FLANDERS' LINEAR PILOT PROJECT – IMPLEMENTING RESIDENTIAL DEMAND-RESPONSE ALGORITHMS

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ABSTRACT

Linear is a public-private pilot project that has been implemented in Flanders (Belgium) between 2009 and end 2014. About 240 households were equipped with smart appliances and participated in a residential demand-response (DR) pilot. The appliances (washing machines, tumble dryers, dishwashers, domestic hot water (DHW) tanks, electric vehicles (EVs)) were able to communicate with a central party and to follow DR control actions, to fulfill 4 business cases.
2 of those are Distribution System Operator-centric: "Transformer Ageing" & "Voltage Control". The 2 other are Balancing Responsible Party-centric: "Portfolio Management" & "Wind Production Balancing".
In this paper, focus is on the Transformer Ageing algorithm implementation, as an example methodology.
Results were published during the ongoing project [2]-[6] (non exhaustive) and eventually, the project's global conclusions were proposed on the closing event on the 9th of December 2014 in Brussels [1].

INTRODUCTION

The real potential of demand response in the residential sector is the central question that was investigated during the field test of Linear, a public-private pilot project that has been implemented in Flanders (Belgium) between 2009 and end 2014. This potential depends on type and number of flexible appliances in place, on user acceptance and behavior, technical and economic constraints.
The need for demand response is based on the need to mitigate the effects of:
- the increasing share of intermittent renewable energy production;
- the increased electrical load due to the shift from fossil-fuel to electrical technology in mobility and heating;
- decreasing capacity of directly-controllable (fossil-fuel) plants.

Business Cases

The demand response algorithms were implemented to use residential flexibility to fulfill four business cases.
1. Portfolio Management: can we make customers shift their energy consumption based on the day-ahead market and nominations?
2. Wind Balancing: can we reduce unbalance costs that are caused by discrepancies between the wind energy that is predicted and actually produced?
3. Transformer Ageing: can load spreading over time prevent the accelerated ageing of transformers?
4. Line Voltage Management: can we prevent voltage deviation issues in local grids?

The first two are Balancing Responsible Party (BRP)-centric, while the last ones are Distribution System Operator (DSO)-centric.

FIELD TEST

The challenge of setting up a residential demand response field test is very different from industrial demand response.
- Customer comfort safeguards are a basic requirement to enable sustained participation of families in demand response schemes.
- The sources for flexibility are small in the quantity of energy but numerous and dispersed.

About 240 households were equipped with smart appliances and participated in the field test. Among them, 110 houses were equipped with smart meters from DSOs Eandis and INFRAX. The other houses involved had standard energy meters for overall consumption and possibly production. Approximately 2,000 sub-metering plugs were installed, and 94 houses had photovoltaic panels accounting for a total of 400 kWp.
Two different consumer interaction models were evaluated:
- Variable Time of Use: energy consumption can be manually altered, based on variable energy tariffs on six timeslots during the day (prices communicated the day before with a display).
- Automated Demand-Side Management: a Home Energy Management System and smart appliances were provided. Demand response and consumer comfort were managed automatically.

The smart appliances were of two types: the first, postponable appliances, such as dishwashers, washing machines and tumble dryers, were 445 in total. The second type consisted of buffered appliances: 15 domestic hot water buffers and 7 electric vehicles. All smart appliances were able to communicate with a central party and to follow DR control actions.

ALGORITHM IMPLEMENTATION

Reference level

Dedicated algorithms were developed to fulfill the different business cases requirements. Some of those optimize towards an absolute consumption level: total current in the transformer, total current at the house connection point. Other need a reference consumption level to optimize towards the difference (e.g. when the effort is "paid" in comparison to that level).
Most methodologies proposed in the literature to address DR "effort" use statistical analysis of historic consumption data as a reference for preparing commands. Those methodologies are not deterministic, and result in some sub-optimal use of the available flexibility. In Linear, a deterministic methodology has been proposed in order to realize the constraints, based on the use of a so-called norm behavior per flexible appliance, being the default behavior the appliances would have showed if no flexibility was asked [5]. The algorithm optimizing for example the "Wind Balancing" business case, makes use of this "norm behavior".
After choosing reference level and methodology to calculate it, the aggregation of smart appliances itself can begin.

