efficient than $\mathrm{MPC_{ib}}$ but **computation time is much lower**

→ $\mathbf{MPC_{fb}}$: good option for real-time management of batteries in microgrids

Perspectives

- test MPC strategies with 7-day simulations
- test MPC strategies with different states of charge
- carry out a sensitivity analysis of the objective function’s weights to evaluate their impact on computation time and performance

Thank you!

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