The research leading to these results has received funding from the European Community's Seventh Framework Progamme (FP7/2007-2013) under grant agreement no 608732

# Optimal Configuration of Distribution Networks under Technical Constraints based on Predictive Methods

Master's Thesis Dissertation by
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M2 - Smart Grids and Buildings

Supervisors:
Raphaël Caire & Vincent Debusschere

June 25, 2014

# Agenda

*for today's presentation*

## Introduction

- Background
- Introduction to the Problem
- Literature Review

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## Preliminary Work

- Work Objectives
- Test Networks
- Day-ahead Load and DRES Models

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- Formulation & Economic Models
- Components
- Working of the Algorithm

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## Results & Conclusions

- Results Obtained
- Conclusions
- Future Work

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*Electrical Distribution Network Optimization*

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- Problems with DRES integration!
- Distribution network optimization has to take a new, giant leap.
- This work proposes a method to take this leap!

# Introduction

*to the problem*

Why is large-scale DRES integration is a problem?

- Variability / Intermittency
- Bi-directional Power Flows
- Grid Weakening
- Network Imbalance
- Fault Current Issues
- And finally: Money!

There is a **real need** to find solutions that assuage the problem with the integration of DRES.

# Literature Review

*Current Work in the Domain*

**Forecasting:**

- A lot of work has been done in forecasting for DRES and Loads
- Persistency / NWP based methods
- Both traditional and stochastic load forecasting: fairly **mature**
- But are they applicable to Distribution Networks?

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- But are they applicable to Distribution Networks?

**Distribution Network Optimization:**

- "Snapshot" based optimization
- Few instances of multi-temporal optimization
- Even they don't take a lot of issues into account
- Hence, there is a real need for a novel tool

# Part II

# Preliminary Work

# Work Objectives

The following requirements were defined for the work to be done. The work should:

- Create a **day-ahead schedule** based on DRES and Load forecasts

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- Be **modular**

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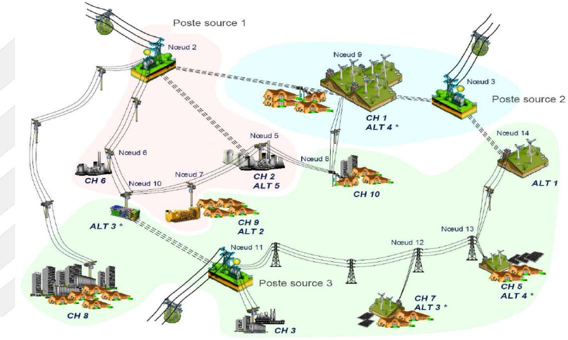
- Be **multi-objective**
- Be **modular**
- Be a **black box** for end-users

# Test Networks

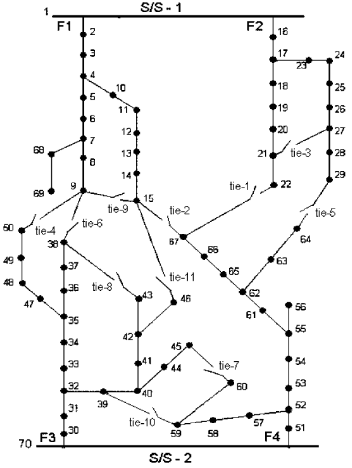
*Network 1 - PREDIS Urban Network*




- Reduced-scale Urban Network
- 14 buses, 17 lines
- Connected Load: 26.5 MVA
- Installed DRES Capacity: 27 MW
- Undervoltage and overcurrent problems

# Test Networks

*Network 2 - IEEE 11kV Rural Network*

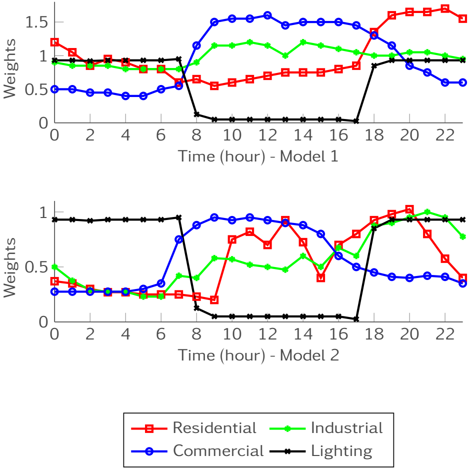



- Larger Network than PREDIS
- 70 buses, 79 lines
- Connected Load: 5.41 MVA
- DRES Info not available

# Day-ahead Load and DRES Models

*Raw Models*

- **Two raw models** extracted from literature.
- Specific weights for different types of loads.
- Residential, Industrial, Commercial, and Public Lighting.
- DRES Models: Values based on characteristic curves.
- Variation of Solar Power etc., taken into account.



# Day-ahead Load and DRES Models

*Models Applied to Networks*

## Load Model A

- This model consists of a simple association of each load type to one node.
- The load in each node varies accordingly for a given 24 hour period.

