Preventing Overloading Incidents on Smart Grids: A Multiobjective Combinatorial Optimization Approach

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Outline

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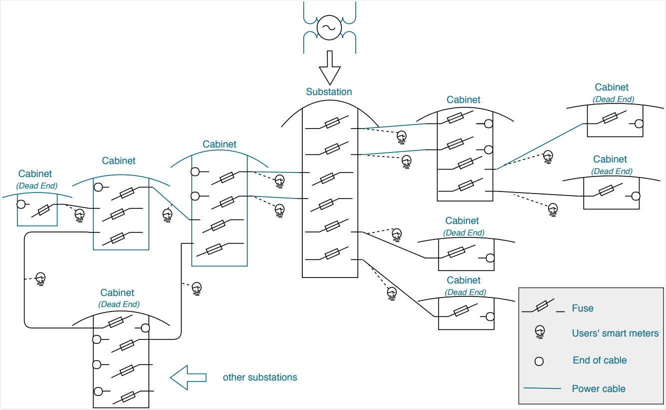
Introduction

- The low-voltage distribution grid is organized in a ***multigraph***
- Its ***vertices*** are the **substations** and **cabinets**
- its ***edges*** are the power lines (**cables**) of the grid
- Every cable starts from a **fuse** in a cabinet and ends in an other's cabinet fuse
- Between the cable and each user installation a **smart meter** is installed



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Problem definition

How to determine the **optimal sequence of actions** to reconfigure a smart grid system?

- Limit the consumption and/or the production of the smart grid's users
- Change the state of the fuses *(controlling the reachability of the cables)*

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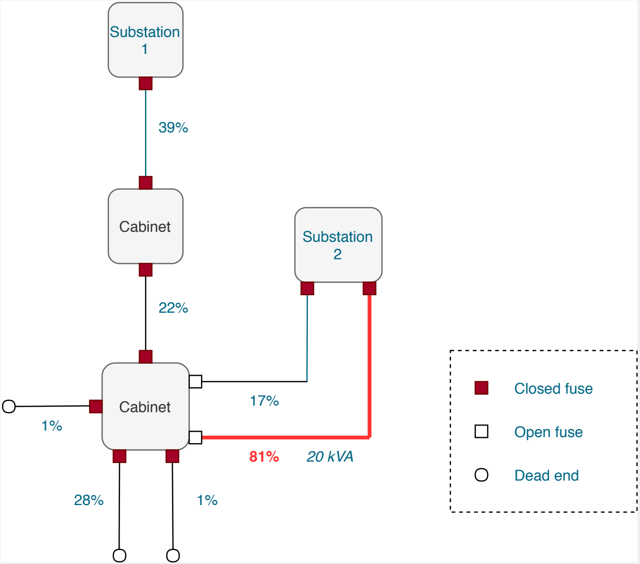
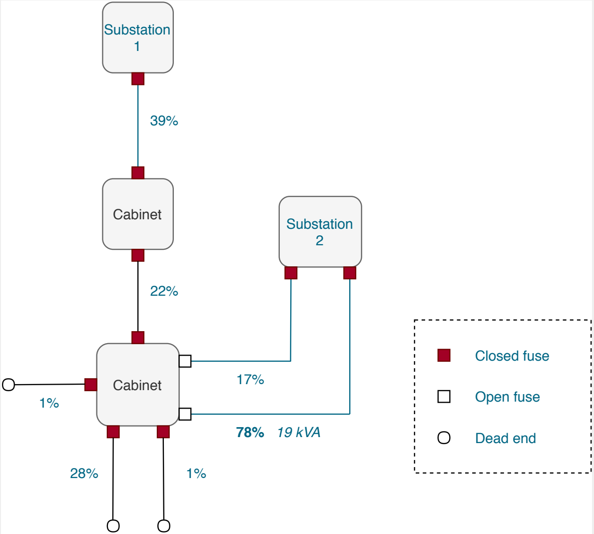
First example: Overloading cable