Example : Transformer Ageing

As an illustration, the "Transformer Ageing" algorithm is described, optimizing towards an absolute consumption level. This scenario answers the local consumption constraint in order to maximize the distribution transformer lifetime in the Linear pilot. The aim of this algorithm is to adjust the power flow of a transformer to an optimum value (see further). This is realized by aggregating residential appliance profiles, i.e. switching on or off smart devices remotely on a quarter hourly base, with respect of absolute comfort for the residential end-user.

In case the correction requires extra load, the flexibility is given by switching on the white goods, EVs and DHW tanks that are available but not currently working. In case the correction requires reduced load, the flexibility is obtained by switching off DHW tanks and/or EVs. Once started, the white goods cannot be stopped; the flexible capacity is therefore asymmetric. The algorithm is defined to limit the possible negative effects of that asymmetry.

The evaluation of the transformer optimal power setpoint is based on the model described in IEC 60076-7. This model provides a method for the calculation of the winding hot-spot temperature in function of time, which is used to calculate ageing. The input parameters are the measured top-oil temperature, ambient temperature and load currents (Figure 2). The optimal load currents are then estimated on the base of the predicted top-oil and hot-spot temperatures on a two hours period.

The standard's reference hotspot temperature is 98 °C for non-thermally upgraded paper and 110 °C for thermally upgraded paper. It is presumed that this corresponds to an ageing factor of 1 and a normal insulation life of 20.55 years [7]. The calculated ageing factor expresses the ageing relative to this default ageing. However, the transformers deployed in the Linear pilot were over-dimensioned and stayed well below these limits and no significant ageing was observed. To artificially increase ageing, a hotspot temperature limit of 60 °C was used in the Linear experiments.

The control algorithm was fully tested in laboratory and has been deployed within the households of a geographically concentrated cluster, connected to several transformers.

Step by step

The algorithm was processed each 15 minutes. For each time step, the hotspot temperature is first calculated. Then, based on the temperature history and current measurements, a 180-minute forecast of the hotspot temperature is drawn up. Based on this data the change in consumption required to lower or increase the hotspot temperature towards 60 °C was derived. The aggregation control algorithm was then used, with the demand response ΔP control point set to this 60 °C consumption change.
The resulting behavior was that consumption was stimulated when the temperature was low and decreased when the temperature was high. Most of the time the ΔP set points were much higher or lower than what the cluster could provide (ΔC). (Figure 3) The goal here was not to track ΔP as closely as possible as for e.g. the wind balancing case, but rather to shift as much consumption as possible to periods with a low transformer temperature.

Control Performance

As ageing occurs primarily during the evening peak, the control's performance can be measured by its success in shifting consumption away from the evening period. The flexible consumption available in LINEAR on the transformer in Genk is composed of 14 washing machines, 14 dishwashers, 7 tumble dryers and 3 domestic hot water buffers.
For white good appliances, the performance was good (Figure 1). However, the performance for the buffers was lower, i.e. although consumption during the evening peak

was lowered and postponed into the night, peak time consumption remained significant.

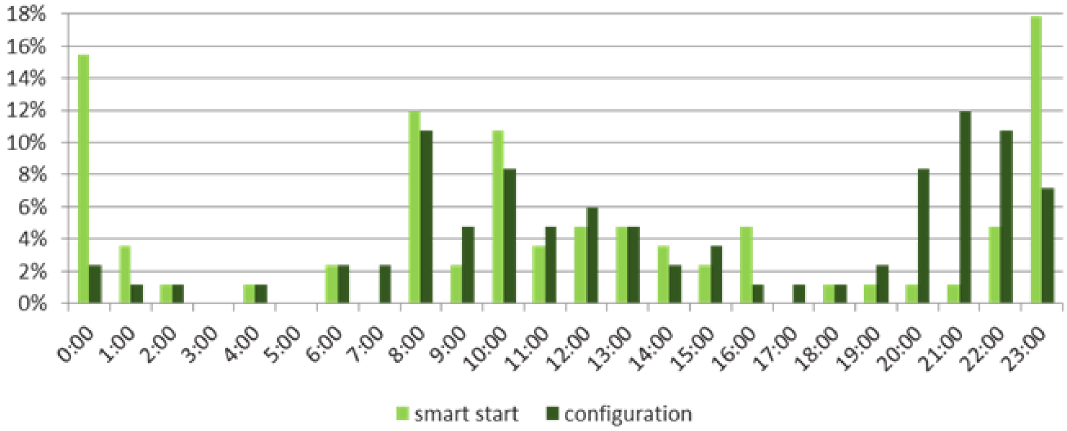

Figure 1 – Appliance performance (e.g. washing machines) in shifting away from (evening) peak consumption moment