## Load Model B

Each node has a particular % of loads of each type.

| Load Type | PREDIS Network | Rural Network |
|---|---|---|
| Residential | 5 – 80% | 8 – 50% |
| Industrial | 5 – 50% | 20 – 75% |
| Commercial | 0 – 50% | 5 – 70% |
| Lighting | 5 – 15% | 5 – 15% |

# Day-ahead Load and DRES Models

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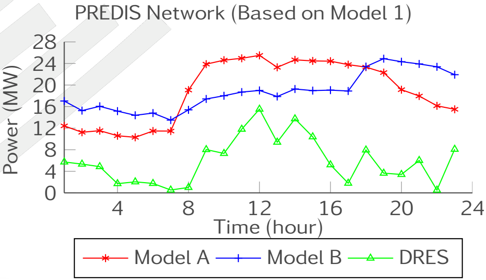
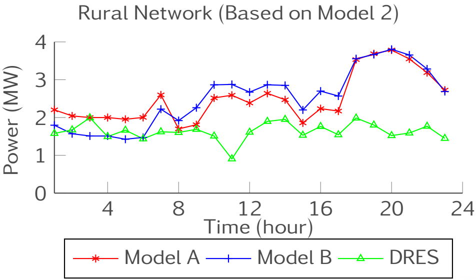


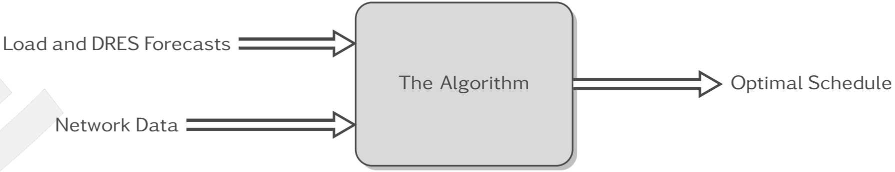



# Part III

# The Algorithm

# The Algorithm

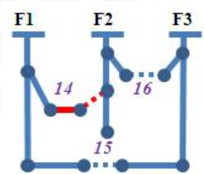
*Formulation*

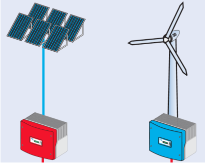


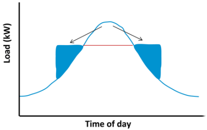
# The Algorithm

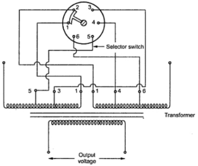
*Formulation*


Available Flexibilities





# The Algorithm

## *Economic Models*

- Switching:

$$Cost/switching = \frac{C_{sw}}{n_{sw}} + C_{OM} + C_{log}$$

$$C_{OM} = c \cdot f(t_{sw})$$

- OLTC:

$$Cost/operation = \frac{C_{OLTC}}{n_{op}} + C_{OM} + C_{log}$$

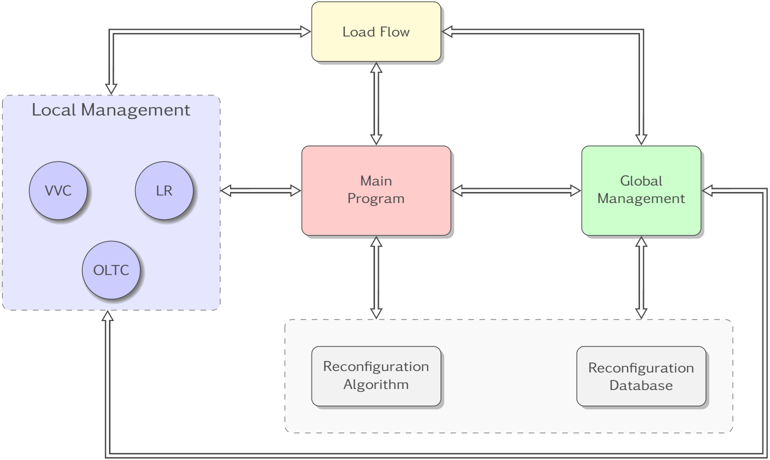
$$C_{OM} = c \cdot f(t_{op})$$

- Models for Load Reduction, VVC, and Violations are more difficult to develop.

| | |
|---|---|
| Switching Operation | 300 € |
| Load Reduction | 6 €/MWh |
| OLTC Operation | 20 €/Tap Change |
| VVC | 132.9 €/MWh |
| Violations | 500 €/violation |

# The Algorithm

*Components*

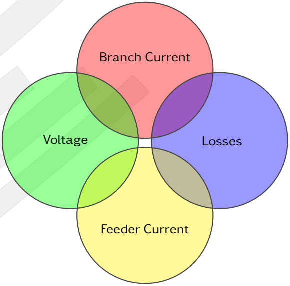



Legend: VVC: Voltage VAr Control, LR: Load Reduction, OLTC: On-Load Tap Changing

# The Algorithm

*Components - Reconfiguration*

Multi-Objective Reconfiguration




- Branch exchange based method with pre-selection
- Membership Functions for Each Objective:

$$x_i = \frac{PLOSS(i)}{PLOSS0} \qquad i = 1, 2, N_k$$
$$\mu L_i = \frac{(x_{max} - x_i)}{(x_{max} - x_{min})} \qquad \text{for } x_{min} < x_i < x_{max}$$
$$\mu L_i = 0 \qquad \text{for } x_i \leq x_{min}$$
$$\mu L_i = 1 \qquad \text{for } x_i \geq x_{max}$$

- Fuzzy min-max principle for finding branch to exchange
- Reconfiguration database based on "maximum" conditions

# The Algorithm

*Components - Local Management*

To manage "local" violations in distribution networks for the hour when it is launched.