First example: Solution

Limiting power to over-consuming user



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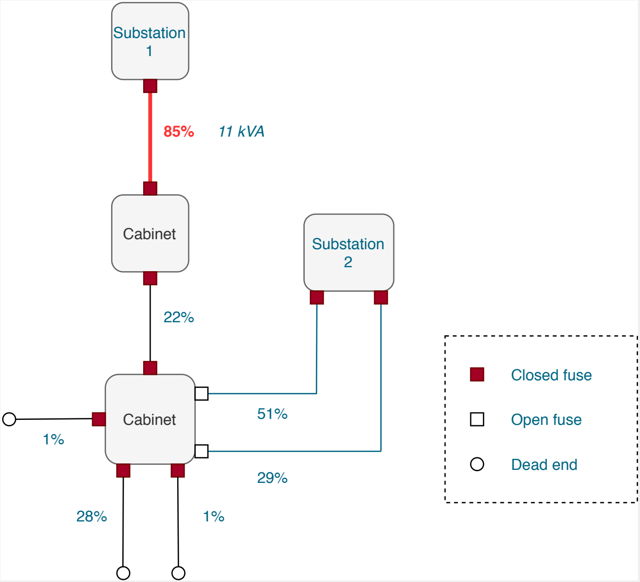
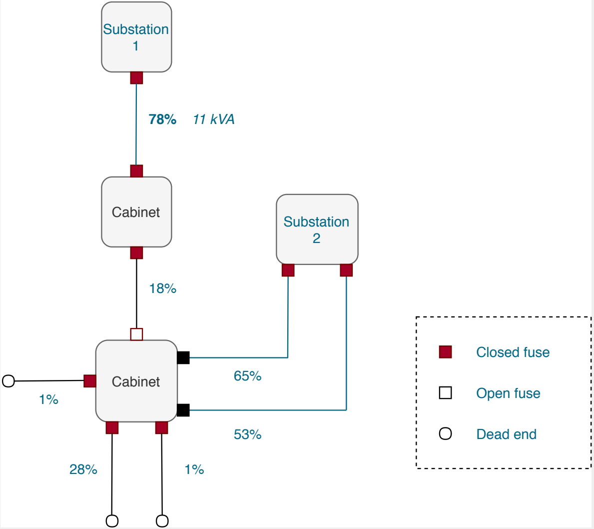
Second example: Overloading cable



Second example: Solution

Change grid's topology when user regulation is not possible



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Nomenclature (1/2)

n	number of cables, $n \in \mathbb{N}^*$
r_i	reachability cable state; 1 if cable i is powered and 0 otherwise
m	number of users, $m \in \mathbb{N}^*$
uc_{ki}	user cable indicator; 1 if user k is connected with cable i, 0 otherwise
o	number of cabinets (including substations), $o \in \mathbb{N}^*$
$dfcab_b$	cabinet visit indicator; 1 if $\sum_{f=1}^{2n} cc_{bf}\lvert x_f - x_f^0\rvert \geq 1$, 0 otherwise
x_f	fuse state; 1 if fuse f is closed, and 0 otherwise; if $f = 2i$, x_f denotes the current state of the *start* fuse of cable i, else if $f = 2i + 1$, x_f denotes the current state of the *end* fuse of cable i
x_f^0	initial fuse state
cc_{bf}	fuse cabinet indicator; 1 if fuse f belongs to the cabinet b, 0 otherwise

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Nomenclature (2/2)

A_{jf}	coefficient matrix element; for equation j and fuse f, $A_{jf} \in \left\{-1, 0, 1\right\}$
wp_f	actual active energy vector energy element for fuse f; $wp_f \in \mathbb{R}$
P_j	active load vector element; $P_j = PI_i \cdot r_i$, if equation j is describing the current flow of cable i, and 0 otherwise, $P_j \in \mathbb{R}$
PI_i	initial active energy for cable i, $PI_i = \delta \sum_{k=1}^{m} uc_{ki} RaE_k$
δ	measurement frequency coefficient; e.g. $\frac{60}{15} = 4$, for 15 min interval
RaE_k	real active energy consumption for user k,
	$RaE_k = aE_k$, if $cur_k < I_{LC}$, (consumer) or $cur_k < I_{LP}$ (producer), and $RaE_k = RGaE_k$ otherwise
aE_k	active energy for user k, $aE_k = aEC_k - aEP_k$, $aE_k \in \mathbb{R}$
aEC_k	active energy consumption for user k, $aEC_k \in \mathbb{R}_+$
aEP_k	active energy production for user k, $aEP_k \in \mathbb{R}_+$
rE_k	reactive energy for user k, $rE_k = rEC_k - rEP_k$, $rE_k \in \mathbb{R}$
rEC_k	reactive energy consumption for user k, $rEC_k \in \mathbb{R}_+$
rEP_k	reactive energy production for user k, $rEP_k \in \mathbb{R}_+$
cur_k	amperage of user k, $cur_k = \frac{\sqrt{aE_k^2 + rE_k^2}}{\sqrt{3} \cdot 230}$
I_{LP}	maximum allowed amperage for producers, e.g. 60A
I_{LC}	maximum allowed amperage for consumers, e.g. 32A
$RGaE_k$	curtailed active energy for user k, $RGaE_k = \sqrt{\lvert 230^2 \cdot 3 \cdot I_R^2 - rE_k^2 \rvert}$, $RGaE_k \in \mathbb{R}_+$
I_R	curtailed amperage for users, e.g. 20A
wq_f	actual reactive energy vector energy element for fuse f; $wq_f \in \mathbb{R}$
Q_j	reactive load vector element; $Q_j = QI_i \cdot r_i$, if equation j is describing the current flow of cable i, and 0 otherwise, $Q_j \in \mathbb{R}$
QI_i	initial reactive energy for cable i, $QI_i = \delta \sum_{k=1}^{m} uc_{ki} rE_k$

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l_i	actual current load percentage, at cable i; $l_i = \max\left(\frac{100\sqrt{wp_{2i}^2 + wq_{2i}^2}}{230 cl_i \sqrt{3}}, \frac{100\sqrt{wp_{2i+1}^2 + wq_{2i+1}^2}}{230 cl_i \sqrt{3}}\right)$
$\hat{n}$	maximum allowed current load percentage for all cables, e.g. 80%
i	cable index, $i \in \left\{1, \ldots, n\right\}$