Since our measurements demonstrated a strong correlation between evening peak and ageing, these heuristics were able to be used to both simplify and improve the control algorithm. The cluster could then prepare for the approaching evening by scheduling white goods appliance cycles before and after the peak, and by fully charging domestic hot water buffers in the afternoon.

When the real behavior (through energy measurements) was confronted with the control system's perception, a difference appeared. Delays in the execution of control commands, communication problems during which no or limited status info was available, inaccurate status information, errors in the power consumption estimates for white goods appliances, as well as comfort overrule switching for domestic hot water buffers, all had an impact.

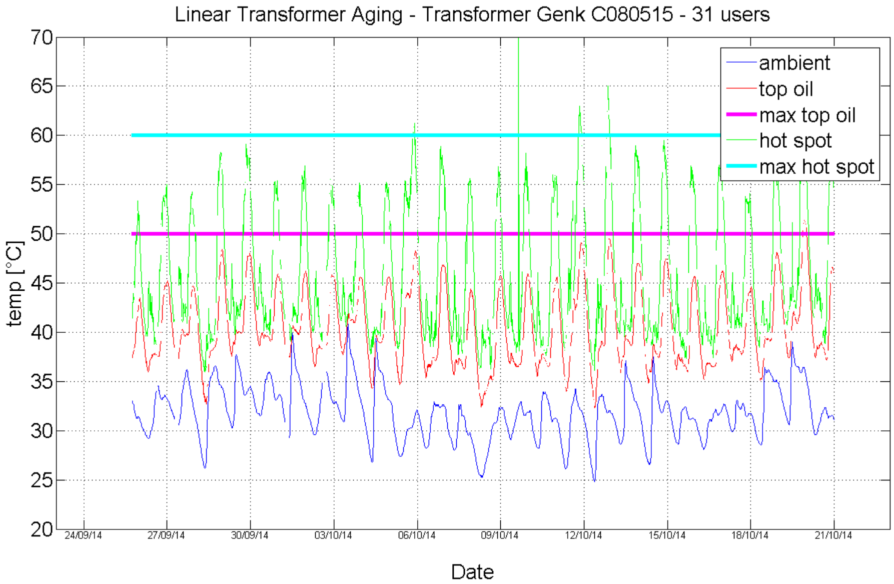

Figure 2 – measured and computed temperatures over 26 days, for transformer Genk C080515