## Voltage Violations

- When $V < 0.95pu$ or $V > 1.05pu$
- Solution: Use nearby nodes to improve voltage profile
- Objective function: $f = abs(V - (0.95 + c))$

## Current Violations

- When $I > I_{max}$
- Solution: Use downstream nodes to try reduce line current
- Objective function: $f = abs(I_{max} - (I + c))$

- When both current and voltage violations exist, consider both sets of nodes, $f = abs(V - (0.95 + c)) + abs(I_{max} - (I + c))$
- Once done, check if $C_{spent} \geq C_{org}$, if yes, do not optimize.
- Return solution to calling function.

# The Algorithm

*Components - Global Management*

Global Management (hour h)

With Reconfiguration

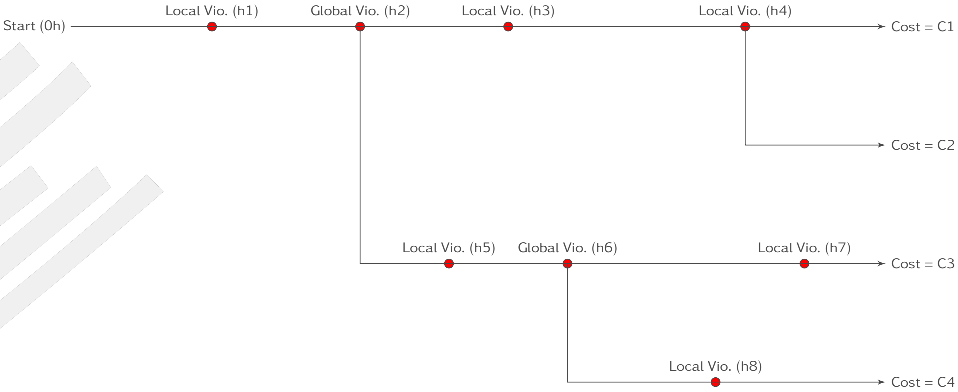
- At hour *h*, perform reconfiguration, and globally optimize using LM functions
- From hour *h+1* to end of the day, check for violations
- Classify violations found and launch the respective management function
- At the end of the day, calculate overall costs and feed it back to calling function

Without Reconfiguration

- At hour *h*, use only LM functions to optimize globally
- From hour *h+1* to end of the day, check for violations
- Classify violations found and launch the respective management function
- At the end of the day, calculate overall costs and feed it back to calling function

# The Algorithm

## *Working*

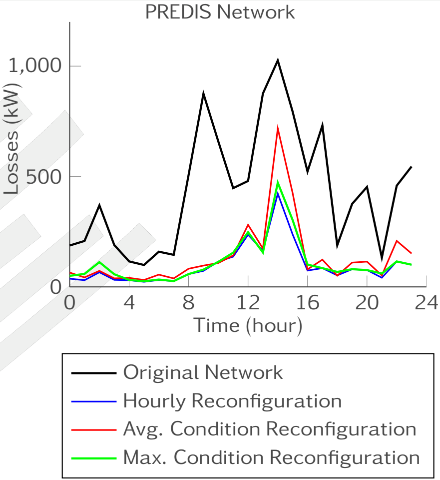


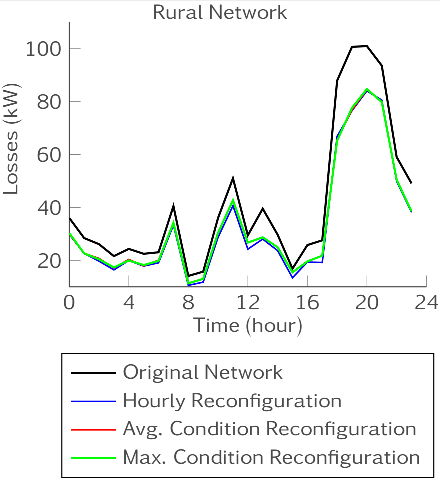
# Part IV

# Results & Conclusions

# Initial Results

*Why "Maximum" Condition was Chosen*



# Results

## *Methodology*

- Both networks were tested with the two load models.
- Two initial configurations were used: the original, and the 24 hour optimal configurations.