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Mixed Integer Quadratically Constrained Program (MIQCP) formulation

1st objective : **Maximize the serviced users of the grid**

$$\max \sum_{i=1}^{n} r_i \sum_{k=1}^{m} uc_{ki} \tag{1}$$

2nd objective : **Minimize the number of visiting cabinets**

$$\min \sum_{b=1}^{o} dfcab_b \tag{2}$$

3rd objective : **Minimize the number of fuses' changes**

$$\min \sum_{f=1}^{2n} |x_f - x_f^0| \tag{3}$$

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Basic constraints

Approximate active energy for the current topology

$$A \cdot wp = P \tag{4}$$

Approximate reactive energy for the current topology

$$A \cdot wq = Q \tag{5}$$

Cable amperage constraint

$$I_i < \mathcal{I}, \forall i \in \left\{1, \ldots, n\right\} \tag{6}$$

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Dataset and experimental setup

- Topology generator
- 10 instances x 10 grid topologies x 216 scenarios = 21600 instances
- Consumption and production energy data based on historical data from *Creos Luxembourg S.A.*
- *Soft curtailment* is applied if
  - a producer overpasses the threshold of 60A, i.e., 80% of 75A, or
  - a consumer overpasses the threshold of 32A, i.e., 80% of 40A
- If a producer or a consumer is curtailed, its active energy is limited to 20A

Research questions

- ***First research question:***
  scalability of our approach wrt. increasingly-large grids
- ***Second research question:***
  how well curtailment policies allow avoiding user disconnections?

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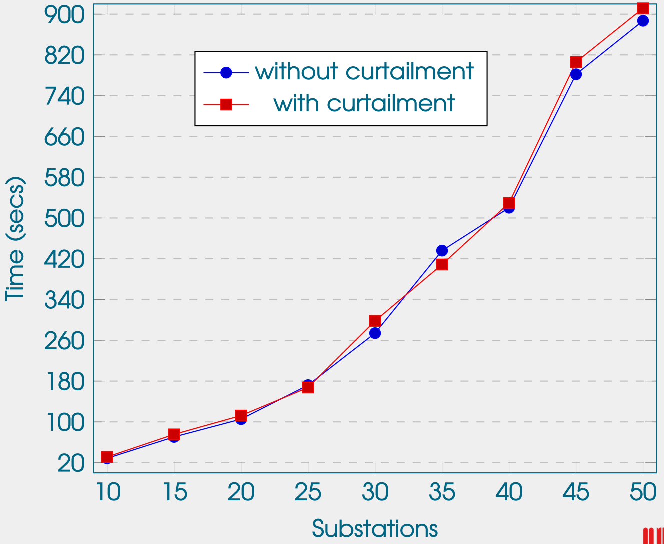
Findings - 1st Research Question



- When the size of the graph doubles, time is five times higher.

Findings - 2nd Research Question

- 10 topologies with 5 substations
  - average time 6.363 sec $\pm$ 1.527 sec
- If overloaded consumers $\leq$ 10% and overloaded producers $\leq$ 25%
  - **no disconnection is needed** (if we curtail all users)
  - 6.98% of cabinets should be visited
  - 3.47% of fuses should be changed
- With no curtailment, even when overload producers $\leq$ 10%
  - 5.43% $\pm$ 0.93% of the users should be disconnected

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Conclusions

- Defined and formulated the overloading prevention problem in smart grids as a Multiobjective MIQCP.
- Suggested a solution method using a state-of-the-art exact solver.
- Can be included in the grid operator's decision-making process.
  - Prevent challenging overloading incidents in a smart grid
  - Minimizing the disconnections of the grid's users.

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Future work

- It would be interesting to analyze the intermediate states to find the ***optimal order*** of fuses' change.
- Also, applying a ***dynamic soft curtailment*** policy would be a desired feature for the smart grid users.
- Another interesting addition should be the appliance of a ***fairness policy*** to avoid curtailing the same users repetitively over time.
- We should also consider the future states of the grid and their inherent stochasticity, as the recovery response solution should ***guarantee stability over the next 24 hours***.
- We also plan to exploit ***metaheuristic methods*** to solve the overloading prevention problem, that may help us to address the additions mentioned above.

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End of presentation

Thank you for your attention!

Contact details

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The 216 scenarios and these slides can be retrieved from
http://tiny.cc/ola2020_antoniadis

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Linear transformation

$$P_j = \sum_{f=1}^{2n} A_{jf} wp_f, \forall j \in \left\{1, \ldots, leq\right\} \quad (7)$$

$$Q_j = \sum_{f=1}^{2n} A_{jf} wq_f, \forall j \in \left\{1, \ldots, leq\right\} \quad (8)$$

$$zp_{jf} = \begin{cases} -wp_f, & A_{jf} = -1 \\ 0, & A_{jf} = 0 \\ wp_f, & A_{jf} = 1 \end{cases} \quad (9)$$

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$$-1y_{jf1} + 0y_{jf2} + 1y_{jf3} = A_{jf}, \quad (13)$$

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