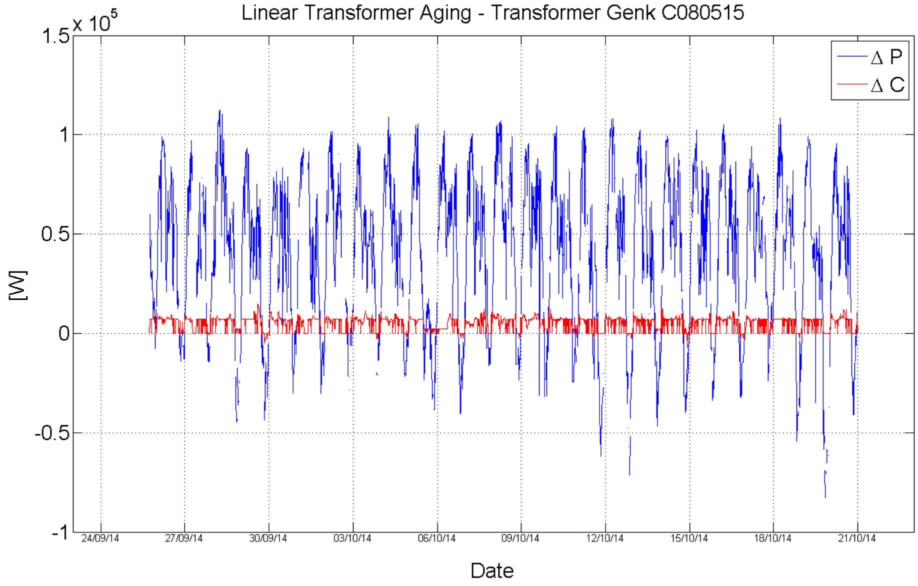

Figure 3 - ΔP and ΔC over 26 days, for transformer Genk C080515

GLOBAL CONCLUSIONS

Algorithm implementation

The 3 algorithms for the other business cases were successfully implemented since end 2013 by the authors on a wide number of households within the Linear project. The tests allowed to evaluate the real impact of the aggregation of residential flexibility, with a deterministic approach.

DSO-centric business cases

The lifetime of the Linear transformer is slightly (<1%) increased using demand response. The reason the improvement was so small is the lack of sufficient flexibility. Only a limited fraction of the houses (160 in total) connected to the transformer are participating in the Linear pilot. This implies that ideally the total local flexibility potential must be addressed.

A similar conclusion can be made for the line voltage scenario. The available flexibility of the residential smart appliances was insufficient for the voltage control system to have a considerable impact on local voltage. However, if there would be enough appliances that have flexibility available continuously throughout the day, the Linear control mechanism [4] would be a viable option for controlling local voltage.

BRP-centric business cases

Automatic demand response helps to compensate the difference between the estimated and the real wind production. When consumption had to be increased due to an underestimation of wind generation, the cluster performed well. However, there is a cluster upper control limit of approximately 150 W per household (Figure 4). When consumption had to be decreased, the cluster underperformed.

The cluster upper control limit should not be confused with the maximum reaction potential of the cluster in case of rare events. The 150W per household was an enduring capacity to compensate the characteristic unbalance signal.

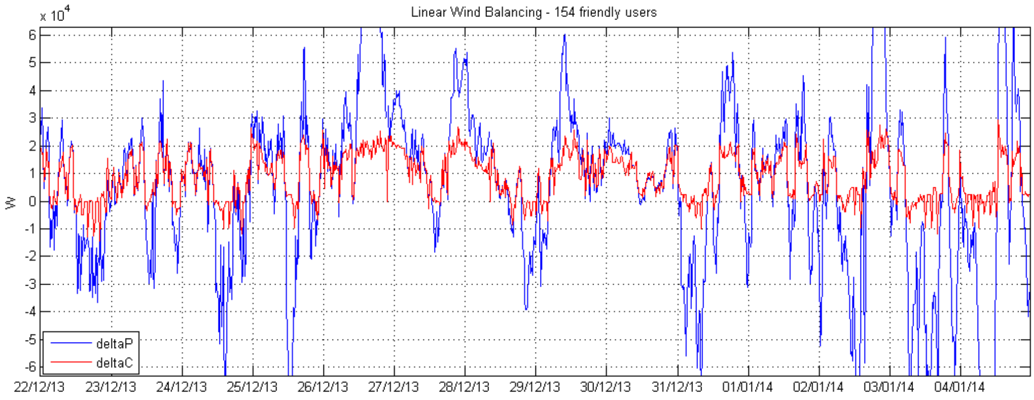

Figure 4 - Example of a (blue) unbalance signal caused by the unpredictability of wind-energy production and of the (red) compensating aggregated residential loads – real-life measurement with 154 equipped families

Interaction models

The response to the variable Time of Use tariff scheme was weak. The Linear tariff scheme turned out to be too complex: the end-user tires of continuously checking prices and the ensuing adverse impact on comfort.

The acceptance of automatic demand response through smart appliances, however, was much better. After 18 months of testing there was still no indication of user fatigue.

The Linear field test demonstrated that automated demand response with household appliances is technically feasible. The implementation of a capacity fee proved to be successful (if automated).

Improvements

At the same time Linear showed that in-house communication should need further development and standardization in order to keep the operational cost affordable.

More information

The complete project booklet can be obtained online [1].
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ACKNOWLEDGMENTS

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Research and industrial players joined forces in close collaboration with the government to develop, implement and evaluate demand response technology.

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