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*Methodology*

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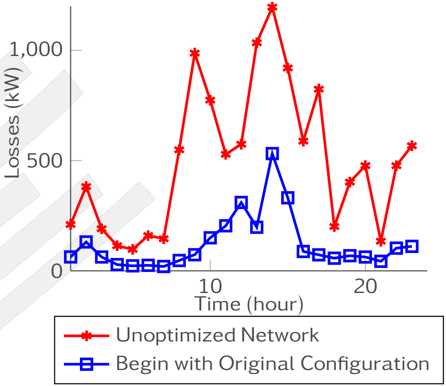
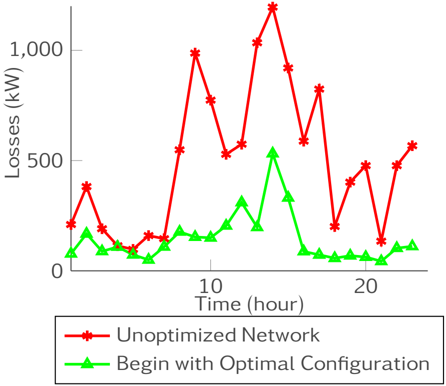
| Output Variables | |
|---|---|
| Money Spent without Optimization | Money Spent with Optimization |
| Load Reduction effected | DRES VVC Outputs |
| Number of Switching Operations | Number of OLTC Operations |
| Loss Curves over the 24h period | Complete Bus Voltage Profiles |
| Violations in the Network | Final Line and Bus statuses for every hour |

# Results

*PREDIS Network - Load Model A*



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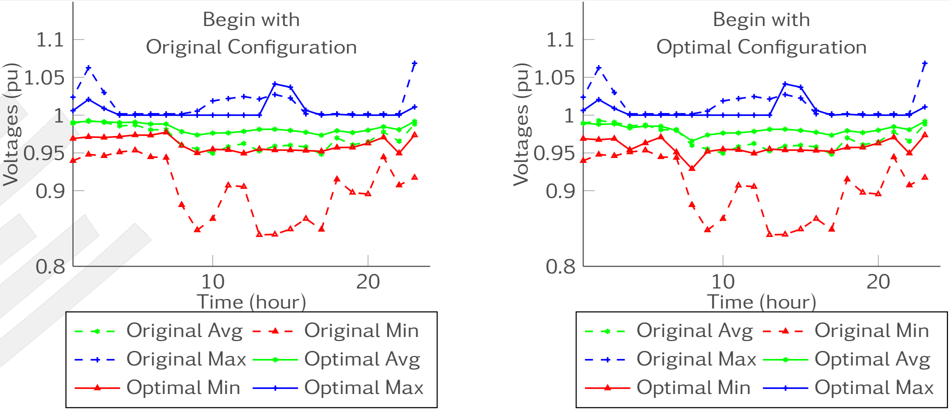
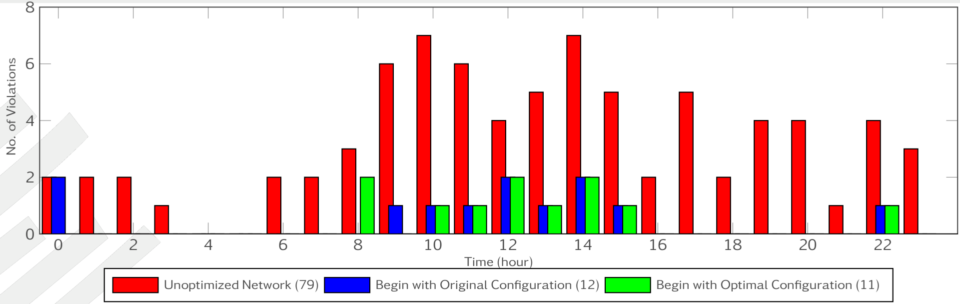



| | Unoptimized Network | Begin With Original Configuraiton | Begin With Optimal Configuration |
|---|---|---|---|
| Minimum Voltage (pu) | 0.8417 | 0.9359 | 0.9290 |
| Average Voltage (pu) | 0.9700 | 0.9826 | 0.9809 |
| Maximum Voltage (pu) | 1.0686 | 1.0413 | 1.0413 |

# Results

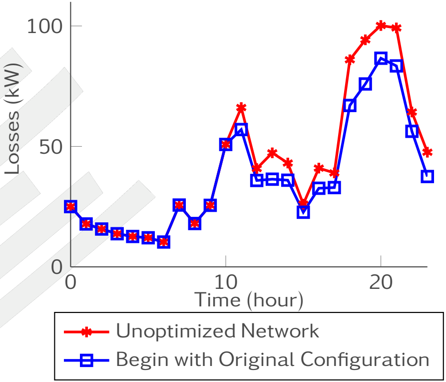
*PREDIS Network - Load Model A*

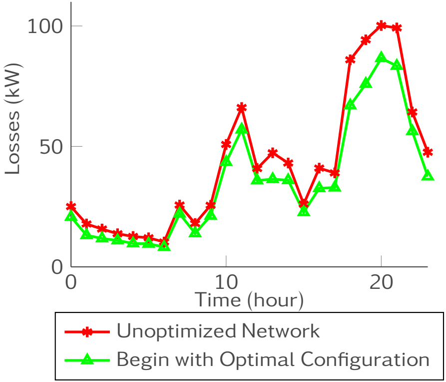



| Network Parameter | Original Configuration | Optimal Configuration |
|---|---|---|
| Money Spent without Optimization | € 41057 | |
| Money Spent with Optimization | € 14096 | € 13994 |
| Original Losses | 11503 kWh | |
| Optimal Losses | 2991 kWh | 3406 kWh |
| Load Reduced | 354 kWh | |
| VVC Energy | 512 kVArh | |
| Switching Operations | 8 (1 Reconfiguration) | 6 (1 Reconfiguration) |
| OLTC Operations | 3 | |

# Results

*Rural Network - Load Model B*



# Results

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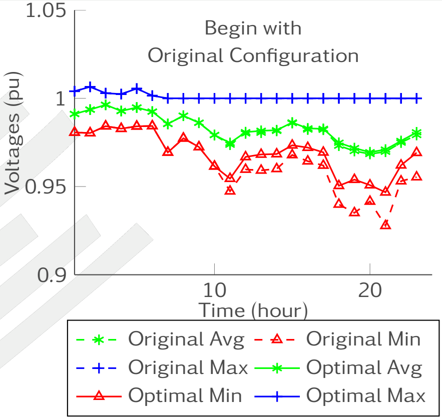
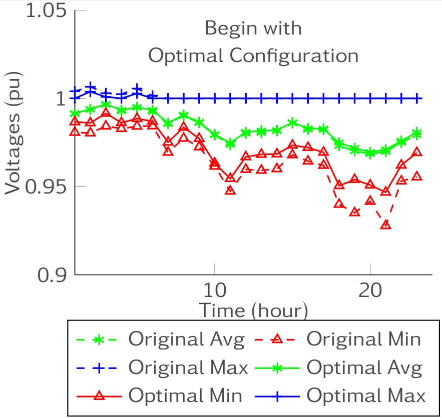
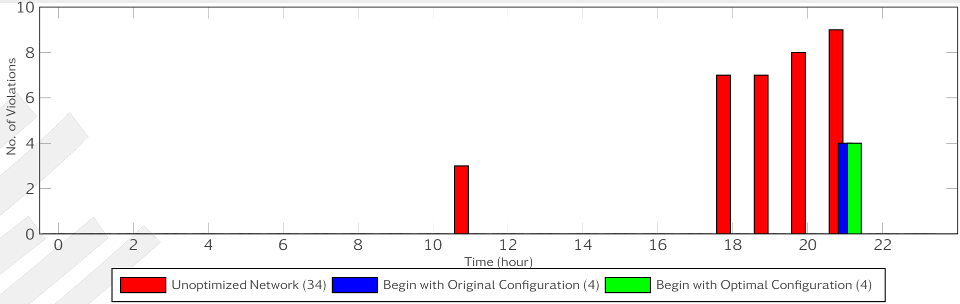



| | Unoptimized Network | Begin With Original Configuraiton | Begin With Optimal Configuration |
|---|---|---|---|
| Minimum Voltage (pu) | 0.9278 | 0.9467 | 0.9467 |
| Average Voltage (pu) | 0.9829 | 0.9834 | 0.9836 |
| Maximum Voltage (pu) | 1.0065 | 1.0065 | 1.0037 |

# Results

*Rural Network - Load Model B*




| Network Parameter | Original Configuration | Optimal Configuration |
|---|---|---|
| Money Spent without Optimization | € 17136 | |
| Money Spent with Optimization | € 7818 | € 10824 |
| Original Losses | 1022 kWh | |
| Optimal Losses | 887 kWh | 845 kWh |
| Load Reduced | ∼ 0 kWh | |
| VVC Energy | 0 kVArh | |
| Switching Operations | 14 (2 Reconfigurations) | 2 (1 Reconfiguration) |
| OLTC Operations | 0 | |

# Conclusions

## The developed algorithm

- Can optimize networks with a variety of characteristics.
- Is multi-objective and multi-temporal.
- Takes into account the day-ahead forecasts of DRES and loads, and uses inherent flexibilities.
- Outputs a day-ahead schedule.
- Provides Up to 70% reduction in **expenditure**, 91% reduction in **violations**, and 75% reduction in **losses**.
- Executes quickly.

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## Professional and Personal Perspectives

- Professional Perspectives: about my work in the laboratory
- Personal Perspectives: studying abroad

# Future Work

## Work envisaged

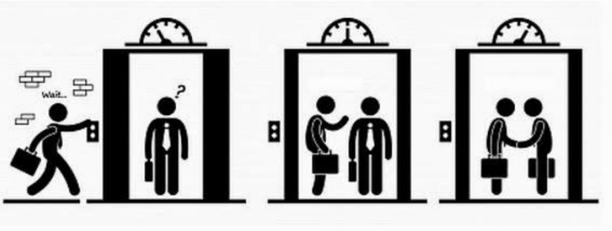
- Sensibility studies
- The development of a novel reconfiguration function
- The development of a better multi-objective constrained optimization function
- The development of a complete economic model
- The development of a day-ahead market based purchase scenario
- The development of a probabilistic load-flow function

All as a part of my PhD here at G2ELab, commencing in September.

# Thank You! ☺

# Questions? ☹

# Elevator Pitch

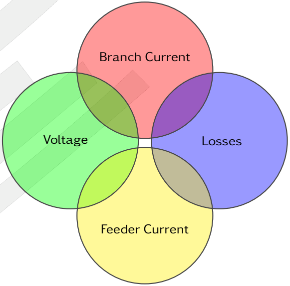


# Back-up Slides

# The Algorithm

*Components - Reconfiguration (Extras)*

Multi-Objective Reconfiguration




- Branch exchange based method with pre-selection
- Membership Functions for Each Objective:

| | |
|---|---|
| $x_i = \dfrac{PLOSS(i)}{PLOSS0}$ $\quad i = 1, 2, N_k$<br>$\mu L_i = \dfrac{(x_{max} - x_i)}{(x_{max} - x_{min})}$ for $x_{min} < x_i < x_{max}$<br>$\mu L_i = 0$ for $x_i \leq x_{min}$<br>$\mu L_i = 1$ for $x_i \geq x_{max}$ | $y_i = \lvert min(V_{nodes}) - V_s \rvert$<br>$\mu V_i = \dfrac{(y_{max} - y_i)}{(y_{max} - y_{min})}$ for $y_{min} < y_i < y_{max}$<br>$\mu V_i = 1$ for $y_i \leq y_{min}$<br>$\mu V_i = 0$ for $y_i \geq y_{max}$ |
| $z_i = max\left(\dfrac{I}{I_{max}}\right)$ for all branches<br>$\mu A_i = \dfrac{(z_{max} - z_i)}{(z_{max} - z_{min})}$ for $z_{min} < z_i < z_{max}$<br>$\mu A_i = 1$ for $z_i \leq z_{min}$<br>$\mu A_i = 0$ for $z_i \geq z_{max}$ | $u_i = max\left(\dfrac{IF_{max} - IF_{feeder}}{IF_{max}}\right)$ for all feeders<br>$\mu B_i = \dfrac{(u_{max} - u_i)}{(u_{max} - u_{min})}$ for $u_{min} < u_i < u_{max}$<br>$\mu B_i = 1$ for $u_i \leq u_{min}$<br>$\mu B_i = 0$ for $u_i \geq u_{max}$ |

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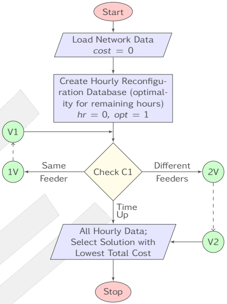
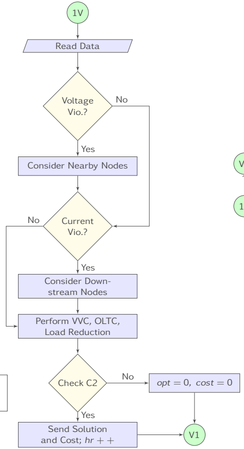
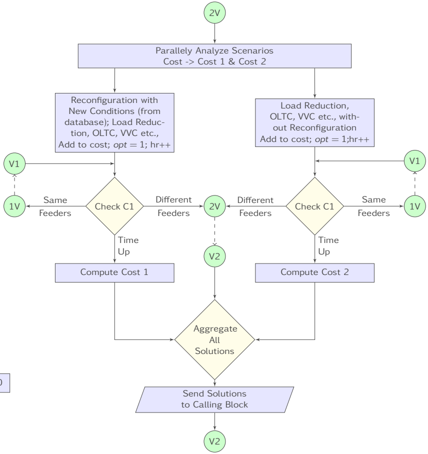
- Creation of the reconfiguration database based on “maximum” conditions

# The Algorithm

## *Working*



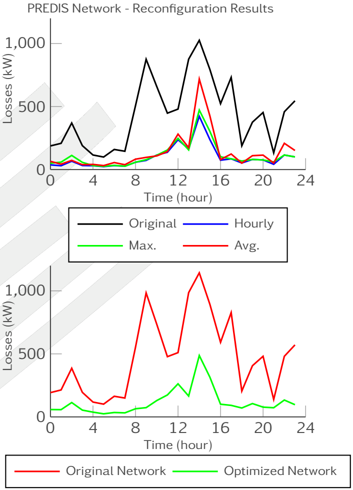



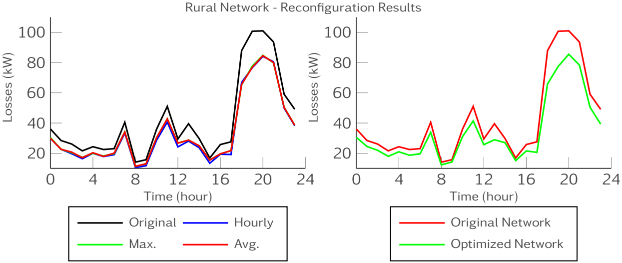

Condition C1:
*if hr* == 24
  go to "Time Up"
*else if opt* == 0
*OR violations in different feeders*
  go to "Different Feeders"
*else if violations in the same feeder*
  go to "Same Feeder"
*else*
  hr++; Check C1
end

Condition C2:
*Check if* $n\_vio\_new \geq n\_vio\_old$
*OR* $cost \geq cost\_vio + cost\_losses$

# Initial Results

## *Why "Maximum" Condition was Chosen*



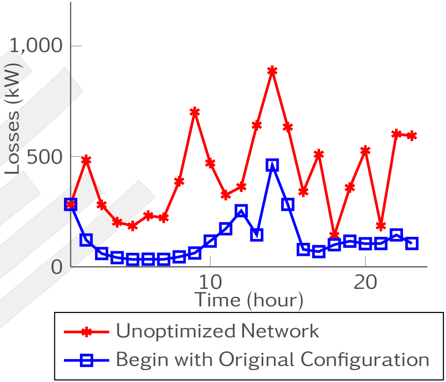



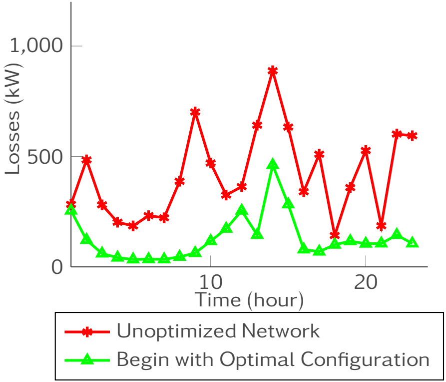

Comparison for "Maximum" Conditions

| Parameter | Original Network | Merlin & Back | Fuzzy Algorithm |
|---|---|---|---|
| **PREDIS Network** | | | |
| Power Losses (kWh) | 11503.77 | 2678.49 | 2796.41 |
| Minimum Voltage (pu) | 0.9359 | 0.9415 | 0.9433 |
| Voltage Violations | 70 | 9 | 5 |
| **Rural Network** | | | |
| Power Losses (kWh) | 999.81 | 814.11 | 822.82 |
| Minimum Voltage (pu) | 0.9262 | 0.9410 | 0.9462 |
| Voltage Violations | 34 | 11 | 7 |

# Results

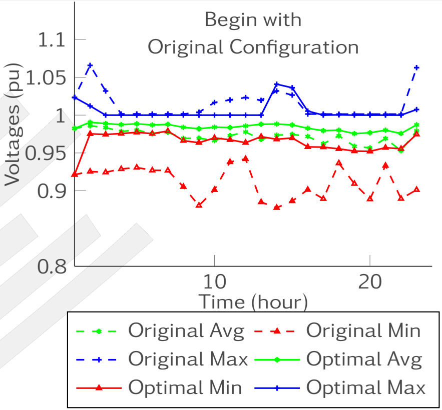
*PREDIS Network - Load Model B*

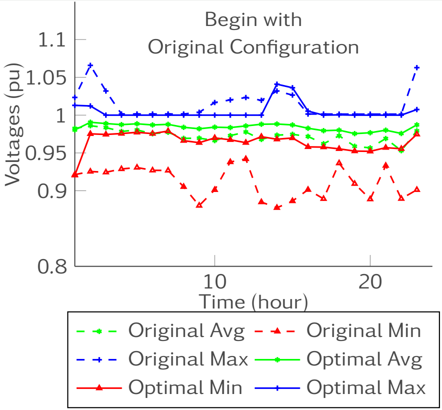


# Results

*PREDIS Network - Load Model B*

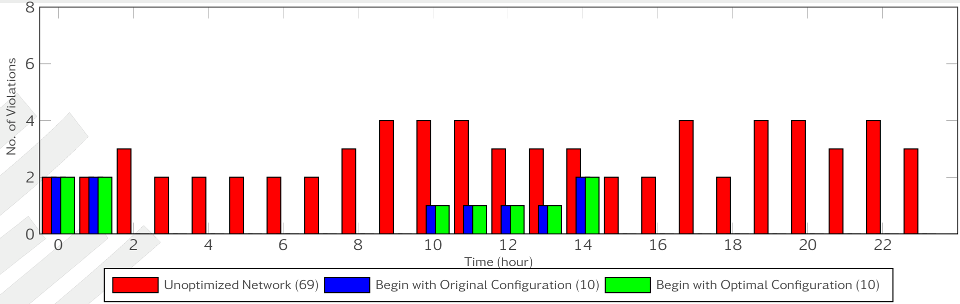



| | Unoptimized Network | Begin With Original Configuraiton | Begin With Optimal Configuration |
|---|---|---|---|
| Minimum Voltage (pu) | 0.8775 | 0.9156 | 0.9122 |
| Average Voltage (pu) | 0.9722 | 0.9836 | 0.9836 |
| Maximum Voltage (pu) | 1.0658 | 1.0409 | 1.0409 |

# Results

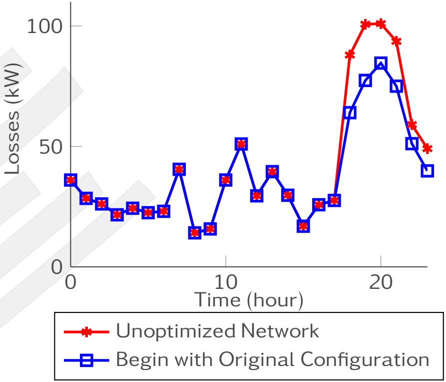
*PREDIS Network - Load Model B*

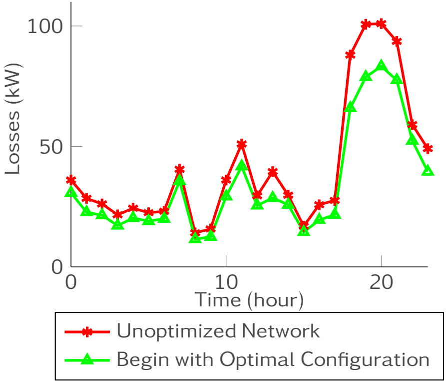



| Network Parameter | Original Configuration | Optimal Configuration |
|---|---|---|
| Money Spent without Optimization | € 35807 | |
| Money Spent with Optimization | € 12560.6 | € 14793.89 |
| Original Losses | 9834 kWh | |
| Optimal Losses | 3247 kWh | 3219 kWh |
| Load Reduced | ∼ 0 kWh | |
| VVC Energy | 0 kVArh | |
| Switching Operations | 10 (1 Reconfiguration) | 6 (2 Reconfigurations) |
| OLTC Operations | 0 | |

# Results

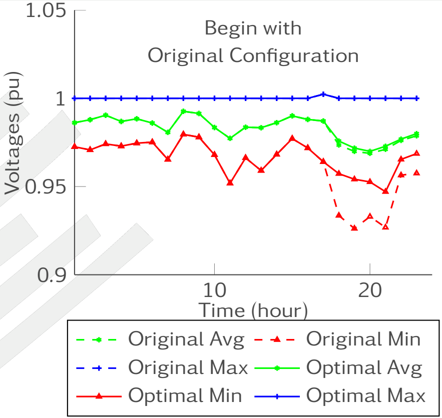
*Rural Network - Load Model A*

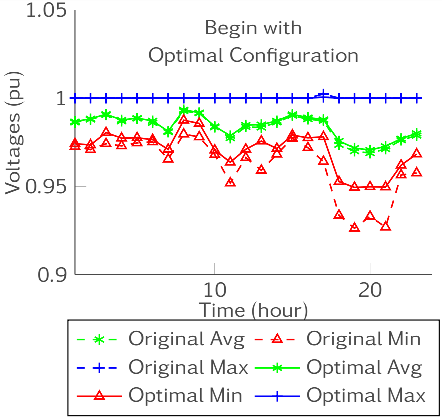


# Results

*Rural Network - Load Model A*

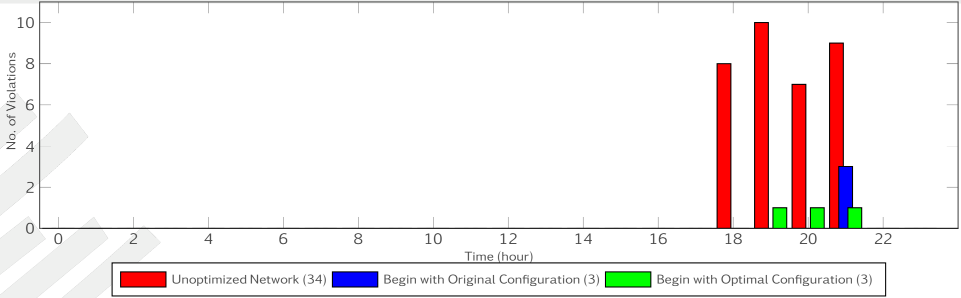



| | Unoptimized Network | Begin With Original Configuraiton | Begin With Optimal Configuration |
|---|---|---|---|
| Minimum Voltage (pu) | 0.9262 | 0.9471 | 0.9494 |
| Average Voltage (pu) | 0.9829 | 0.9833 | 0.9838 |
| Maximum Voltage (pu) | 1.0023 | 1.0023 | 1.0004 |

# Results

*Rural Network - Load Model A*




| Network Parameter | Original Configuration | Optimal Configuration |
|---|---|---|
| Money Spent without Optimization | € 17133 | |
| Money Spent with Optimization | € 5246 | € 6243 |
| Original Losses | 1000 kWh | |
| Optimal Losses | 900 kWh | 814 kWh |
| Load Reduced | $\sim$ 0 kWh | |
| VVC Energy | 45 kVArh | 40 kVArh |
| Switching Operations | 12 (1 Reconfiguration) | 0 (0 Reconfigurations) |
| OLTC Operations | 1 | |